B4EST

Adaptive BREEDING for productive, sustainable and resilient FORESTs under climate change

Deliverable D5.6

Layman's report on benefits, costs and risks related use of improved FRM in Atlantic regions of Southern Europe

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1 Summary

The changing climate has been identified is an important driver of change in forests. It can increase forest vulnerability to damage and disease occurrence and intensity, reduce forest health and productivity, and cause economic losses. On the Atlantic coast in southern Europe, profitability of local production forests is threatened by both increasing abiotic (extreme heat, drought, fire) and biotic damages. At the present moment, it is important to note that in Spain and Portugal the profitability of maritime pine as well as Monterrey pine forestry is facing serious problems with growing abiotic and biotic damages, especially by the pine wood nematode and fungal diseases, worsened by increasing droughts, and with the rural abandonment as an underlying structural problem.

This deliverable focuses on benefits, costs and risks related use of improved forest reproductive material (FRM) of two pine species, maritime pine, *Pinus pinaster* Ait., and stone pine, *Pinus pinea* L. under future climate change scenarios. This report provides insights into how these two species are expected to perform and therefore lend assistance for forestry planning and decision making at the landscape and regional levels. Further steps will be to support forest management decisions at the unit scale for forest owners (mostly smallholders). Present findings are of great interest, because in Spain and Portugal non-improved local FRM continues to be the main sources for forestry. Only in south-western France, advanced maritime pine breeding programmes exist allowing supply from seed orchards.

In this scenario of multiple and synergic challenges and threats, decision making in forest management cannot limit itself to maximise private profitability of single smallholdings, but requires coordination between governance at landscape and regional level, to ensure the sustained provision of multiple ecosystem services from the future forests we aspire to, most notably the provision of structural timber and wood biomass, as an essential basis for a forest-based bioeconomy. The use of improved FRM in pine plantation forestry or artificial regeneration of pine forest ecosystems must be integrated within.

This deliverable shows the risks associated to *Pinus pinaster* and *Pinus pinea* FRM used in the Atlantic region and the limitations in the transfer of FRM to reduce these risks. The actions should be based on the results of the existing breeding programs of the species and the inclusion of some traits (nematode and fusarium resistance, abiotic stresses) in the breeding programs. These traits are under evaluation in some of the breeding programs and the benefits of using this improved material should be disseminated to the end users.

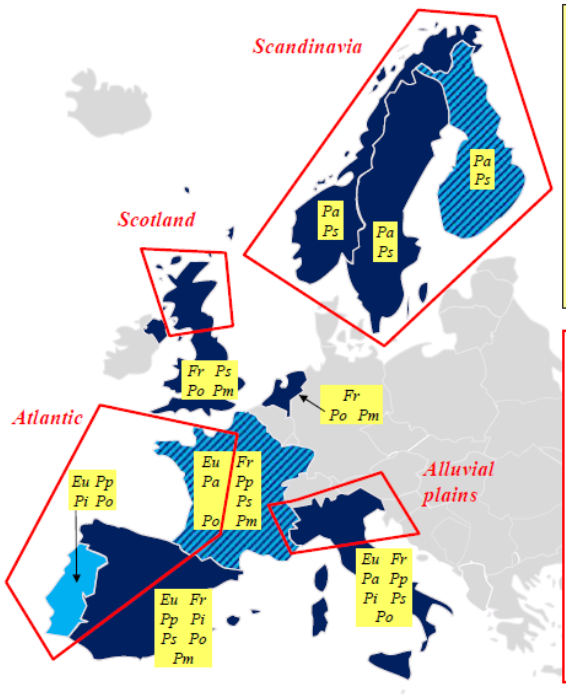
2 Tree breeding and deployment of FRM to meet challenges of European forestry

The changing climate is an important driver of change in forests. It can increase forest vulnerability to damage and disease occurrence and intensity, reduce forest health and productivity, and cause economic losses. However, it can also have positive effects, offering opportunities for growing trees in previously suboptimal regions.

The strategic goal of B4EST is to increase forest survival, health, resilience and productivity under climate change and natural disturbances, while maintaining genetic diversity and key ecological functions and fostering a competitive EU bio-based economy. B4EST has provided forest tree breeders, forest owners, managers and policy makers with: 1) better scientific

knowledge of adaptation profiles to increase sustainable forest productivity, and added value of raw materials for economically important tree species, 2) new and flexible adaptive tree breeding strategies and tools, 3) decision-support tools for the choice and use of Forest Reproductive Material (FRM) for balancing production, resilience and genetic diversity, 4) robust management and transfer recommendations for FRM deployment at stand and landscape levels, 5) policy recommendations to adapt European forest production systems to the challenges posed by climate change and natural disturbances, and to meet societal demands set to sustainable and multifunctional utilization of forest resources.

Benefits, costs and risks related to the deployment of improved FRM in Europe have been assessed by carrying out analyses indicating the impacts of revised deployment strategies in four different regions of Europe focusing on regionally prevalent challenges. The four different regions differ for growth conditions, tree species, structure of forests, operational environment of forestry, and expected biotic risks and other impacts of environmental change.



Tree species resources available for B4EST in the consortium countries

Tree species	Breeding populations (for WP1, 2, 3)	Multi-environment genetic experiments (for WP1, 2, 3, 4)
Eu	FR, PT, ES, IT	FR, PT, ES, IT, UK
Fy	FR, UK	FR, NL, UK
Pa	FI, NO, SE	FI, NO, SE, FR, UK
Pp	FR, ES, IT PT	FR, PT, ES, IT, UK
Pi	PT, ES	FR, PT, ES
Ps	FI, NO, UK, SE	FI, NO, SE, UK, FR, ES
Po	FR, IT	FR, IT, ES
Pm	FR, IT	FR, IT, ES, UK

EU zones with regionally prevalent challenges selected for the socio-economic impact analyses related to the deployment of improved FRM

Zones	Species	Indicators analysed
Scandinavia	*Pa, Ps*	Biomass production, financial performance, carbon sequestration, forest resilience and biodiversity
Scotland	*Ps*	Forest resilience, carbon sequestration, biodiversity, biomass production
Atlantic zone	*Eu, Pi, Pp*	Biomass production, carbon sequestration, forest resilience, biodiversity, seed production
Alluvial plains	*Po*	Biomass production, carbon sequestration, biodiversity

This report presents the main results from Atlantic zones of southern Europe (France, Spain and Portugal) where negative impacts of climate change are already visible and are expected to grow in the coming decades.

3 Context and regional prevalent challenges

3.1 Forest breeding and forest reproductive materials and forestry demands

Forests ecosystem services contribute to human prosperity and well-being through the provision of essential renewable resources, the regulation of air and water cycles, as well as with their cultural, spiritual and educational values (Hetemäki *et al.*, 2017). In the transition to a bio-based economy, ever more reliance will be needed on managed forests, particularly planted forests, in

order to satisfy an increasing demand for wood and non-wood forest products (Gardiner & Moore, 2014). Timber and non-timber forest productions are considered essential for promoting European bio-economy by increasing the amount of renewable high quality raw material for industries and markets (EC, 2021; Martínez de Arano *et al.*, 2021). The impacts of an increased use of improved FRM must also take into account the impacts and risks associated to climate change, as well as to pests and diseases.

Currently, many new challenges and threats have arisen whose background and driver are more often than not the ongoing climate change that is already altering the structure, composition and dynamics of forests in Europe, and which could threaten the continued provision of forest ecosystem services. Drought-induced tree mortality has increased in Europe in recent years, especially in the Mediterranean region, and is expected to worsen in the coming years (Allen *et al.*, 2010; Carnicer *et al.*, 2011; Benito Garzón *et al.*, 2013c; Vicente-Serrano *et al.*, 2014). Additionally, forest pathogen invasions have grown exponentially in Europe in the last decades (Jactel *et al.*, 2020).

In this context, it is critical to understand how tree species and populations will perform under future climate and biotic conditions, for decision support in forest planning, especially about profitability of productive forest plantations. Drought mitigation strategies, forest fire risk reduction and prevention, and increased resistance to pests and diseases are outstanding as key topics that can and must be pursued to help our forests to adapt to climate change, and it is likely that both innovations in silvicultural practices and adapted genetic resources are needed to address them (Silva *et al.*, 2018).

In plantation forestry, the management is supposed to aim at increased profitability, using best plant material available, genetically improved FRM resulting from forest tree breeding programs, whose goals have been usually growth (indirectly local adaptation), product quality (stem straightness and taper, fibre angle, etc.), or other relevant traits, for instance resistance to specific abiotic or biotic stresses (Ruotsalainen, 2014). But as Silva *et al.* (2018) have emphasized, the even-aged forestry practices dominant in 20th century in Europe must adapt to the changing conditions and social values of the 21st century. It needs to move toward more resilience and increased diversity of species and structures both at stand and at landscape scales, and it needs to bring abandoned forest land back into active management, for avoiding fuel continuities that favour mega-fires – these are major challenges that cannot be addressed by single forest smallholders alone, nor assisted by forest breeders.

Even under near-to-nature silviculture and in semi-natural ecosystems, forest tree species and populations are expected to get increasingly maladapted to their changing local climate conditions if the pace of climate warming is faster than trees can adapt, with marginal climatic populations at the rear (xeric) edge being particularly vulnerable (Pedlar & McKenney, 2017; Fréjaville *et al.*, 2020). One potential management option to assure forests persistence under new climates is the introduction of forest reproductive material from other provenances adapted to the expected new climatic conditions, a process known as assisted migration (AM) (Aitken & Bemmels, 2016). These transfer guidelines for forest reproductive material proposed within the framework of AM present different theoretical and practical approaches with varying uncertainties. For instance:

i) its adequacy in terms of co-evolution, or lack thereof, of biotic interactions with the rest of the organisms present in the ecosystem of the new site, such as pests and diseases;

or with those accidentally propagated with the translocated plant material (Ikeda *et al.*, 2014; Grady *et al.*, 2015; Bucharova, 2017).

ii) the appropriateness of translocating plant material when the expected benefits, either measured in productivity or resilience, can be small (Vizcaíno-Palomar *et al.*, 2019b; Fréjaville *et al.*, 2020).

iii) possible maladaptation not only due to a mismatch between the expected local average climate of the site and that of the provenance, but due to other abiotic or biotic selective pressures in the new site not considered in the AM decision. Close examples include the high mortality occurred in the extreme winter of 1985 in *Pinus pinaster* plantations in Aquitaine after introducing the fast-growing but frost-intolerant Portuguese provenances like Leiria (Benito Garzón et al., 2013a, c; Montwé et al., 2018). Also, the massive failures in plantations of the same species in Provence observed when using Corsican seed sources, highly susceptible to a local endemic pest, the pine bast scale *Matsucoccus feytaudi* Duc. (Di Matteo & Voltas, 2016).

Other strategies alternatives to AM, can relate to local predictive, climate-predictive, climate-adjusted, composite or admixture strategies, if relevant information about climate sensitivity of forest reproductive materials were available (Notivol *et al.*, 2020). Selection of the most suitable tree provenance in designing forest management plans must consider not only the expected average climate trends of the site, but also the dynamic nature of genetic conformation of tree populations as well (related to local adaptation and phenotypic plasticity) (Valladares *et al.*, 2014; Des Roches *et al.*, 2018).

Genetic improvement can offer solutions for drought resistance and resilience to pathogens, but it will make sense only embedded within a framework of sustainable, integrated forest and landscape planning that allows tackling proactively others looming challenges, first of all wildfires. In maritime pine, the genetic control of important traits (growth, stem form and responses to drought and some pathogens) has allowed for advanced breeding in SW France, and some breeding activities in NW Spain and Portugal (Alía *et al.*, 1995; de Miguel *et al.*, 2014; Cantero & et al., 2019b; Serrano-León *et al.*, 2021).

The advanced breeding programme for maritime pine in the Atlantic south-western France supplies more than 90% of the FRM used in the region from advanced seed orchards. Genetic gains have been estimated in +15% for first generation (plus trees or progenies of plus-trees) and up to 40% for the current 2.5 generation seed orchards (progeny tested first-generation trees) under the standard rotation length of 45 years (Bouffier *et al.*, 2013). A recent study has translated these genetic gains into expected economic gains by simulating growth, yield and financial performance of the genetically improved material in comparison with unimproved material. The gains in soil expectation value were estimated in +85% for 2.0 generation seed orchard FRM and in +115% for 2.5 generation seed orchard FRM (Serrano-León *et al.*, 2021).

Nevertheless, for southern Europe profitability of plantation forestry has recently been questioned from the perspective of private investors, with the exception of alluvial hybrid poplar cultivation and eucalyptus plantations. Maritime and radiata pine forestry in northern Spain present lower return rates, suffering the situation of depressed stumpage prices not recovered since the 2008 economic crisis, which strongly affected the sawmilling sector (Pra, 2018; Cantero et al., 2019a).

The analysis of current stakeholders demands and perceptions on the needs and requests for improved FRM has been reflected in the outcomes of the mentioned Europe-wide stakeholder survey realised in the B4EST project (EFI, 2021). The actual panorama has changed and in general reveals less fixation in productiveness, but a clear understanding and awareness of present challenges and threats for pure plantation forestry. In a prioritisation exercise within the survey, the criterion “Productivity (faster growth)” ranked last, or last but one, among all selection criteria and in all species. It was the last and least also in maritime pine, behind the need of: 1. a “higher resilience to biotic disturbances”, viz. in case of maritime pine the pine wilt nematode (PWN, discussed below) and fungal pathogens; 2. a “higher resilience to abiotic disturbances”, namely quoting drought and windstorms; and even behind 3. “enhanced genetic diversity for resilience to unknown disturbances” [sic], 4. “better wood quality”, and 5. “Survival rate".

Clearly the main results of this survey highlight that stakeholders involved in forestry are concerned on the fact that environmental risks are increasing, and hence they request for higher resilience, relegating the perspective of potential gains from higher final volumes harvested. Then again, even technical wood quality (and therefore its price and profitability) is determined not only by the genetic materials planted, but to a large extent by the correctly applied tending practices and silviculture regime. In northwest Iberian (Spain and Portugal) smallholdings, delayed thinning and absence of pruning do often result in overstocking and low-diameter, still fully branched logs with low market value, reducing profitability of pine plantations that do not allow to obtain structural timber, but low-priced industrial wood (Cantero & et al., 2019a). Even the best available improved genetic material will not translate in higher revenues if adequate plantation management is lacking.

Concluding, we are in a context of multiple uncertainties, including the risk of total lost by hazards before the plantation reaches rotation age and final felling (cf. Fitzgerald *et al.*, 2013; Forzieri *et al.*, 2021). In this situation, B4EST survey shows that forest managers and stakeholders are aware that the business-as-usual model of pure even-aged plantation forestry, searching the highest profitability in the shortest time, is not straightforward. This message has been learned by heart from experiences in the past decades of windstorm disasters in southwest France, growing incidence of fungal diseases, and the looming expansion of the fatal pine wood nematode from Portugal to the whole Spanish Atlantic coastlands and France, without neglecting the ongoing changes in wildfire regimes of northwest Iberia (Cantero et al., 2019a).

3.2 Maritime pine FRM in the Atlantic range of Southern Europe

Pines are keystone species in European ecosystems and have been often used for ecological restoration and in multi-purpose plantations, but they support also a high proportion of European timber production from plantation forestry, and sawmills are specialised in processing their logs. In particular, native maritime pine is one of the main timber species in the Atlantic range of Southern Europe: Portugal, Spain and France (Table 1), together with the exotic *P. radiata,* Monterrey pine, and several eucalypt species, especially *Eucalyptus globulus.* The plantations of the latter are expanding along the southwestern European Atlantic coast, often replacing former pine plantations (Tomé *et al.*, 2021). Eucalyptus deployment is not treated further here, being the objective of deliverable D5.9.

Table 1. ***Roundwood removal in Spain 2018*** (m^3 over bark)

	Atlantic Regions (NW Spain)		All Spain	
Pinus pinaster	1,984,421	13%	3,184,441	16%
Pinus radiata	4,779,295	32%	5,020,460	25%
Eucalyptus spp.	7,733,119	51%	7,813,543	40%
Sum 3 species	14,496,836	96%	16,018,443	81%
All species	**15,110,132**	**100%**	**19,747,342**	**100%**

(MITERD, 2020)

Maritime pine is versatile from an eco-evolutionary point of view, growing across a wide range of elevations (from sea level to up to 1,300 m, even 2,000 m in its southern range in Morocco) and under different climates (semi-arid to humid). Moreover, maritime pine is well known for a pronounced spatial genetic structure that has promoted locally patchy adapted populations across its range (González-Martínez *et al.*, 2002; Serra-Varela *et al.*, 2015; Vizcaíno-Palomar *et al.*, 2020; Archambeau *et al.*, 2021).

In the three SW-European Atlantic countries, Portugal, Spain and France, maritime pine has a remarkable social, economic and environmental importance. For instance, in Portugal it represents more than 80% of the forestry sector, both in industrial companies and employment, and produces 50% of sectoral industrial companies' gross added value, 36% of forest industrial exports and 3% of overall Portuguese exports (Calado *et al.*, 2020). But in the last decades, this wealth is threatened by the ongoing drastic reduction in forest resources of Portuguese maritime pine, a 37% decrease in volume growth between 2005 and 2019, leading to an increasing deficit of wood accounts estimated currently in more than 60% of annual consumption (Calado *et al.*, 2020).

In Spain, maritime pine has been ceding space to eucalyptus and Monterrey pine forestry, but also to the abandonment of plantations resulting in shrub encroachment. In Galicia (NW Spain), maritime pine has lost more than half of its planting area since 1970, passing from 0.49 to 0.21 million hectares (Mha), while eucalyptus incremented more than tenfold from 0.03 to 0.30 Mha since. In Portugal, maritime pine has lost one third of its area, going down from 0.98 to 0.67 Mha in the period 1995-2019. Only in the catastrophic 2017, wildfires consumed 0.44 Mha, of which 0.26 Mha were forests, often maritime pine. Evidently, high incidence and frequency of forest fires in plantations of maritime pine affect significantly their expected profitability, resting interest for private landowners. In Aquitaine (SW France), storms are the main cause of the reduction in forest stand extension and volume, which between 2000 and 2010 went down from 140-160 Mm^3 to less than 100 Mm^3 (Cantero et al., 2019; Picos &Rodríguez-Soleiro, 2019; Soares & Santos, 2019; Calado *et al.*, 2020; Picos, 2020a; Soares *et al.*, 2020).

Beside the fire risk, Portuguese maritime pine forests are suffering since 1999 a mortal biotic threat, the pine wilt disease (PWD). It is caused by the exotic pine wood nematode *Bursaphelenchus xylophilus* (PWN), one of the most dangerous pests for European coniferous forests that causes tree decay and mortalities in many pine species, maritime pine included (Nunes da Silva *et al.*, 2015; Zas *et al.*, 2015). This quarantine organism has recently reached also the maritime pine forests of Atlantic Spain (Galicia) (Abelleira *et al.*, 2020). PWN is expected to expand further through its vector, the longhorn beetle *Monochamus galloprovincialis*, and by *hitchhiking* human long-distance transports. Climate conditions in the northern regions of Spain might limit the expression of the pine wilt disease, while three southerner corridors through maritime pine forests along mountain ranges in Mediterranean Spain are seen more likely for the spontaneous spread

of PWN. These open a gateway for its subsequent expansion towards the rest of the Iberian Peninsula and, in the longer term, towards other European countries (de la Fuente *et al.*, 2018). On the other hand, fast-growing coastal *Pinus pinaster* provenances from Portugal and northern Spain have been found to be the most susceptible to PWD (Menéndez-Gutiérrez *et al.*, 2017). Moreover, Monterrey pine, *Pinus radiata*, the most relevant tree for plantation forestry in the Spanish Basque Country, is not resistant to PWD, either (Menéndez-Gutiérrez *et al.*, 2018a), despite it might show higher inducible defences to the pathogen (Pimentel *et al.*, 2017).

In addition, maritime pine as well as Monterrey pine plantations are very susceptible to fungal diseases present in the Atlantic Spanish and Portuguese territory. Pine pitch canker (PPC) caused by *Fusarium circinatum* is considered among the most devastating known diseases for pine plantations in the world, but there is growing incidence also of tip blight (*Diplodia pinea*) or red band needle blight (*Dothistroma septosporum. D. pini*), among others (Martínez-Álvarez *et al.*, 2014; Elvira-Recuenco *et al.*, 2020). When Serra-Varela *et al.* (2017) analysed the risk of exposure to PPC under different climate scenarios to support management decisions of maritime pine plantations and natural forests, they predicted for the next decades higher abiotic stress due to increased droughts for almost the entire Spanish distribution of the species. However, drought stress would further increase susceptibility to PPC (Zamora-Ballesteros *et al.*, 2019). Setting up breeding programs for resistance is recommended for highly exposed productive plantation forestry, while silvicultural methods and monitoring are an alternative for less productive, but still exposed, populations managed based on natural regeneration.

As a consequence, growth and yield losses, or even mortalities or premature felling, due to pine wilt disease or fungal diseases might definitively jeopardise the profitability expectation of private conifer plantation forestry and favour their replacement by even more eucalyptus (Freer-Smith *et al.*, 2019). This situation would lead to further losses in structural complexity and diversity of the landscape and of the socio-economic fabric in rural areas of Atlantic south-western Europe. Therefore, using resistant forest reproductive material of pines can be an alternative to curb this situation. Six families of maritime pine have recently been registered in Spain as less sensitive to PWN, at least as seedlings in nursery trials (78% survival rate vs. 53% in other seed lots). This might open a pathway toward resistant materials, though possible trade-offs against improved growth traits must still be studied (Menéndez-Gutiérrez *et al.*, 2018b; Díaz Vázquez *et al.*, 2020). In other pine species affected by the PWN, breeding and precocious selection for resistance to the disease, based on micro-propagation and in-vitro evaluation, are yielding promising results for incrementing the genetic base for resistant forests (Zhu *et al.*, 2018). In conclusion, if 73% of total Spanish roundwood is sourced by plantation forestry of these two coastal pine species and eucalyptus in the north (Table 1), and more so in Portugal, forest policy cannot neglect the existing and upcoming risks and uncertainties for their sustainable supply chains. To tackle the challenges of the European transition towards a bio-economy until 2050, increased sourcing and effective mobilisation of forestry-based resources will be a core element for accomplishment (Picardo, 2020; Picos, 2020b).

In this context, another looming uncertainty to be managed is the expected degree and effect of ongoing climate change on forestry. Therefore, assessing whether assisted migration could be a useful tool in maritime pine, or whether stone pine could offer an alternative to replace maritime pine have been the objectives of the modelling part of the present deliverable.

3.3 Mediterranean Stone pine FRM in the Atlantic range of Southern Europe

If diversification of the forest landscape and income is pursued, the use of the Mediterranean stone pine, *Pinus pinea* L., has been proposed for new forest plantations on the coasts of south-west Europe. This tree is native of Mediterranean climate zones in Spain and southern Portugal, though rare along the northern Iberian coastline, planted only locally, mostly for soil protection or landscaping in coastal sands. Its traditional afforestation around the Mediterranean has aimed at soil protection, sand dune stabilization, biodiversity refuge, space for public and recreational activities, and carbon sequestration (Martínez & Montero, 2004; Mutke et al. 2012; Nunes da Silva *et al.*, 2015; Amaral *et al.*, 2019). In the last decades, there has been a boost in commercial private plantations for cone production, namely in southern Portugal (Mutke *et al.*, 2000, 2012, 2019).

That is why Mediterranean stone pine might offer one profitable alternative for diversifying or replacing part of maritime pine stands also in Atlantic coastal areas, offering a high-valued non-wood forest product, Mediterranean pine nut kernels, which are gourmet nuts that can exceed 70-100€/kg in retail (Mutke *et al.*, 2012, 2019). Moreover, it is more tolerant to drought and less susceptible to the prevailing risks of PWD or *Fusarium circinatum* (Pimentel *et al.*, 2017; Bragança *et al.*, 2020). Profitable stone pine cultivation allows for maintenance of plots of low-density plantations without understory, which is an effective fire-resistance landscape element (Guadaño *et al.*, 2016). Along its southern range, stone pine appears often mixed with cork oak, *Quercus suber*, combining two of the most emblematic Mediterranean non wood forest products, cork, acorns and pine nuts, with grazing (Correia *et al.*, 2018; Martínez de Arano *et al.*, 2021).

Stone pine is characterized by a very low genetic variation (Vendramin *et al.*, 2008b) compensated by a high phenotypic plasticity that increases its global fitness (Mutke *et al.*, 2005, 2010; Chambel *et al.*, 2007). In the late 20th century, prospection of plus trees for cone production and comparative common garden trials have allowed for registering the first 15 elite clones as tested basic materials for production of graft scions in Spain, as well as a qualified clone mixture in Portugal (Guadaño *et al.*, 2016).

4 Methodology for the prediction of FRM performance under future climate change scenarios

4.1 Climatic scenarios

Climate-sensitive modelling and scenario assessment for improved forest reproductive materials (FRM) requires parametrising physiological or process-based models, e.g. 3PG merges physiological processes with empirical forest data and it has been used for different latitudes (Forrester & Tang, 2016; Trotsiuk *et al.*, 2020) and in even-aged eucalyptus stands in Portugal (Barreiro *et al.*, 2016).

However, both studied pine species lack sufficient data from advanced field trials located along the southern European Atlantic coastlands which is the targeted region. This drawback has limited possible climate scenario assessments to compute extrapolations of tree growth performance to the area of interest based on field trials located outside the targeted zone. For instance, classical species distribution models predict a substantial north and upwards shift of climate zones suitable for profitable eucalyptus and maritime pine plantation forestry in Portugal (Costa *et al.*, 2017), and an upwards expansion of profitable maritime pine cultivation, without expecting any rearing edge retraction in the lowlands in northern Spain (Barrio-Anta *et al.*, 2020).

At the same time, it must be kept in mind that profitability of plantation forestry for private landowners is determined not only by the genetic materials employed, but also by applying a sound plantation management. Another relevant factor, out of the scope of decisions by individual landowner, is the need of an improved landscape planning for tackling rising uncertainties linked to abiotic and biotic risks, such as climate change, wildfire regime, pests and diseases (Magalhães *et al.*, 2021).

In this context, we have used existing provenance-based models of the two species (Vizcaíno-Palomar *et al.*, 2020), developed with a different purpose, as an exercise to evaluate the potential differences between geographic origins of plant materials for possible translocation (assisted migration). We have evaluated current and future climatic scenarios, including two representative concentration pathways (RCP 2.6 and RCP 8.5) and 5 realisations of UK Climate Projections 2018 (UKCP18). These should be contrasted with the recently published future climatic niches of the two species in Mauri et *al.* (2022) (Figure 2). Results will provide criteria to assist forestry planning and decision-making at the landscape and regional levels, for example, assess the risk of using existing FRM in the region under climate change scenarios.

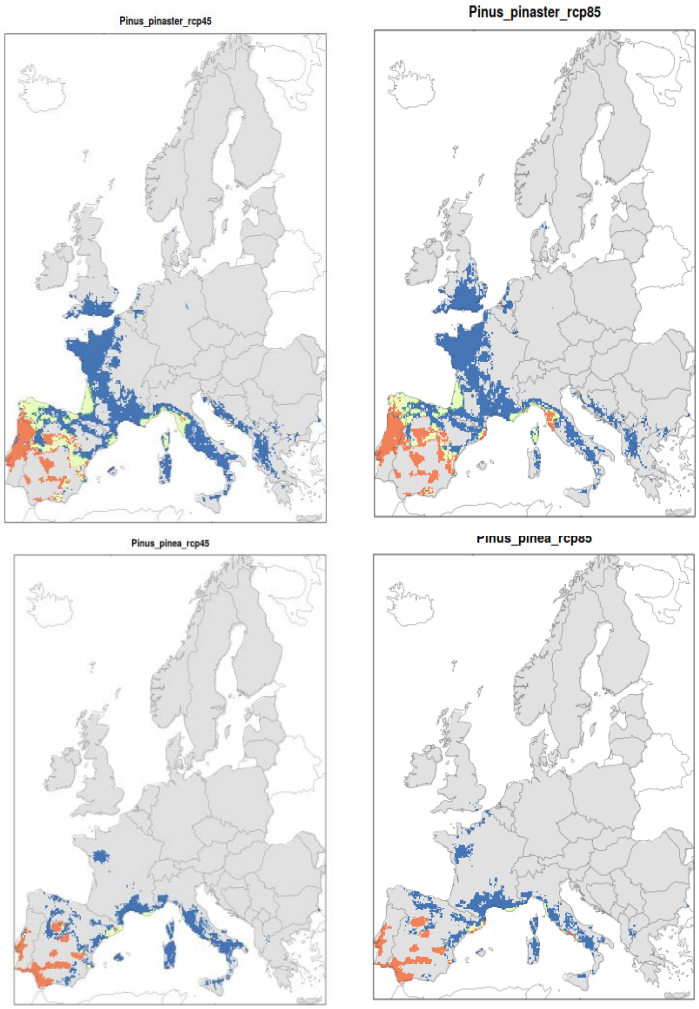


Figure 2. Maritime pine (first row) and stone pine (second row) expected niches modelled until the end of the century (2100) for two emission scenarios RCP 4.5. (left) and 8.5. (right). *Light green: 'Stable presence' denotes areas that will remain suitable habitats from the present until the end of the century. Orange: 'Decolonized', indicates areas that will become climatically unsuitable by the*

end of the century. Blue: 'Suitable but not occupied', represents areas that will become climatically suitable by the end of the century but will not be naturally colonized due to dispersal limitations. Gray: always absent. Figures taken from Mauri, A. et al. (2022).

4.2 Tree height measurements and provenance tests

We used tree height data of maritime pine and stone pine compiled in networks of provenance tests located across species ranges (Vizcaíno-Palomar *et al.*, 2019a).

For maritime pine, we used 123,801 measurements of individual tree height recorded in 14 trials established across three countries (France, Morocco and Spain) and 182 provenances covering the range of the species. Trials were installed between 1966 and 1992 and tree heights were measured over a period of 32 years (Figure 3).

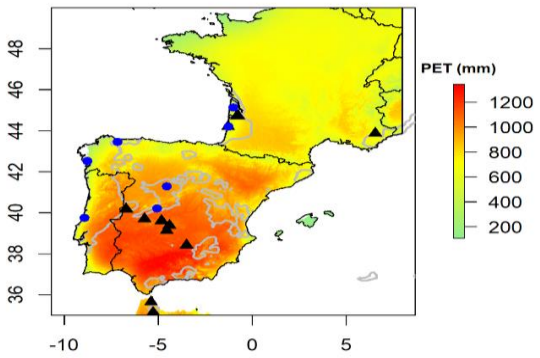


Figure 3. ***Provenance test network of maritime pine, P. pinaster***. Black triangles represent common garden sites and blue circles represent selected provenances. Grey lines represent the species natural distribution range. Right legend represents mean annual potential evapotranspiration (PET, mm) for the period 1967-1982.

For stone pine, we used 56,624 measurements of individual tree height recorded in 9 trials established in France and Spain, though none of them sited within the Atlantic climate zone, where a total 55 provenances covering the range of the species were planted. Trials were established between 1993 and 1997, and tree heights were measured over a period of 20 years (Figure 4).

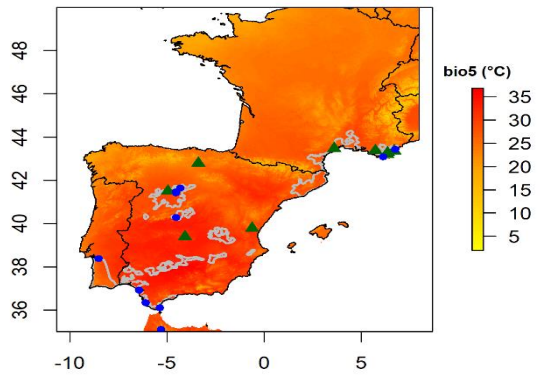


Figure 4. ***Provenance test network of stone pine, P. pinea.*** Green triangles represent common garden sites and blue circles represent selected provenances. Grey lines represent the species natural distribution range. Right legend represents the maximum warmest temperature (bio5, °C) for the period 1995-2010.

For each species, we selected a set of contrasted provenances to evaluate their performance along the European Atlantic coastline in a climate change context. For maritime pine, we selected nine provenances: two from Morocco (Tamjout and Ibel Tassali, both from high altitudes), two from inland Spain (Arenas de San Pedro and Íscar), two from the Spanish Atlantic area (Ribadeo and Cambados), one from South of Portugal (Leiría) and two from the French Atlantic area (North and South of the Landes) (Figure 3). For *P. pinea*, we selected 10 provenances: two from southern Spain (Andalucía Occidental and Doñana), four from inner Spain (Vega Sicilia, Portillo, Cogeces

and Caldalso), one from Portugal (Sul do Tejo) and two from the French Côte d'Azur (St. Raphaël and Hyéres) (Figure 4).

4.3 Climate data

We used ClimateDT dataset that provides annual climate between 1901 and 2098, at 30 arc-seconds (~1 km grid) of resolution (https://ibbr.cnr.it/climate-dt/), of a large variety of raw climatic data and indices (see variables: https://ibbr.cnr.it/climate-dt/?action=fldlist). We computed the following climate values previously selected for modelling in Vizcaíno-Palomar *et al.* (2020):

1. Climate at the provenance origin. We averaged winter precipitation (prec.djf) for maritime pine and summer precipitation (prec.jja) for stone pine over the period 1901–1950. Based on the assumption that this climate reflects the past climatic conditions under which seeds development of the studied provenance took place.
2. Climate across the European Atlantic area. For the following two variables, annual potential evapotranspiration (PET) for maritime pine and maximum temperature of the warmest month (bio5) for stone pine, we computed:
    - **Present climate.** We computed the average climate between 1967-1982 for maritime pine and 1995-2010 for stone pine trials, as climate representative of the contemporary climatic conditions to which trees have been exposed since they were planted up to the age of 15 years.
    - **Future climate**. We calculated the average climate from 5 variants included in UK Climate Projections (UKCP18) for the following two periods: 2036-2065, called hereafter 2050s, and 2066-2095, hereafter 2080s, of two scenarios (RCP 2.6 and RCP 8.5). RCP 2.6 is an optimistic, strict mitigation scenario that aims to keep global warming probably below 2°C above pre-industrial temperatures. RCP 8.5 represents a less utopic scenario with continued high greenhouse gas (GHG) emissions. The increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is likely to be between 0.3-1.7°C under RCP 2.6, and between 2.6°-4.8°C under RCP 8.5. The following figures show the climate under present climate conditions (period 1960-1990) and future conditions and RCP scenarios (Figures 5-8).

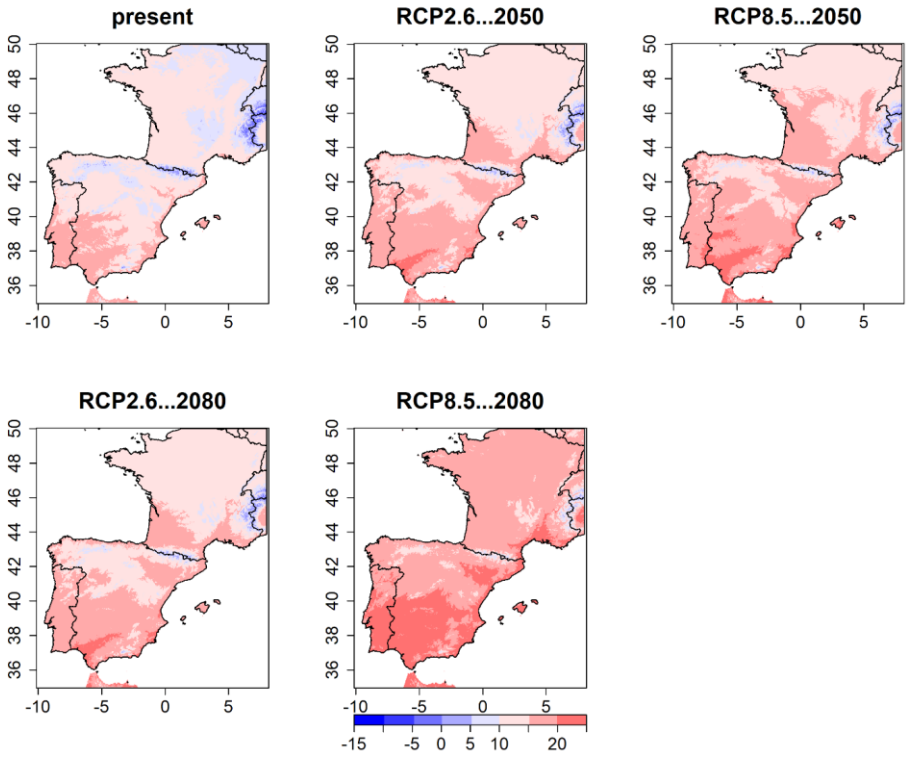


Figure 5. ***Mean annual temperature (°C)*** under present climatic conditions (period 1960-1990) and for 2050 and 2080 year and RCPs 2.6 and 8.5.

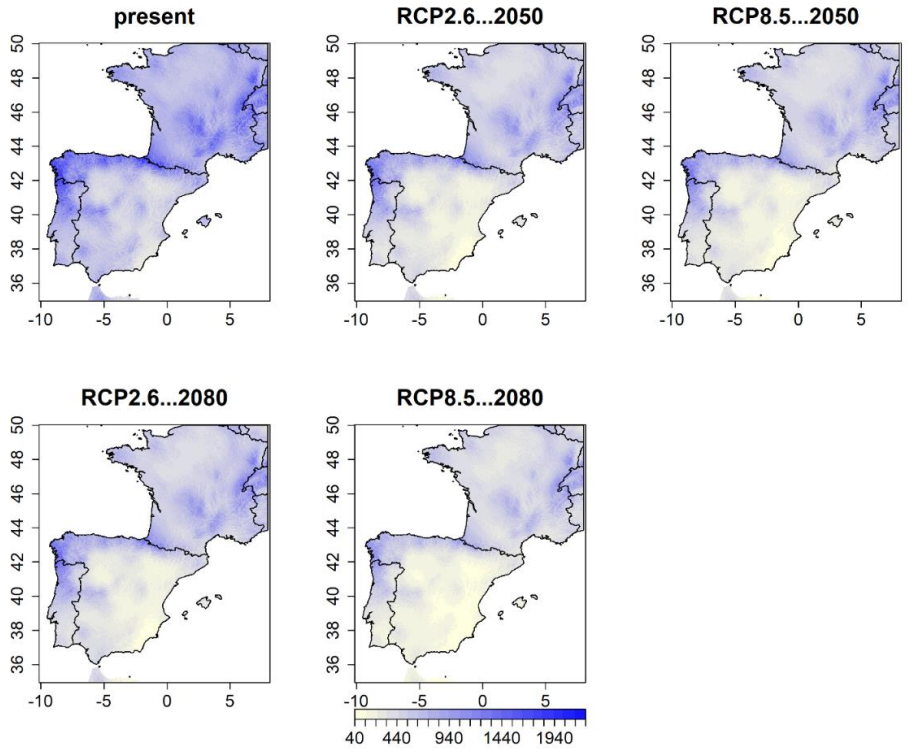


Figure 6. ***Annual precipitation (mm)*** under present climatic conditions (period 1960-1990) and for 2050 and 2080 year and RCPs 2.6 and 8.5.

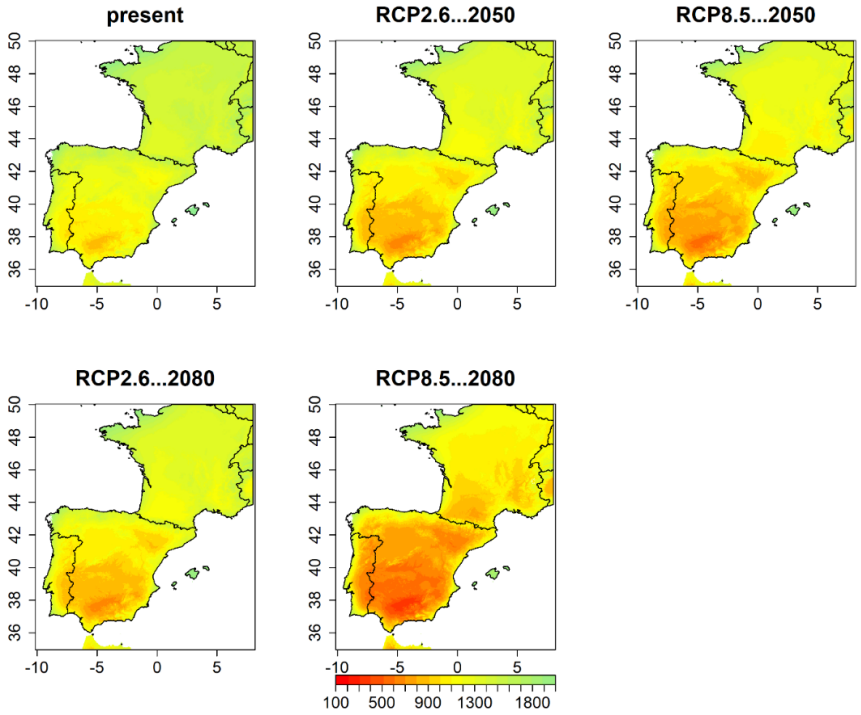


Figure 7. ***Annual potential evapotranspiration (mm)*** under present climatic conditions (period 1960-1990) and for 2050 and 2080 year and RCPs 2.6 and 8.5.

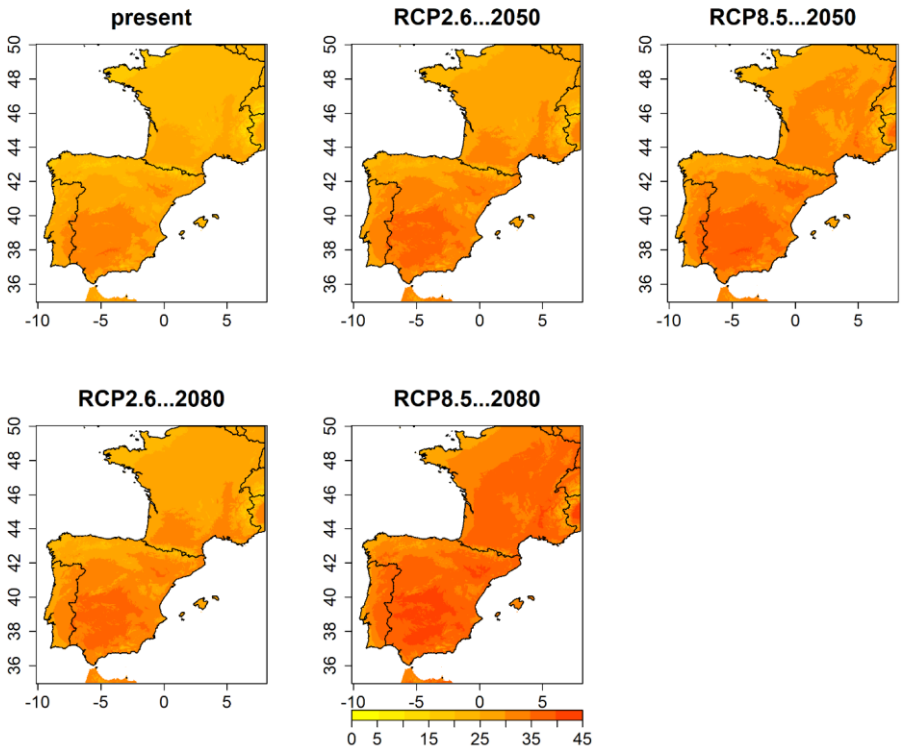


Figure 8. ***Maximum temperature of the warmest month (°C)*** under present climatic conditions (period 1960-1990) and for 2050 and 2080 year and RCPs 2.6 and 8.5.

4.4 Species' tree height models

For each species, we used the linear mixed-effects model developed in Vizcaíno-Palomar *et al.*, (2020). These models included the effects of the contemporary climatic conditions where trees grow, as a proxy of phenotypic plasticity, $clim_t$, and the past climatic conditions that affected the seed development of the populations, as a proxy of the effect of the provenance, $clim_p$, on tree height phenotypes, and tree age and asymmetric competition as covariates in the fixed part of the model. The experimental design of the provenance tests (block, test site and provenance) and tree individuals were included in the random part of the model to control for unaccounted environmental differences among sites and populations, and for temporal autocorrelation for individual trees measured over years. The log mean tree height *H* was fitted as follows:

$$log(H) = \sum_{i=1}^{p} \alpha_i X_i + \varepsilon_{ran} + \varepsilon_{res} \qquad \text{Eq. 1}$$

where *H* is tree height, α_i is the set of *p* parameters associated with the fixed effects of X_i (tree age, $clim_p$, $clim_t$, competition), ε_{ran} is the variance component associated with the random terms, and ε_{res} is the residual distributed error following a Gaussian distribution.

4.5 Shifts in tree height prediction along the European Atlantic coast under climate change scenarios

Our evaluation analyses is based upon the spatial predictions of the mean tree height along the European Atlantic coast for each selected provenance and species. First, we predicted tree height using the species' linear mixed-effects model, at age 15 years, setting both asymmetric competition and random effects to null. Second, we run spatial tree heights predictions under present and future climate scenarios (RCP 2.6 and RCP 8.5) based on 5 variants of the UKCP18, resulting in a total of 190 scenario-variant-provenance predictions. Lastly, we calculated for each species and provenance the difference between future and present spatial tree height predictions and represented the spatial average prediction for each RCP across all 5 variants. Negative values in the spatial predictions mean that the tree height of local provenance is expected to decrease in the future, and the contrary with positive values (Figures 9 & 10). Previously, we excluded all sites with predicted tree heights under current climate not reaching 200 cm at 15 years.

5 Predicted Shifts in tree height along the European Atlantic coast under climate change scenarios

On one hand, the spatialized predicted mean tree height under current climate conditions hardly varied among provenances of each species (Figures 9 & 10). On the other hand, under future climate conditions, we found for both species, that the expected change in mean tree height at 15 years was smaller for the moderate RCP 2.6 (both in 2050s and 2080s), with tree height variation ranging between ca. -115 and +95 cm in maritime pine and between ca. -105 and 110 cm in Mediterranean stone pine. Under the more pessimistic scenario, harsher RCP 8.5, shifts on predicted tree height would range between ca. -160 to +145 cm in maritime pine in the 2050s and between ca. -165 to +168 cm in stone pine, reaching variation between ca. -250 and +270 cm in maritime pine and ca. -270 and +292 cm in stone pine in the 2080s (Figures 11 & 12).

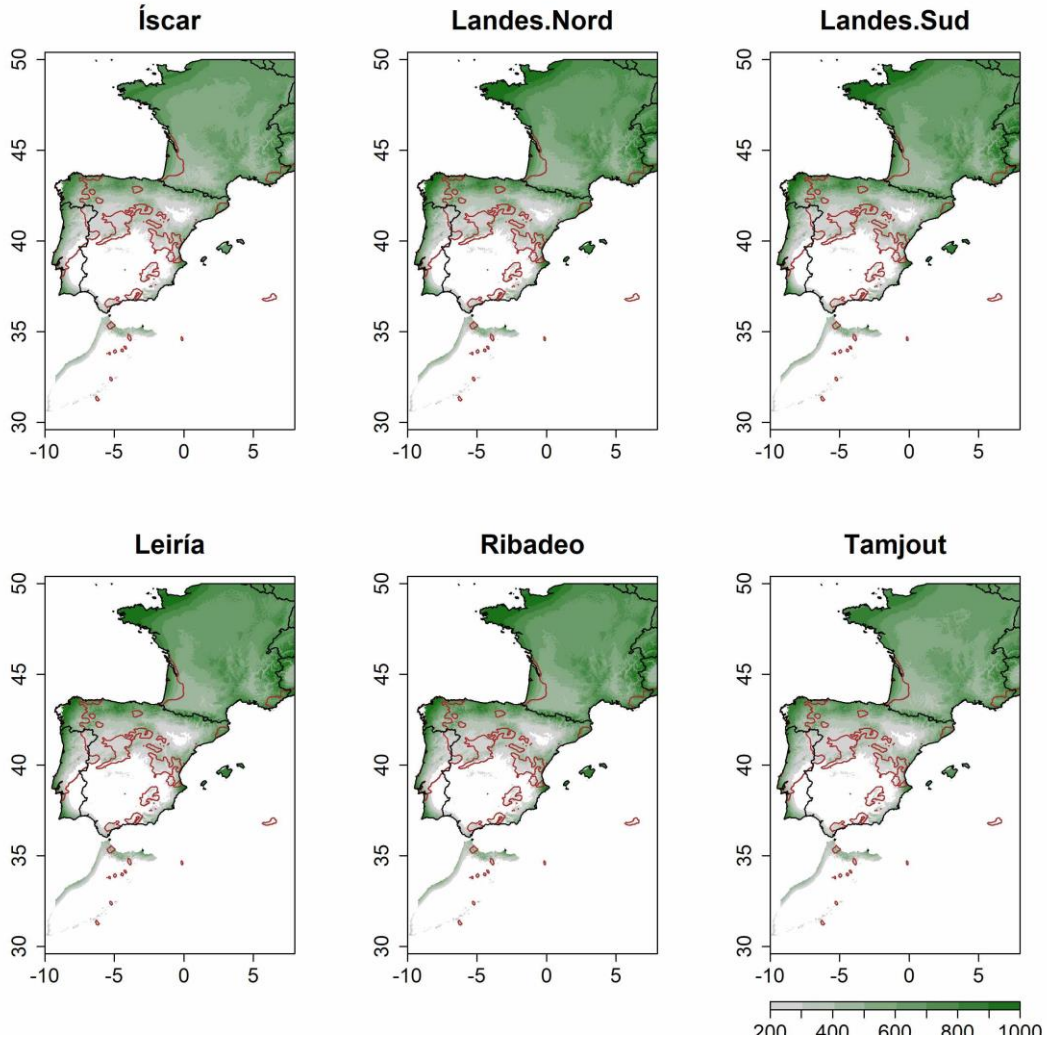


Figure 9. ***Predicted average tree heights for maritime pine provenances at age 15***, expressed in cm, ***under present climatic conditions (***PET). The red lines enclosure the species natural distribution range. While maritime pine grows well in its Atlantic range, inner Spanish growing regions under Mediterranean-to-continental climates present a delayed growth (grey) or are considered as too xeric for the species (white). [This prediction is restricted to the climatic suitable area of the species, see Fig. 2].

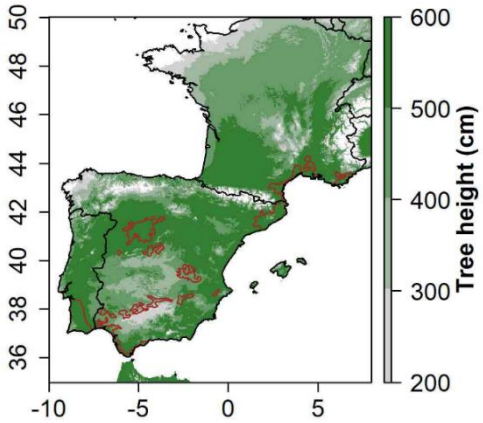


Figure 10. ***Predicted average tree height for Mediterranean stone pine at age 15***, expressed in cm, ***under present climatic conditions*** (maximum summer temperature, bio5). Red lines enclosure the species natural distribution range. Regions with colder summers (NW Spain, N France and higher mountain ranges) are expected to yield less height growth in this thermophile species, while the middle Guadalquivir basin (S Spain) would be excessively hot. [This prediction is restricted to the climatic suitable area of the species, see Fig. 2].

5.1 Predicted shifts for maritime pine

In the case of maritime pine, we found slight variation of the evaluated performance among the provenances for both RCP scenarios and periods studied, although these differences were much more pronounced for RCP 2.6 in the 2050s. Particularly, we distinguished two groups, the provenances whose climate of origin was Atlantic (Leiría, Ribadeo, Cambados, and the two from the Landes), and those provenances whose climate of origin was Mediterranean-continental (inland Spain and Morocco). From north to south, both groups are predicted to either remain the same or to worsen slightly, especially in the north of the Iberian Peninsula (Cantabrian Sea). Moderate increases are predicted for the southern façade of Portugal, with larger increases for the Atlantic climate group (Figure 11). These results on performance are matched with the future climatic niche of the species (Figure 2) and we note that the slight increase predicted for the species will be possible in the north-west of the peninsula, Galicia, as well as in the northern part of the Landes and Bretagne in France. Whereas the entire Portuguese Atlantic coast is predicted climatically unsuitable for maritime pine.

5.1 Predicted shifts for stone pine

For stone pine, we found no relevant variation among provenances in the average shifts in tree height performance along the European Atlantic coast. Therefore, we present these results as the average prediction performance of the species for the two RCP scenarios and periods (Figure 11). Tree height performance would vary among the RCP scenarios and time periods. In general, the performance of stone pine along the European Atlantic coast is expected to worsen, with a tree height decrease between 0 and 104 cm in the RCP 2.6, but up to 270 cm under the RCP 8.5 scenario. After comparing these results with the future climatic niche for the species (Figure 2), we note the entire european atlantic coast is predicted to be climatically unsuitable for stone pine in agreement with our predicted worsening performance.

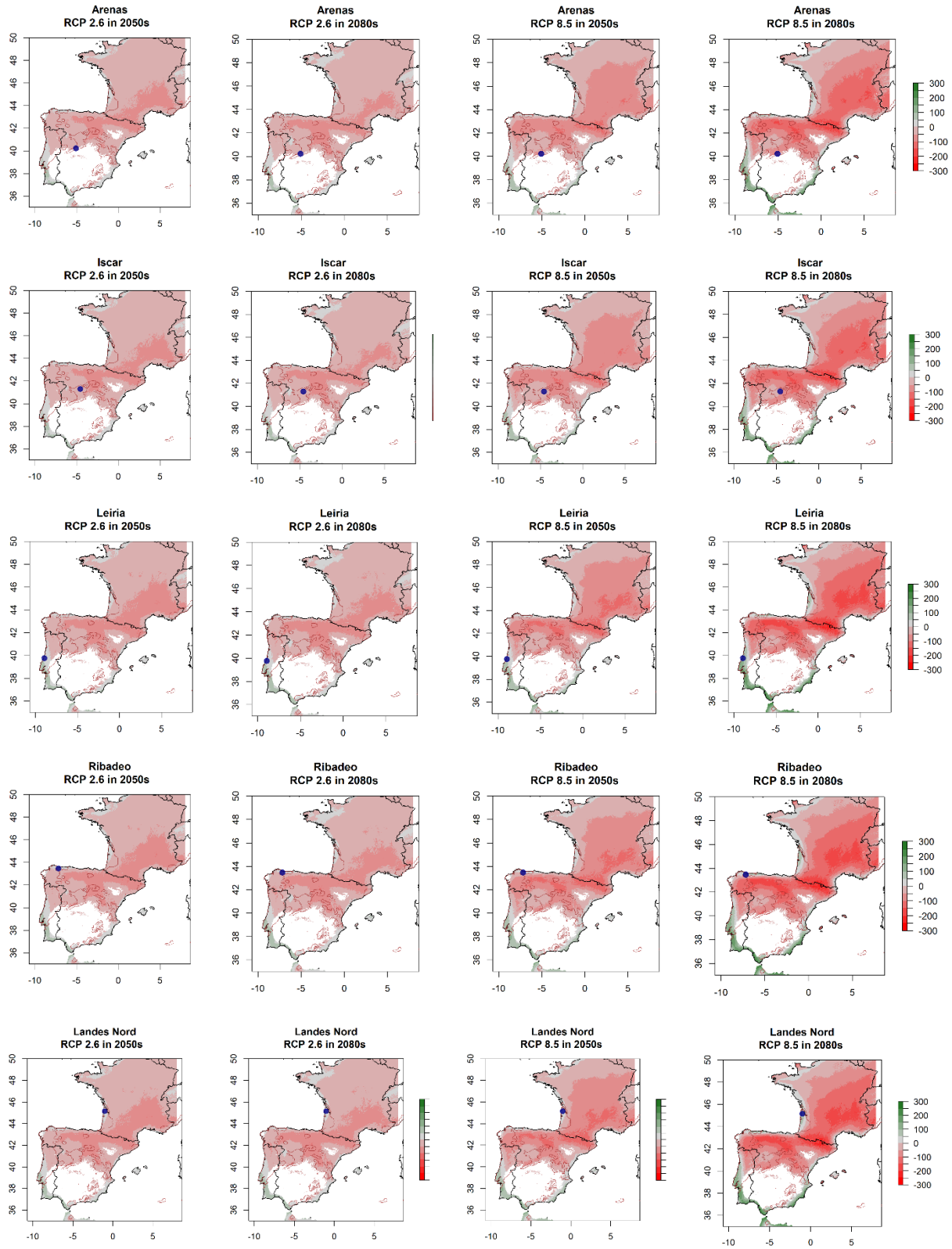


Figure 11. ***Average shifts in performance (cm) at 15 year-old for maritime pine provenances*** expressed as the difference in tree height between predicted future and present climatic conditions for two RCP scenarios and two time periods (2050s and 2080s). *Blue dot represents the geographic origin of the provenance tested and brown enclosures are the species natural distribution range. Right legends represent the predicted performance variation in cm: red colour means performance decline, grey means from*

null to moderate improvement, and lately, green represents performance improvement. [This prediction is restricted to the climatic suitable area of the species, see Fig. 2].

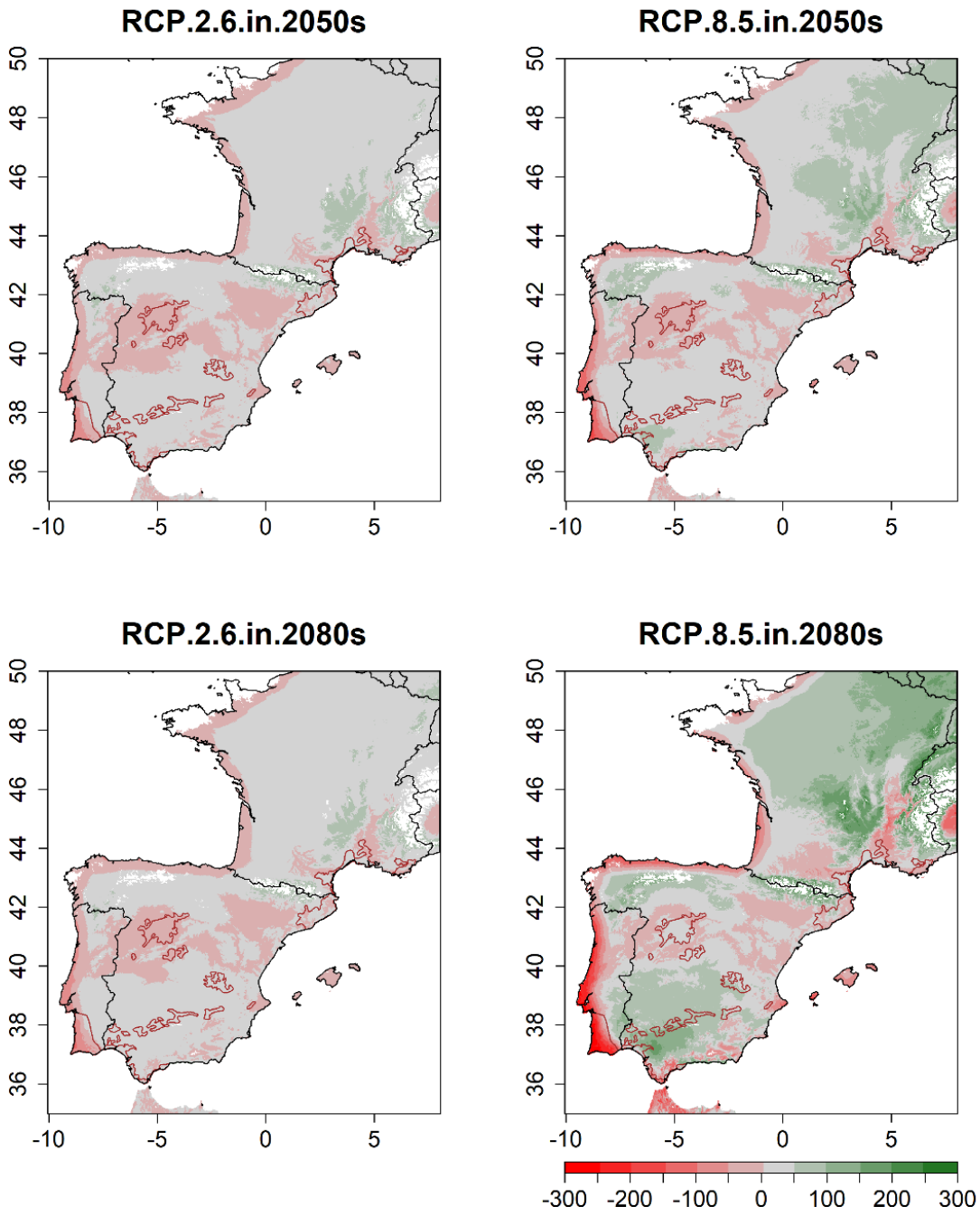


Figure 12. ***Average shifts in performance performance (cm) at 15 year-old for stone pine***, expressed as the difference between predicted future and present climatic conditions for two RCP scenarios (2.6 and 8.5) and two time periods (2050s and 2080s). Brown enclosures the species natural distribution range. Bottom-right legend represents the predicted performance variation in cm: red colour means performance decline, grey means from null to moderate improvement, and lately, green represents performance improvement. [This prediction is restricted to the climatic suitable area of the species, see Fig. 2].

6 Discussion of predicted shifts for maritime pine and stone pine

Overall, forecasts obtained from these models need to be interpreted with caution as they inform us about tree height performance under new climates where they are present today. Therefore our results should be restricted to those recent published future niches of the two species (Mauri et *al.* 2022). In addition, these results are based on previous models (Vizcaíno-Palomar *et al.*, 2020). One step forward should be to analyse the data of the Reinfforce consortium, to monitor tree mortality, vulnerability to abiotic (e.g. frosts) and biotic (pests) factors and growth trends under climate change and compare with present results.

6.1 Intraspecific variation of predicted performance in maritime pine

Forecasted variation among populations in maritime pine was expected, as this species is known for variation among provenances in phenotypic traits (Alía *et al.*, 1997; Fréjaville *et al.*, 2020; Vizcaíno-Palomar *et al.*, 2020), genetic markers (Burban & Petit, 2003; Santos-del-Blanco *et al.*, 2012; Serra-Varela *et al.*, 2015) and provenances' realized niches (Serra-Varela *et al.*, 2015). These differences are the result of each population's demographic history, together with adaptations to the local environmental conditions that have contributed to the current differentiated genetic structure of the species (González-Martínez *et al.*, 2002; Burban & Petit, 2003; Serra-Varela *et al.*, 2015; Fréjaville *et al.*, 2020). Atlantic populations whose climate of origin is oceanic would perform better than those from harsher inland climates, characterised by lower, irregular precipitation and higher temperatures, results in agreement with the subdivision of maritime pine in two subspecies (subsp. atlantica present in Atlantic lowlands, and the circum-Mediterranean subsp. mesogeensis) (Barberó et al., 1998). These populations have been shown to differ largely in growth: Atlantic maritime pine is more productive than Mediterranean maritime (Alía *et al.*, 1995, 1997; Bravo-Oviedo *et al.*, 2011). However, the present results are contradictory in the framework of assisted migration theory as we expected that provenances whose climate of origin was more similar to the expected one were expected to increase their performance. Again, these findings demonstrate that it is not appropriate to base recommendations on the climate at the provenance origin alone, as previous studies have also reported (Benito Garzón *et al.*, 2013a, 2018; Montwé *et al.*, 2018).

Based on the model forecast, the performance for maritime pine along the European Atlantic coast is projected to improve, in accordance with other studies developed at high-resolution spatial scales performed in NW Spain (Barrio-Anta *et al.*, 2020), and local provenances performing best. If this finding were confirmed in further analyses, no assisted migration effort would hence be justified or needed for bringing more drought-resistant to this region, which is an excellent result facing climate change, securing genetic diversity in improved FRM for maritime pine would offer relevant phenotypic plasticity to meet the resilience challenge.

6.2 No intraspecific variation of predicted performance in stone pine

The lack of differences in the projected performance among populations in stone pine was expected, due to the low genetic diversity reported with allozymes, chloroplast and nuclear microsatellites for this species (Fallour *et al.*, 1997; Vendramin *et al.*, 2008a; Jaramillo-Correa *et al.*, 2020), together with the low phenotypic variation measured in provenance tests, e.g. tree height, specific leaf area, etc. (Court-Picon *et al.*, 2004; Mutke *et al.*, 2010; Vizcaíno-Palomar *et*

al., 2020). However, this near absence of genetic variation has not impeded stone pine to colonise a wide-range territory along the Mediterranean shores, though probably mainly via human seed transfer as archaeophyte (Mutke *et al.*, 2019; Jaramillo-Correa *et al.*, 2020).

The findings of the modelling exercise predict that stone pine is under a high risk of decline along the Atlantic coast except in the Gulf of Cádiz (southern Spain). This result agrees with previous studies which predicted that stone pine might lose habitat suitable areas under future climate projections (Mauri et al. 2022). However, our projections for future also predict a performance increase in inland Spain as in Mauri et al (2022), but these areas will require the assistance of human in order to be colonised.

6.3 Limitations of the modelling approach and future perspectives

Our modelling approach presents the advantage of relying on observed phenotypic data which allow us to consider phenotypic plasticity and local adaptation, two key processes in tree species to get acclimated *in situ.* However, our models present some limitations.

First, this approach has been developed with the existent network of provenance tests. However, none of the analysed common gardens but two French are located within the region of interest and this has forced us to extrapolate our results. And second, our models evaluate provenances/species tree height performance where they exist today but prevent us to analyse the suitability of projected areas. This is the reason why our findings are dependent of species climatic niches. In the mid-term, it is planed the use of the data generated in the network of 38 arboretums supported by the Reinfforce consortium. This network ranges from latitude 37° in Portugal to latitude 58° in Scotland, and will be of high interest to monitor tree mortality, vulnerability to abiotic (e.g. frosts) and biotic (pests) factors and growth trends under climate change. Modelling this data will allow us to: (i) model data in the targeted area and (ii) model tree performance from a multi-trait approach like: growth, survival, pest exposition, etc.

6.4 Risks and benefits of using improved FRM of maritime pine and stone pine in the Atlantic area

Risks of using improved FRM of maritime pine and stone pine in the Atlantic area are related to different factors (biotic and abiotic) that are reducing the interest of these species in the area. Especially in the case of maritime pine, the nematode, pine pitch canker, and the limitations due to climate change are now limiting the use of the species in the area. For stone pine, the uncertainties associated to climate change limit the assessment of profitability for orchards of the species and their commercial cone production, not quantified in the study region despite of predicted the growth of the species. These factors are new objectives in the breeding program of the species, at least in Portugal and NW Spain.

Use of FRM of different origins, as shown by this preliminary study, do not provide evidence for transfer of material with a potential use in these areas. Therefore, the future of the species in the area should be based in the results of the breeding programs of the species.

Breeding programs in Galicia and Aquitaine regions for maritime pine are focusing on improving the resistance and tolerance to nematode, pine pitch canker, and other factors (insects, constitutive and induced defences) and on promoting the adaptation of the species to drought. At this moment, there are some qualified materials selected for the resistance to the nematode, and the material is being tested for other objectives, indicating the existence of FRM improved for different traits.

Breeding programs in the Atlantic region for stone pine are less developed. In Portugal, the material selected has not been evaluated in north of the Alentejo region, and the material from the breeding programs in Spain have not been tested in Atlantic climate zones at all. The qualified FRM in the Spanish national register has not been evaluated outside of the area where they were selected (Castilla y León, Madrid or Cataluña), and therefore it would be necessary to expand the evaluation of these material to new areas to identify possible deployment areas of the FRM of this species. Within the B4EST project, the results obtained for this species indicate the existence of trade-offs between growth and reproduction in the selected material, and a limitation for the commercial use of this species in different climatic areas. We still need to improve our knowledge on the performance of this material in all the EU areas with possible use of the species.

However, despite the role of improved material in offering significant genetic gains for different traits of interest (including the biotic and abiotic resistance) it is not clear to what extent those materials would prevent the owners of selecting other species for commercial planting (though it has not been the case in SW France) as it seems the trend in the area in the last years.

In conclusion, this deliverable shows the risks associated to *Pinus pinaster* and *Pinus pinea* FRM used in the Atlantic region and the limitations in the transfer of FRM to reduce these risks. The actions should be based on the results of the existing breeding programs of the species and the inclusion of some traits (nematode and fusarium resistance, abiotic stresses) in the breeding programs. These traits are under evaluation in some of the breeding programs and the benefits of using this improved material should be disseminated to the end users.

7 Collaboration and dissemination

Authors of this deliverable: Natalia Vizcaíno-Palomar (INRAE), Sven Mutke (CSIC-INIA), Maurizio Marchi (CNR), Marta Benito-Garzón (INRAE), Annie Raffin (INRAE), Laurent Bouffier (INRAE), Ricardo Alía (CSIC-INIA).

Activities under WP5 and preparation of this deliverable have contributed to a number of strategic or outreach activities and regional stakeholder events, namely:

- Active expert contribution to the EIP AGRI Webinar *Turning forest Innovation into practice*, 24-25 November 2021
- Presentation *The role of planted forests in resilient landscapes and forest-based bioeconomy* and Round Table on *Forest plantations and the future European Forest strategy*, IEFC Annual Meeting, Lisbon, 23 June 2022
- Session C Round table *The forests we want: deployment of forest reproductive material (FRM) for forest-based solution*, B4EST International Conference, Lisbon, 20-23 June 2022

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