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Summary

This deliverable has been prepared in a format of an article which analyses the innovation system for tree breeding in Europe, which covers the activities related to genetic selection, the multiplication of improved seed and seedlings and the extension services for the use of the improved varieties. The analysis relies on several case studies: Maritime Pine in France, Eucalyptus in Portugal et Norway Spruce in Finland and Sweden. These case studies are based on several documentation and a series of interviews.

The analysis is based on a conceptual framework combining the literature on both economics of innovation and innovation systems. We show that a rather complete innovation system for creation and deployment of improved varieties has been created. Indeed, all key activities and regulations are in place for each tree species and in each country. We also show that, on the demand side, several constraints explain why forest owners have limited incentives to adopt innovation, leading to a limited demand for innovation. On the supply side, we show that, despite the long duration of the breeding cycle and the limited demand for improved tree varieties, private incentives to invest in breeding can be observed in some cases. In the case of Eucalyptus in Portugal and Norway Spruce in Sweden, we observe private investment in tree breeding by large forest industry companies. This investment is part of an overall investment in upstream activities (breeding, seed, seedling and wood production) to secure the supply of their mills. When such investments are not made by private companies, tree breeding relies on public research organizations.

We conclude by showing that the private incentives in the innovations systems for forest tree breeding are rather different compared to the innovation system for annual crop breeding, that is more commonly studied in the literature.

Private incentives in the innovation systems: a comparative analysis of forest tree genetic innovations in Europe

1 Introduction

Climate change represents both a threat and an opportunity for forests and their management. Although contexts vary globally, it is clear that forest disturbances are sensitive to climate and that ongoing climate change raises multiple abiotic risks (e.g., fire, drought, wind, snow and ice) and biotic risks (insect pests and pathogens) (Seidl et al., 2017; Venäläinen et al., 2020), with potentially adverse effects on forest health, productivity, ecosystem services and economic activity.

At the same time, the need to decrease net carbon emissions rapidly to reduce the risk of catastrophic climate change has given renewed importance to forests and their management. Forests have a key role to play in future carbon cycling (Reisch, 2011), as they have the potential to take up and store large quantities of carbon, although that potential depends crucially on how forests are managed. For instance, Pan et al. (2011) estimated over the 1990 to 2007 period that forests sequestered a quantity of carbon equivalent to 60% of emissions from fossil fuel burning and cement production, but the net carbon emissions were considerably lower due primarily to deforestation in tropical areas. More recently, Pugh et al. (2019) offered a more conservative estimate, concluding that the remaining uptake potential in forest biomass under current disturbance rates was equivalent to seven years of emissions from fossil fuel burning at 2016 levels. Thus, although quantifying the carbon captured by forests is fraught with difficulties and inherently uncertain, the scientific consensus considers that the sink from forest is potentially large.

From the large potential of carbon capture in forests and their soils as well as the anticipated enhanced vulnerability of forests to climate change follows the need to raise the resilience and productivity of forests globally. One relatively unexplored option in pursuit of that goal is forest tree breeding and related deployment of forest reproductive material (FRM). Conventional tree breeding is not new but the efficiency of all breeding programmes is hampered by the long time interval of a typical breeding cycle, which may last several years to decades, and the late expression of important traits such as wood properties (Grattapaglia, 2014). Those elements imply high costs and uncertainty of tree breeding programmes, but scientific progress also offers considerable room for improvement. As an example, the potential shortening of tree breeding cycles by early selection based on genetic markers was recognized by forest geneticists in the early 1990s (e.g., Neale and Williams, 1991). However, to date the promises of genomic breeding have not been realised, which is explained in part by scientific and technical issues discussed by Grattapaglia (2017).

Against this background, this article analyses the innovation system for forest tree genetic innovation in Europe, which covers the activities related to genetic selection, the multiplication of improved seed and seedlings and the extension services for the use of the improved varieties. The analysis relies on several case studies: Maritime Pine in France, Eucalyptus in Portugal et Norway Spruce in Finland and Sweden. These case studies are based on several documentation and a series of interviews. We first show that a rather complete innovation system for creation and deployment of improved varieties has been created. We then analyze the private incentives to adopt innovation on the demand side and create and deploy innovation on the supply side. On the demand side, we also show that several constraints explain why forest owners have limited incentives to adopt innovation, leading to a limited demand for innovation. On the supply side, we show that, despite the long duration of the breeding cycle and the limited demand for improved tree varieties, private incentives to invest in breeding can be observed in some cases like Eucalyptus in Portugal and Norway Spruce in Sweden. This analysis enables us to put to light on the bottlenecks that may prevent the benefits from tree breeding from being realised, and offer some solutions for the removal of those bottlenecks.

We proceed in four steps. The section 2 presents a conceptual framework supporting the analysis of innovation processes, combining two different approaches from the literature, namely the innovation system approach and the economics of innovation. The section 3 explains the empirical material and methods, while the section 4 discusses the results. The section 5 develops the implications of the results and offers some conclusions.

2 Conceptual Framework and Previous Applications

2.1 The economics of innovation

The economic theory of innovation treats research and development (R&D) activities as investments in the production of knowledge with immediate costs and uncertain benefits in the form of increased productivity that will only materialize in the future. The rise in productivity may originate from various sources, including new or improved outputs, new, better or cheaper inputs, more responsiveness to changing circumstances or better combinations of inputs and outputs (Alston et al., 1995). As with any other form of capital, knowledge increases through investment, depreciates over time, and generates a flow of services that form an input in the production function.

In this framework, the normative assessment of innovation systems starts from the possibility of market failures, or situations where private costs of and benefits from R&D differ from their social counterparts. The key concern is that because of this divergence, R&D and innovation opportunities that would be socially desirable may not be exploited by private agents (Alston & Pardey, 1999), leading to suboptimal outcomes and opening the door to government intervention.

The primary source of market failure results from the public good nature of the output of research, knowledge, which in its purest form is both non-rival and non-excludable (Stiglitz, 1999). Non-excludability means that appropriation of all benefits from investments in R&D is not possible due to knowledge spillovers, while non-rivalry implies that full appropriation of those benefits would not be socially desirable anyway. Of course, in the real world, the output of R&D is only a partial public good and institutions/regulations (e.g., patents) have been developed in order to define and protect intellectual property rights (IPRs), but the situation varies tremendously across sectors due to inherent differences in technologies as well as other specificities. The results section will therefore address this question empirically for the case of the tree breeding sector.

The non-rivalry of knowledge created by R&D investment also implies that knowledge development represents a fixed cost for the firm since, once produced, the marginal cost of its use is zero. However, the dynamics of competition in a perfectly competitive sector means that firms do not make excess profits and are therefore unable to recoup this type of fixed cost. It follows that R&D investments will be low unless imperfect competition creates opportunities for market rents, as proposed by Schumpeter (1942) and nuanced more recently by Aghion et al. (2005). This is likely to represent a more significant issue in commodity markets (Potts et al., 2017), including those for natural resources. Given that the extracted rent is also a function of the size of the market, this implies that R&D efforts are generally low in markets with limited demand or markets where the consumer has a limited valorization of the innovation (Cohen 2010).

In addition to the public good nature of knowledge and technology, there are other potential sources of market failures in R&D investments. The process of innovation remains fundamentally uncertain at the level of the individual firm, creating disincentives to invest in R&D particularly in situations where credit and insurance markets are incomplete and the firm is small, limiting the possibilities of diversification. The length of the planning horizon due to long lags between investment and rewards may also result in sub-optimal levels of investment in research and innovation. At another level, research-led innovation may be hindered by informational asymmetries. The producers of innovations typically have access to more and better information than the end user of the innovation, resulting in a potential "lemon problem" (Akerlof, 1970) where the market only provides technologies, goods and services of relatively low quality, with limited innovation and quality differentiation.

Altogether, this classical approach to the economics of innovation considers that the innovation problem is essentially an allocation problem resulting from market failure and characterized by infra-optimal investments in R&D. From this diagnosis and the implicit assumption that governments can fix market failures follows government-led solutions involving the strengthening of IPRs, Pigovian subsidies or direct public provision of R&D efforts (Potts et al., 2017). In the agricultural sector, for instance, those ideas have been instrumental in the development of a public science push model in which much agricultural research is carried out by public research institutes, universities and international organizations (e.g., CGIAR).

2.2 Innovation systems

The empirical observation that in agriculture and other sectors, increases in the supply of knowledge and technologies does not necessarily translate into innovation and sectoral growth has forced a reexamination of the "innovation problem" and its solutions outlined above (World Bank, 2006). The linear model of innovation based on the premise that basic science leads to applied science, innovation and growth has proved too simplistic, leading to more attention being paid to the role of diverse actors and market forces in innovation processes. In a first step, alternative models of innovation have been proposed, as illustrated by the demand-pull model that considers that technological innovation is stimulated by market demand rather than scientific discovery (Lane & Godin, 2013). However, more fundamental rethinking of innovation also took place by recasting the innovation problem as one of entrepreneurial discovery taking place in markets rather than knowledge creation in laboratories (Potts et al., 2017).

The idea of innovation as involving complex systems of disruptive and discontinuous events resulting from the actions of networks of actors ultimately resulted in the mid-1990s in a new paradigm falling under the broad umbrella of "innovation systems" (Tidd, 2006). Those are defined as "all important economic, social, political, organisational, and other factors that influence the development, diffusion, and use of innovations" (Edquist, 1997, p. 14, cited in Purkus et al. 2018). The basic elements of an innovation system typically subject to empirical scrutiny are the actors, networks/interactions as well as institutions (Islam et al., 2012). However, the traditional approach to the analysis of innovation systems has been criticized for an excessive focus on structures in a largely static framework, resulting in a revised empirical approach emphasizing the dynamic processes underlying innovation, or "functions" of the innovation system (Hekkert et al., 2007). These functions include the knowledge development emphasized in the linear model of innovation but also many other aspects, such as entrepreneurial activities, knowledge diffusion through networks, resource mobilization, the selection of potential innovations and the creation of legitimacy.

2.3 Review of existing applications in the agricultural and forest sectors

To our knowledge forest tree breeding and the deployment of improved FRM conceived as an innovation process have not been the subject of previous empirical investigation, but important insights can be derived by broadening the scope of the literature review to include breeding activities in agriculture as well as generic innovation in the forest sector.

The market failure perspective on innovation has been studied extensively in agriculture, in particular through the analysis of rates of return to R&D investment in the sector, as reviewed recently by Rao et al. (2019). After gathering data from 461 studies, those authors concluded that the most up-to-date evidence was fully consistent with the professional consensus of very high returns to agricultural R&D investments, with a mean value of 66% in developing countries and 54% in developing countries (Rao et al., 2019, Fig. 1). This evidence supports the view that innovation in agriculture suffers from an allocation problem since high rates of returns are indicative of significant under-investment in R&D. Evidence pertaining specifically to breeding innovations in agriculture is limited but suggests that this general conclusion also applies to that sub-sector. For instance, von Witzke et al. (2004) concluded to significant underinvestment in German plant breeding research, with an estimated social rate of return in the range of 16 to 28%. Another study by Fuglie and Walker (2001) established econometrically that private investment in US plant breeding was strongly influenced by market size, hybrid seed technology and the relative ease of breeding improvements, in line with the predictions of the conventional economic theory of innovation.

The study of livestock genetic improvement in Scotland of Islam et al. (2013) illustrates how the innovation system perspective can fruitfully be applied to breeding activities in land-based sectors. It was motivated by the paradoxical observation that, although Scotland's research outputs in farm animal genetics are widely perceived to be excellent, uptake of related technologies has been slower in the sheep and beef sectors in comparison to the dairy, pig and poultry sectors. The authors identified several systemic and structural weaknesses of the Scottish sheep sector explaining its relative slow rate of innovation, including the lack of integration of the value chain, where breeders and lamb producers face different incentives, or the Common Agricultural Policy (CAP), which for a long time provided support to sheep production based on the number of sheep rather than their productive quality.

The state of innovation research in forestry and forest-based industries has recently been summarized by Weiss et al. (2020), who reviewed a total of 230 studies identified through a systematic search. Forest tree breeding or FRM deployment does not appear in the topical focus of the articles (see Fig. 3 or this article) The vast majority of studies published to date applied qualitative approaches to models of innovation diffusion and innovation systems, while little attention has been paid to measuring the efficiency of innovation processes. It is worth noting that the literature review does not mention explicitly any market failure nor any of the concrete elements of the "allocation problem" outlined above. This absence of application of classical innovation economics to the forest sector contrasts with its popularity in other natural resource sectors such as agriculture (Potts, 2017). However, some case studies have investigated the costs and benefits of genetic improvement programmes. As an example, Chamberland et al. (2020) compared different approaches to varietal improvement and deployment for white spruce in Quebec to conclude to the higher financial performance of scenarios involving genomic-based schemes, compared with traditional schemes. In another example, Jansson et al. (2017) concluded their review of the genetic and economic gains from forest tree breeding programmes in Scandinavia and Finland by stating that such programmes typically resulted in a positive benefit-cost balance when using conventional discount rates in the 2% to 4% range.

The more common application of the innovation system approach to the forest sector has allowed the identification of various systemic deficiencies preventing or slowing down innovation. Multiple lacks of interactions among stakeholders have been highlighted, in particular between researchers and practitioners (Stone et al., 2011), with public agencies (Aboal et al, 2018) or along the value chain (Weiss et al., 2017). The literature also focuses on other structural and functional characteristics of innovation systems in forest-based value chains, including the intensity and quality of knowledge exchange, resource mobilization (i.e., funding), missing public or private actors, innovation support policies, coordinating institutions (e.g., associations) or openness to other sectors (Weiss et al., 2020).

Altogether, although the analysis of innovation in the forest sector is not new, this summary highlights important gaps, including: 1- the lack of application of the innovation system perspective to the specific issue of forest tree breeding and FRM deployment; 2- the near absence of application of the traditional economic analysis of innovation to the forest sector; and 3- a relative lack of cross-country analyses of innovation in the forest sector, allowing to put national contexts into a border perspective, as underlined by Weiss et al. (2020). Thus, analysing forest tree breeding and FRM deployment through the prism of innovation theory is largely novel and has the potential of identifying salient entry points for improvement in the sector.

3 Methodology and background information

Breeding activities and FRM production and deployment are specific to species and, most of the time, also countries. As a consequence, the case studies correspond to combinations of tree species and European countries. Each case corresponds to a tree species that represents a significant area in the country and for which at least one breeding programme is conducted in the country. The three cases correspond to three different zones of Europe: Portugal (southern), France (central), and Sweden and Finland (Northern). These cases were also chosen to represent contrasted organization and institutional contexts.

We present here the methodology used for collecting data and general background information. Background information covers, for each of the cases studied, the context of forest production and wood transformation and a description of tree genetic innovation during the last decades. The innovation system related to FRM research and production will be analyzed in detail in the result section.

3.1 Data collection

To elaborate this analysis, we used bibliographic resources (websites, technical reports, articles, etc.) and information gathered through semi-structured interviews with stakeholders related to each case study.

Table 1. Number of interviews per case studied and type of organization

Tree species		Eucalyptus	Maritime Pine	Norway Spruce
Country		Portugal	France	Finland and Sweden
Upstream	Breeding organizations	2	3	2
	Seed producers and nurseries	2	6	2
Forestry	Confederations of associations, cooperatives, farmers and forest owners	3	3	2
Wood processing	Industry association	1	1	1
Transversal	Interprofessional organization	1	1	0
	Regulatory organization	1	1	4

36 semi-structured interviews were conducted with different stakeholders between January and October 2020 (see table 1 for details). Most of the interviews, which lasted an average of one and a half hours, were conducted by telephone or videoconference. The interview guideline included two sections common to all the interviews: the presentation of the interviewee and the missions of his or her organization, and a personal opinion on the issues and prospects for the sector for the species and country of interest. The other sections of the interview guideline were systematically adapted to the organization and aimed at understanding the organization of the sector and its related regulations. Thus, our

interviewees were asked to describe the functioning of the sector in their field of activity (research in varietal improvement, dissemination of improved varieties, forestry, wood processing) by presenting the actors involved and their respective missions, their perceptions of the issues specific to their activities, the regulations and their justification, as well as the link with the other actors in the sector.

These interviews were systematically recorded in agreement with the interviewees. A detailed report of each interview was drafted and sent to each of our interlocutors for review and validation. Four reports have been elaborated from each of the case studied (for Norway Spruce, a specific report was made for each country). These reports synthetize the features collected in the bibliography and during the interviews. The current article is the transversal analysis of these case studies.

3.2 Background information on the three case studies

Table 2 synthesizes some key figures for each of the case studies. Each species covers from 0.845 to 6.4 Mha per country studied and represents the most -- or one of the most -- important forest species in each country. In all cases, the stands are mainly owned by a very large number of small forest owners who manage very small areas, the forest activity being generally a secondary activity. In the case of Maritime Pine in France, and more specifically in the main growing area (Massif des Landes de Gascogne which is part of Aquitaine), the average area grown by independent owners is 38 ha on average, which is larger compared to the other cases.

On the side of these independant forest owners, in Portugal and Sweden, private forest industry companies also grow a significant part of the surface (17% for Portugal and 25% for Sweden). At last, forest can also be owned by the State, which is the case in Scandinavian countries for a significant proportion of the forest, and in France where the public entity ONF owns and manages the narrow strip of coastal forests located along the Atlantic Ocean. In this last case, Maritime Pine is used mainly for the environmental management of the dunes of sand.

Except for Eucalyptus, the forest production cycle is very long and lasts several decades. For Eucalyptus, growers can harvest after 12 years and keep the same stand during three rotations. Thinnings operations are made for Maritime Pine and Norway Spruce but they do not generate significant revenues. The revenues come mainly from the wood harvest, with levels that are quite similar among the cases (between 200 and 250€/ha/year). Replanting cost ranges from 1000 to 2000€/ha and wood price ranges between 40 and 60€/m3. Hence, the main difference between these different cases is related to the duration of the production cycle which is particularly short for Eucalyptus.

A large part of private forest owners subcontract the management of their forests to service providers. The services cover soil preparation, stand installation, forest management (thinning for example), harvest and tree logging. Indeed, these operations actually require specific and expensive equipment that can hardly be afforded by small forest owners. Service providers are generally small business units. They play an important role for stand installation in Portugal (contractors), in France (ETF – Entrepreneurs de Travaux Forestiers) and in Sweden and Finland. In France, big cooperatives like Alliance Forêt Bois or UniSylva are also major actors who provide forest management services. In Sweden and Finland, large forest industry companies have procurement units offering all aspects of forest management and local associations of forest owners provide forest planning and management services.

The wood produced by forest can be used for multiple purposes. In Portugal, eucalyptus is mainly processed as pulp and, from pulp, into paper and cardboard. The transformation process is operating in mills. The main pulp and paper companies are The Navigator and Altri. Pulp production is the core of their business, but they have vertically integrated forest production as well as FRM related activities. The other forest industry companies – which are not vertically integrated – are Renova, DS Smith and Goma Camps. The outlets for maritime pine are numerous. A same stand and a same tree can supply various outlets depending on the parts of the trees (thinning wood with low diameter, trunks with large diameter, bark…). The main outlets are lumber (factory and shop lumber, structural lumber, furniture, wooden floor…), industrial wood (wood chips and paper pulp), chemistry and wood energy. The case of Norway Spruce in Scandinavian countries is somewhat intermediary between the case of Eucalyptus in Portugal and Maritime Pine in France. 55% of the outlets in wood volume corresponds to the production of structures, panels, furniture etc. Spruce also has long lean and straight fibers which makes it raw material for the forest industry companies (40% of the outlets). It is also a source of biomass for the production of renewable energy (5%). There are five large forest industry companies in Sweden (i.e., the “big five”): Sveaskog, Holmen Skog, Stora Enso, SCA and Södras. Some of those are multinationals. These companies are vertically integrated as they own forest land, orchards, tree nurseries in addition to their core wood processing facilities. Some large industry companies also process Norway Spruce wood in Finland (e.g. UPM, Stora Enso, Metsä Group – which is a cooperative).

Forest production may be affected by specific events. Portugal is regularly affected by wildfire and Eucalyptus is often mentioned as a prominent cause[1]. As a consequence, since 2018, eucalyptus growing has been highly constrained by a restrictive legislation which prohibits the increase of the eucalyptus area and aims to decrease it. Planting new eucalyptus stands is then forbidden, and the replanting has to be approved after submitting a project. Forest owners have to decrease their plantation area by 10% until the regional area reaches a certain limit. In France, the Maritime Pine production has been affected by two major storms in 1999 and 2009 which destroyed a significant share of the production. Replantation on these surfaces has been subsidized but this created a demand shock on FRM. Finally, in Nordic countries

[1] This issue is rather controversial. Interviewees reported that the general public sees eucalyptus plantations as responsible for the dramatic propagation of these forest fires, while scientific studies show that eucalyptus does not propagate fire more easily than other tree species.

substantial forest damages are caused by a variety of factors, including storms, excessive snow loads, freezing and fungi (e.g., annosum root rot).

Table 2. Key figures of the forest sector for each case studied[2]

	Maritime Pine - France	**Norway Spruce - Sweden**	**Norway Spruce - Finland**	**Eucalyptus - Portugal**
Total area	1,03 Mha	6,4 Mha	Polyculture - spruce is the dominant species on 5 Mha	845.000 ha
Number of forest owners	250.000 in Nouvelle Aquitaine	>300.000	500.000	400.000
Ownership structure (percentage of the area)	Private forest owners: 87%	Private forest owners: 50% State: 20% Companies: 25%	Private forest owners: 58% State: 37% Companies: 5%	Private forest owners: 83% Companies: 17%
Age of logging	about 40 years	60-70 years in the South / 100-120 years in the North	from 50 to 100 years - more generally about 60-70 years	1 rotation: 10-12 years - generally 3 rotations
Thinnings	3 to 4 between 10 and 30 years	1 or 2	2 to 3 at 25-30 years and 40-45 years	None
Productivity	about 12 m3/ha/year	3-8 m3/ha/year	2-6 m3/ha/year	6-10 m3/ha/year
Incomes Revenues from silviculture	Gross margin: 200-250€/ha/year	Revenues: 205€/ha/year	Revenues: About €250/ha/year	Gross margin: about 260 €/ha/year
Replanting costs	about 1000€/ha	930€/ha	1500€/ha	1800-2000€/ha
Wood price	about 40€/m3	45€/m3 (for logs) and and 30/m3 for pulp	57,8€/m3 for logs and 17,7€/m3 for pulpwood	about 45€/m3
Wood volume	growing stock: 143 Mm3 uptakes: 6,9 Mm3/year	growing stock: 1300 Mm3 annual fellings: 40 Mm3	growing stock: 740milo m3 31,6 Mm3 drained annually	pulp&paper companies' supply in portuguese wood: 5,5 Mm3/an
Wood processing outlets	Lumber: about 60% Industrial wood (wood chips and paper pulp): 30% Chemistry/ wood energy: 10%	Main outlets: sawlogs and pulpwood Residuals are used for bioenergy production and heating	Logs - strucutures, panels, furniture: 55% Pulp / paper: 40% Energy: 5%	Mainly pulp and paper

[2] A conversion rate of 0.093€/SEK is applied for Sweden (average rate over the five last years).

3.3 Tree genetic innovations

Genetic improvement of Norway spruce and the diffusion of improved FRM has occurred at roughly the same pace in Finland and Sweden. In Finland, the seed orchards established in a first round in the 60s and early 70s are still the source of most improved FRM, which falls in the qualified category. However, new seed orchards of "generation 1.5" using progeny-tested material have been established since 2002, some of which are now starting to produce seeds of the tested category. The establishment of new 1.5 generation orchards is planned to continue until 2028, when 2nd-generation material will become available.

Although Sweden uses a different terminology based on orchard rounds rather than generations, the two programmes of genetic improvements and FRM diffusion have progressed in parallel, with the Swedish 3rd round orchards being essentially equivalent to the Finnish 1.5 generation orchards.

Haapanen (2020) has recently quantified the performance of genetically improved spruce in Southern Finland, concluding that first-generation seed orchard progenies have a clear superiority over unimproved trees with a realized genetic gain of 8.4% in height growth, 9.0% in diameter growth, and 20.6% in stem volume growth. The respective genetic gains expected from 1.5-generation seed orchards are 12.8%, 13.5% and 36.9%. Although those figures cannot be directly interpreted as increases in productivity of genetically improved stands, they seem consistent with the estimate by Rosvall et al (2001) of a 10 to 25% increase in per hectare volume growth attributable to the superior genetic quality of the spruce seeds originating from Swedish orchards (Haapanen, 2020).

In the case of Maritime pine, four generations have been released since the beginning of the breeding program. The first generation (VF1 - Strength and Shape 1), released between the end of the 80s and the end of the 90s, led to an increase of the performance of +15% on average on wood volume and straightness, in comparison with non-improved trees. This increase reached +30% with the second generation VF2, and +40% with the third generation VF3. Furthermore, with this third generation, trees were selected for their resistance to pine rust. For the fourth generation VF4, the deployment is more dynamic, with a new improved FRM released every 3 years. The VF4-1 FRM, currently bred, is selected on growth, straightness, drought resistance and wood quality.

In the case of eucalyptus, the Altri Florestal genetic breeding program concluded its third breeding cycle, and the basis for a fourth cycle is now launched. On its side, RAIZ is now running the fourth generation of breeding and is developing the fifth one. The selection is made simultaneously on growth and wood quality. Other characteristics such as stem straightness and tolerance to biotic or abiotic threats have been of secondary importance. The current improvement programs provide material with the capacity to increase forest productivity by 25 to 50%, and the best families now released show performances in volume/ha of +80% compared to original material from Australia.

4 Results

4.1 A structurally sound system of innovation

In the three cases studied, we can observe a rather complete structure of the innovation system for development of new FRM and their deployment and adoption. The tree genetic innovation system covers multiple complementary activities, intermediary markets where the products or services related to these activities can be sold and, at last, a regulation framework that provides garanties on FRM quality. The activities of this innovation system cover tree breeding leading to new tree varieties, the production of improved FRM, and various extension activities enabling the forest grower to choose adequate FRM and silviculture practices.

The breeding activity consists in creating new varieties with interesting characteristics on various criteria. For each species, the breeding program started in the 50-60's by the selection of particularly interesting trees (called "Plus trees") in wild stands. Since then, several breeding cycles have been carried out recursively. As for the breeding of any other species, each cycle consist of two successive steps: (i) the crossing through fecondation of parental trees that has been selected at the previous cycle, each cross generating offspring that are candidates for selection, and (ii) the evaluation of the performance of the candidates and the selection of the best ones. New varieties can be created at each cycle on the basis of some of the selected trees. Tree breeding has several particularities compared, for example, to annual crop species. First, the breeding cycle lasts one or several decades. Indeed, multiple years are necessary to get mature trees ready for crossing and the performance of the candidates can only be evaluated with old enough trees. The second particularity is that, in order to have a good enough evaluation of the genetic level of the candidates, breeders use statistical techniques which combine the performance of both the candidates and its relatives. As for the breeding of any other species, tree breeding requires specific skills. Breeding programs correspond to a specific activity carried out in particular fields within the producing region of the selected species. Within one country we observe generally one and possibly two breeding programs for a given tree species. For Maritime Pine, two breeding programs were launched initially by two public institutions (INRA and FCBA) and, since 1995, they have been jointly funded and coordinated within a specific structure (GIS "Pin Maritime du Future"). For Norway spruce, there is one breeding program in both Finland and Sweden, carried out by public institutions. In Finland, LUKE (Natural Research Institute Finland) is publicly funded while the breeding program in Sweden is funded half publicly and half privately. At last, for Eucalyptus in Portugal, two breeding programs are carried out by the two main pulp and paper companies in Portugal: Altri and The Navigator Group.

FRM production consists in producing seedlings of improved material that can then be sold to forest owners for planting new stands. Two main technical channels of FRM production are possible: the cloning of the selected trees, but this operation is not always possible at moderate cost; and the production of seedling from seed harvested in a dedicated stand (seed orchards) installed with trees from the breeding program. The production of clones or seedlings from seed is made in nurseries. The installation, maintenance and harvesting of seed orchards can be independent from the nursery activity. In both cases, capacity constraints can be observed, which are related to the size of the nursery equipment or the several years required for setting up a seed orchard before harvesting it. Because of this capacity constraint and uncertainty related to the demand and the production yield, shortage of improved seed can be observed. To overcome this problem, seeds can also be collected in selected stands, i.e. forest stands which were not installed for seed production but whose characteristics are considered interesting for seed production.

Seeds, clones and seedlings are FRM whose commercialisation is regulated by the European Directive 1999/105/EC. The main objective of this regulation is to define traceability rules and quality standards to guarantee the origin and the quality of the FRM sold to forest owners. In other words, this regulation reduces information asymmetry between FRM producers and users. Different categories of FRM are defined, depending on the type of provenance and the level of information available on this material: source-identified, selected, qualified and tested. Each category corresponds to a coloured label (yellow, green, pink and blue).

Table 3 synthesizes the actors involved in FRM production. Most of these activities are now carried out by private actors. It should be noted however that, for Norway Spruce in Finland, Tapio Silva Oy and Siemen Forelia are joint-stock companies with a high level of involvement of the Finnish state. Also, for Maritime Pine in France, the installation of seed orchards was highly supported by the State in the past. Seed production, which requires rather long term investments, is more concentrated than seedling production. Seed and seedling production are not necessarily integrated. When this is the case, it is made either by big enough nurseries (Maritime Pine in France) or large forest industry companies (Norway Spruce in Sweden and Eucalyptus in Portugal). In this last case, these large companies are also investing in the breeding activities.

Table 3. Actors involved in FRM production

	Maritime Pine - France	**Norway Spruce - Sweden**	**Norway Spruce - Finland**	**Eucalyptus - Portugal**
Seed orchards	Consortium between seed companies (ONF or Vilmorin) and nurseries	Big five forest companies : Sveaskog, Holmen Skog, Stora Enso, SCA and Södras	Tapio Silva Oy and Siemen Forelia (partly owned by the Finnish State)	Altri and Navigator

Seedling production from seed	Independent nurseries (e.g. Forélite, Planfor, Le Plant Landais, Naudet)	Big five forest companies (85-90%)	Numerous independent nurseries	- Subsidiaries of Altri and Navigator - Independent nurseries (50%)
Clone production	*Not possible*			Mainly Navigator

Extension activities are important for the deployment of improved tree varieties by providing information on the performance of these varieties. These activities cover more broadly all advice related to legal, fiscal and regulatory issues, as well as economic and technical topics, including the choice of the FRM. They combine on the one hand a back-office activity which consists in reference acquisition based for example on field test comparing different FRM and, on the other hand, a front-office activity which covers multiple forms of exchange with forest owners leading to the diffusion of the information. Many players are involved in these activities and, as is common in agriculture, forest owners do not pay directly for this service. For eucalyptus, this advice is mainly given by forest owner's associations, cooperatives and technicians from the industry. In the case of Maritime Pine, the main actors of the extension are public entities (CRPF), forest owner's associations (SPFA) and cooperatives (e.g. Alliance Forêts Bois, UNISYLVA). In Sweden and Finland, forest owner associations also play a key role in diffusing technical and economic information to forest owners, togethers with the procurement arms of the main forest industry companies. Service providers specialized in tree production also provide advice to forest owners because they have generally knowledge of FRM material and silviculture practices.

Although the structure of the analysed tree breeding sectors appears sound in the sense that all the markets, actors, activities and networks are in place, the capacity of those systems to deliver all the functions necessary for the efficient production of innovation is much weaker. With reference to the seven functions of innovation systems proposed by Hekkert (2007), the collected information suggests that current setups present several limitations. There is no doubt that sector-specific knowledge develops constantly through both public and private investments in R&D, and that it diffuses through formal and informal networks. However, the current systems leave rather little room to entrepreneurial activities, with limited influence of market forces in guiding the search for new technologies and FRM products. Hence, in both Finland and Sweden, public institutions and researchers strongly lead the innovation process, with market participants adopting a largely reactive role through contributions to various forms of consultations. At another level, our empirical analysis did not detect meaningful advocacy coalitions promoting tree breeding as a promising solution to tackle the multiple challenges faced by European forests. In fact, the interviews revealed that the potential benefits of tree breeding, and the potential interest of new technologies (e.g. genomic selection) for accelerating this breeding process, were largely unknown to not only forest owners but also many forest professionals directly or indirectly involved in reforestation decisions.

4.2 Lack of demand pull

Several arguments explain why the market for improved varieties of trees is limited. All these arguments are related to the fact that trees are perennial crops harvested after several decades. We illustrate these arguments more particularly with the case of Maritime Pine in France, for which the production cycle lasts approximately 40 years, but the ideas are applicable to all countries and species under investigation. Table 4 provide illustrative features related to these issues for each of the case studies.

First, the market size for new varieties to consider is defined by the surface planted each year. However, this surface is only a small fraction of the total acreage for this forest tree. Maritime Pine in France covers more that 1Mha but only 30 000 ha is planted each year (about 1/30).

Table 4. FRM production, commercialization and use for the studied species (source: interviews)

	Maritime Pine - France	**Norway Spruce - Sweden**	**Norway Spruce - Finland**	**Eucalyptus - Portugal**
Area of basic material	Seed orchards: 300ha currently in production - 124 selected stands on 13211 ha	mainly seed orchards, in 44 sites and on 470 ha	- 30 seed orchards: 348 ha - selected stands	- 8,2 ha of seed orchards (open-pollination) and 40 ha of propagation parks (controlled crosses) : 48 ha - 330.000 clone plants (17 genotypes) - selected stands
Area replanted each year	30.000 ha	100.000 ha	50.000 ha	10.000 ha in 2018 (decrease)
Seedlings sales	36 millions/an - 96% of the annual planted area is installed by seedlings, of which 96% come from seed orchards	190 million seedlings / year	100 millions/year - about 60% are improved but varies a lot	About 20 millions seedlings/year - 25% clones, 25% improved seedlings - 50% commercial seedlings
Replanting costs	about 1000€/ha	10.000kr/ha	1500€/ha	1800-2000€/ha
Seedlings price	0,20€/seedling -	0,1 - 0,5€	0,20 €	clones: 0,20-

	300€/ha			0,30€ improved seedlings: 0,15-0,20€ commercial seedlings: 0,10-0,20€

Second, for most tree species, the harvest is made at the end of the production cycle. Thinning may occur in between, but it only generates moderate profit. For Maritime Pine, it is generally considered that the sale of wood from thinning is just enough to cover the cost. Most of the traits that are improved for tree production are related to the yield and the quality of the wood. Hence the benefit from using improved varieties is obtained after several decades while the cost of the seedling occurs in the first year. As a consequence, the benefit is highly discounted compared to the cost. For example, with a 4% discount rate, 1€ of benefit after 40 years is equivalent to 0.2€ the first year. In addition, the forest owner faces multiple risks during this long production cycle, as several problems may affect the plantation (storm, fire, pest, etc.) and wood prices can also fluctuate[3]. For these different reasons, the potential benefit from using improved varieties is highly discounted at the time where the farmer has to make his planting decision. Some approximative figures related to Maritime Pine can illustrate the argument. Average yield after 40 years is 320m3/ha leading to a 12800€/ha sale. A 1% yield gain represents 128€, but 27€ after discounting and much less if risk is taken into account. Knowing that seedling cost is about 250€/ha for Maritime Pine, the maximum potential price premium for improved seedling is rather limited.

The two arguments mentioned above depend a lot on the duration of the production cycle. In this aspect, Eucalyptus is specific with a short cycle of 10-12 years between harvest. Note that Eucalyptus can regenerate after harvesting so that plantation occurs only after 2 or 3 rotations (24 or 36 years). Hence the surface planted each year is very small compared to the total surface of Eucalyptus, as for the other tree species. However, the effect of benefit discounting is smaller because of shorter rotations.

A third complementary argument corresponds to the perceived gain of the forest owners from using improved FRM in their specific context. Because of interaction between genotype and environment, the best improved FRM may be different from one field to the others. With annual crops, this explains why a farmer generally does not use only one seed product and prefers to experiment a new seed product on a limited area before using it more widely. This strategy is not possible with tree production because of the much longer duration of the production cycle. Hence even if forest owners are informed by extension services about the

[3] The forest owner can face short term price fluctuation by postponing the harvest. However price fluctuation that is more structural and lasts for a long enough period is a source of uncertainty.

potential performance of improved varieties, the perceived benefit they can get from this improved FRM on their specific land is more uncertain and lower.

These different arguments can be applied to all tree species with some variation depending on the specificity of each species. Additional arguments are related to regulation uncertainty and may vary depending on the country. In Portugal, the wildfires led to important restrictions on eucalyptus plantation. New surface of Eucalyptus cannot be planted and forest owners can only replant the surface that is cut if an authorization is granted. As long as this regulation is in place, the total surface of Eucalyptus in Portugal can only decrease and the forest owner may decide to keep their plantation for a longer period. In France, and some other European countries there is a controversy about clear cutting. This practice is currently not regulated but there is uncertainty about possible restrictions in the future.

In summary, the markets for improved tree varieties are limited for the tree species considered here because of the limited area planted each year and the limited willingness to pay of forest owners for improved varieties. To give an illustration, the market for Maritime Pine seedling, which is the largest among tree species in France, represents about 7.5M€. Most of these seedlings are produced from seeds coming from seed orchards, and seed cost represents about 25% of this figure. Interviews indicate that a large part of this amount is related to seed and seedling production cost, leaving limited margin for research funding. The annual license fee paid by seed producers to public research for having access to new improved varieties is 35K€.

We also argue that the discounting and uncertainty of future gains explain why forest owners have limited incentive to adopt tree varieties adapted to specific use. For example, the wood from Maritime Pine is commonly used primarily in lumber (construction or furniture) but the use for bioenergy increased during the last decade. Even if it was possible to develop new varieties with increased efficiency for bioenergy production, all the supply chain from seed producer to forest owner may have limited interest because of the uncertainty of the downstream industrial demand for this particular outlet after one or two decades. Hence, it is generally recognized that the heterogeneity of the demand is mainly driven by adaptation to the producing condition and there is no differentiation with respect to the final use of the wood.

At last, the demand is also limited because the markets are generally national so that international trade in FRM remains small, even if the FRM regulatory framework is harmonized across Europe and a large number of countries worldwide. In some cases, this lack of trade can be explained by the adaptability to local production conditions, with an improved tree selected in one country likely to perform poorly in another. Trade can also be limited for sanitary reasons. For example Pine nematode has been a source of major damages in Portugal since 1999 and Spain since 2008. It is not yet present in France but it represents a major threat, so that FRM imports from these countries are prohibited. In a similar vein, policies aimed at preserving biodiversity, such as Norway’s Nature Diversity Act, create non-tariff barriers to trade. Finally, the previous arguments explaining the low willingness to pay of forest producers for improved FRM apply to all countries. Hence, the potential benefit from exporting FRM is limited, while engaging in international trade imposes a minimum fixed cost at least to contract with local actors.

4.3 Private incentives on the supply side

Supply side covers the multiplication of FRM and the breeding for developing improved material. The two activities are important for innovation. Breeding defines the level of innovations and multiplication of FRM is key for the diffusion of innovations and for creating the impact from these innovations. For both activities, the long time interval for growing trees creates specific problems that drive the private incentives to invest in these activities.

FRM production is constrained by production capacity because of the cost for building these capacities and the inertia for adjusting these capacities. Production capacity corresponds to hectares of orchards for producing seed or, in the specific case of Eucalyptus clone production, the growing of mother plants. As an illustration, one hectare of Maritime Pine cost 10K€/ha for the set up and 2K€/ha/an for the management during the first ten years. The inertia for adjusting these capacities is related to the time length before the maturity of the tree which is necessary for producing seed (8 to 10 years for conifers). Because of this production capacity constraint and possibly specific problems like pests or bad weather that can affect yields, shortage of improved seed can be observed. For example, the share of improved Norway spruce seedlings from nurseries has fluctuated between 20% and 75% in Finland over the past decade. This shortage is typically more pronounced for the most recent improved material that embed highest genetic gain.

In addition to the shortage problem, the production time of seed orchards is generally longer compared to the interval between generation of new improved material. As investments in seed orchards are more easily covered when seed harvests are continued in existing orchards, seed producers have a low incentive to replace their old but still productive seed orchards by new and genetically more advanced ones. Seed shortage problems could obviously be avoided by oversizing production capacity with a frequent turnover. However, such a strategy requires high investment that cannot usually be covered by the sales of rather moderately priced seed.

Concerning breeding, the common wisdom in the agricultural economics literature corresponds to the situation observed for annual crops where we observe that breeding is carried out as a stand alone activity by seed companies, who can cover their research cost by the sale of improved seed. In this case, market size is a major driver of research incentives (Charlot et al. 2015). This scenario is never observed for tree breeding because of the long duration of the breeding cycle and the limited demand for improved material. In other words, for the three species studied here, private seed or nursery companies can be involved in the multiplication of the improved material, but they do not fund breeding programmes on the basis of the expected revenues from seed or seedling sales.

However, we observe important breeding investment by forest industry companies in the case of Eucalyptus in Portugal and Norway Spruce in Sweden. In both cases, the companies are not only involved wodd transformation but also in tree production. In Portugal, Altri and Navigator, the two major pulp and paper companies manage 20% (0.17 Mha) of Eucalyptus production. In Sweden, the major forest industry companies (Sveaskog, Holmen Skog, Stora Enso, SCA and Södras) manage 25% (6 Mha) of Norway Spruce production. For Eucalyptus, both Altri and Navigator manage their own breeding program. For Norway Spruce, the companies fund half of the breeding program that is managed by Skogforsk. In both cases, interviews show that breeding is a long term investment to guarantee the supply of wood as close as possible from the pulp and paper mills and other factories processing wood. Indeed, these plants represent major investments that require the regular supply of good quality wood in sufficient quantity. These constraints explain the investment in breeding, seed, seedling and production. It should be observed that, even if these companies are involved in tree production, most of the wood used in the mills comes from independent forest owners. Indeed, as the central aim of these companies is the supply of wood to mills, they are generally open to disseminate to independent forest owners both the genetic material and management practices they apply in their own forest. When this occurs, this diffusion is made at a moderate price, as the prime objective of these companies is not to make profit out of seeds or seedlings but to increase the supply of wood to their mills.

In summary, these case studies show that, despite the long duration of the breeding cycle and the limited market size for improved tree varieties, we can observe a private incentive to invest in breeding. However, the business model that drives this incentive is different from the classical business model that usually drives the incentives for breeding investment by major agricultural seed companies. Here the investment is made by downstream companies that invest in all the upstream activities to secure the supply of their plants. One interviewee explains that, worldwide, the forest industry companies that invest in breeding are only those who are also involved in the production of wood on large areas. Hence, the breeding investment is part of a general investment of these companies in upstream activities.

This case with major private investment in tree breeding is rather exceptional. For most of the tree species, private investment for breeding is very limited, and breeding activities only rely on public research organization and public investment. For Norway spruce, the breeding activities rely on LUKE in Norway and Skogforsk in Sweden with the participation of private funds for half of the budget, as described above. For Maritime Pine, the breeding relies on two public organizations, INRAE and FCBA, coordinated within an ad hoc structure (Pin Maritime du Futur). To provide more precise figures, we estimate the investment in breeding for

Maritime Pine over the period 2015-2020. The average investment was 693 K€/year. The sources of funding were 95% public[4] and 5% private (seed producer or forest owners).

5 Discussion and Conclusion

In the context of global environmental change and increasingly frequent natural disturbances, European forests are expected to fulfill a broad range of functions into the foreseeable future, including the resilient and productive supply of raw materials to foster the development of the EU-bioeconomy, the maintenance of genetic biodiversity, and the provision of important ecological services (for example, carbon capture). Given fast progress in applied genetics, and the observation that crop breeding is being revolutionized by rapid DNA sequencing and genome editing (Huang et al., 2016), it is clear that the selection of genetically improved forest trees and related diffusion of FRM has a potential role to play towards the achievement of those goals. However, little is known about the organisation of EU forest tree breeding conceived as an innovative activity and, thus, about the capacity of the sector to translate new genetic knowledge into improved trees that are likely to be adopted by forest owners. In particular, a literature review reveals that forest tree breeding has not been previously analysed through the prism of innovation theory and that cross-country analyses, which are necessary to compare institutional settings and derive general conclusions, are particularly lacking.

To fill this gap, this study analysed forest tree breeding for maritime pine in France, eucalyptus in Portugal, and Norway spruce in Finland and Sweden, using a conceptual framework that combines two perspectives: the innovation system perspective, which conceives of innovation primarily as a coordination problem among stakeholders subject to systemic failures, and the economics of innovation perspective, that addresses innovation primarily as an allocation problem subject to potential market failures.

Overall, we find that the prospects for a forest tree breeding "revolution" – to use a terminology often applied to crop breeding (Guang et al., 2016) and animal breeding (Ruan et al., 2017) – remain rather distant because of a combination of structural specificities of the forest sector, market failures and systemic issues.

Above all, innovation rates in the sector are impaired by a lack of demand-pull resulting from several factors. First, the long rotation period (Norway spruce, maritime pine) or possibility of vegetative regrowth (eucalyptus) imply that only a small share of the total forest area is replanted annually, resulting in limited demand for FRM. Second, the "tyranny of discounting" (Lozhnikova et al., 2014) and current round wood prices imply that price premia for improved FRM would be limited even if forest owners were only driven by profit maximisation and

[4] Self-funding by the two public organizations covers 67% (of the total investment) and subsidies by the Region Nouvelle-Aquitaine, State and Europe cover 27%.

behaved as perfect homo economicus. The fact that those owners often have limited knowledge of the potential benefits from planting genetically improved trees, display risk aversion and maximize multiple objectives further reduces their willingness to pay for genetic improvement. Third, the adaptability of FRM to agro-climatic conditions limit the possibilities of expanding the market through international trade.

Those demand-side factors are compounded by issues with the supply of tree breeding innovations, depending on the specific national context and species. In the case of Norway spruce for instance, the biology of the species and, in particular, its late sexual maturity, severely constrain the speed of the selection process and hence the rate of return to investment in genetic improvement. At another level, the current regulatory framework, although simple and common across the EU, remains rather rough with its only four categories of FRM, which may limit the incentives for differentiation based on genetic attributes. Finally, and although it may not apply to the case of eucalyptus, there is considerable variability in seed orchard yields, which complicates the short- to medium-term viability of businesses aimed at diffusing improved FRM.

Those demand and supply considerations severely reduce incentives for innovators to invest in the genetic improvement of FRM, as potential returns are low, far into the future and uncertain while up-front costs are high and immediate. In the current context, the only situation where those incentive problems are overcome correspond to the vertical integration of all operations, from the provision of seed and seedlings to the processing and valorisation of the final biomass into pulp, paper and other forest products. Whether this is observed depends on each species, with short rotations facilitating vertical integration as observed in the case of eucalyptus in Portugal, and national context, as evident with Norway spruce in Sweden but not Finland due to historical differences between the two countries in the structure of forest ownership. Thus, the main benefit from the production and diffusion of improved FRM currently lies with the additional volume and security of supply of raw material processed by the forest industry in its capital-incentive facilities that need to operate at maximum capacity. This is a clear indication of systemic problems where the incentives of the different segments of the supply chain do not align unless vertical integration is achieved.

The situation that we observe in those four EU countries makes it unlikely that transformative changes linked to private investments into tree breeding, or the emergence of new companies specialised in specific aspects of the breeding process (e.g. gene mapping) as observed in agriculture, will see the light in the forest sector in the short- to medium-run. However, the analysis also identifies areas for potential improvements in order to stimulate innovation in forest tree breeding.

First, there is a need to better inform forest owners about the benefits of improved FRM in order to enhance trust and raise demand for genetically improved seedlings. Indeed, interviews carried out for this study revealed a great level of confusion among stakeholders about tree breeding, as illustrated by the common misconception that genomics and genetically modified organisms were synonyms. More readily available information about the magnitude of the economic gains from planting improved FRM would also help, as this information currently remains rather elusive even in the academic literature. However, although it represents a necessary first step, the supply of raw scientific information about genetic and productive gains is unlikely to be sufficient by itself to induce broad behavioural change given the evidence that forest owners come in many types and pursue different objectives (Ficko et al., 2019). Any message to promote the advantages of improved FRM should therefore be carefully tailored to the target audience and, in some cases, insist on non-monetary benefits, such as carbon capture, that are likely to be more important than pecuniary rewards for forest owners usually classified as “indifferent”, “recreational” or “multiobjective”.

Second, the provision of ecosystem services by forest owners currently represents a positive externality that is under-supplied. The correction of some of those externalities could create additional incentives for a better management of forest stands and the adoption of improved FRM. For instance, compensation of owners for the carbon captured in their forests would increase the willingness to pay for fast growing FRM.

Finally, given the long planning horizons inherent in forest management, there is a need to provide clarity about future changes in the regulatory and policy environment to allow the stakeholders of the wood supply chain to make long-term investment plans, including investments in FRM. Yet, our interviews revealed much perceived uncertainty about future developments in regulations, for instance regarding the authorization to plant eucalyptus in Portugal, or about the implications of the recently adopted EU directive on biodiversity for the management of Swedish and Finnish forests.

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Dissemination plan

This deliverable corresponds to an academic article in economics based on the four case studies. This article will be submitted to an academic journal in forest economics in the coming weeks. The four case studies correspond to four specific reports that are available from the author upon request. We may decide to provide these reports as supplementary material for the article. They are all written in English except the report on Maritime Pine in France that is written in French.