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Monitoring and control of forest seedling quality in Europe

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ABSTRACT

The relationship between the quality of forest seedlings and their outplanting survival and growth has long been recognized. Various attributes have been proposed to measure the quality of planted seedlings in forest

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regeneration projects, ranging from simple morphological traits to more complex physiological and performance attributes, or a combination thereof. However, the utility and meaning of seedling quality attributes can differ significantly among regions, nursery practices, site planting conditions, species and the establishment purpose. Here, forest scientists compiled information using a common agreed questionnaire to provide a review of current practices, experiences, legislation and standards for seedling quality across 23 European countries.

Large differences exist in measuring seedling quality across countries. The control of the origin of seed and vegetative material (genetic component of plant quality), and control of pests and diseases are common practices in all countries. Morphological attributes are widely used and mandatory in most cases. However, physiological attributes are hardly used at the operative level and mainly concentrated to Fennoscandia. Quality control legislation and seedling quality standards are less strict in northern European countries where seedling production is high, and quality control relies more on the agreements between producers and local plant material users. In contrast, quality standards are stricter in Southern Europe, especially in the Mediterranean countries.

The control of seedling quality based on plantation and reforestation success is uncommon and depends on the conditions of the planting site, the traditional practices and the financial support provided by each country. Overall, European countries do not apply the "target seedling concept" for seedling production except for seed origin. Seedling production in many countries is still driven by traditional "know-how" and much less by scientific knowledge progress, which is not adequately disseminated and transferred to the end-users.

Our review highlights the need for greater harmonization of seedling quality practices across Europe and the increased dissemination of scientific knowledge to improve seedling quality in forest regeneration activities.

1. Introduction

Since the early 20th century, forest practitioners have been interested in identifying the functional attributes that drive seedling outplanting performance in forest plantations (Grossnickle and MacDonald 2018a). Several reviews have stressed the importance of forest seedling quality for plantation success (e.g., Puttonen 1989, Grossnickle and Folk 1993, Sampson et al., 1997, Colombo et al., 2001, Jacobs et al., 2012, Mataruga et al., 2012, Tsakaldimi et al., 2013, Andivia et al., 2021). Many morphological, physiological and molecular attributes, as well as several performance tests have been proposed to assess seedling quality (Mattsson 1997, Mohammed 1997). However, only a limited number of seedling attributes and tests are c used at the operational level, mostly those that are cheap, easy to implement, nondestructive and of quantitative nature (Zaerr 1985).

Evaluating seedling quality is crucial for understanding the effect of nursery practices on seedling development and subsequent field performance (Haase 2007, Haase 2008). Quality evaluation is also a valuable tool for assessing the achievement of forest restoration objectives and preventing disease spread (Villar-Salvador et al., 2009). Although using seedlings with "desirable" functional attributes does not guarantee high field survival, it increases survival chance (Grossnickle 2012). Additionally, seedling quality criteria are necessary for commercial purpose, providing a means to qualify traded products.

In the field of industrial engineering and services, the technical quality of many products may be evaluated by using technical standards, "compliance with the requirements" or "fitness for use". This definition was originally developed by Joseph M. Juran to measure the quality of products and services (Juran 1951, Juran 1988). One of the first definitions of forest seedling quality was coined at the first symposium of forest stock quality in 1979 that stated: "fitness for purpose" (IUFRO 1980, Ritchie 1984). Sutton (1979) defined the quality of planting stock as "the degree to which a stock meets the objectives of management at minimum cost". Seedling quality has also been defined as the capacity of seedling to survive and grow after being transplanted in a specific environment (Ritchie 1984, Duryea 1985, Wilson and Jacobs 2006).

At the beginning of the 20th century, the emphasis was placed on morphological attributes related to seedling size, such as shoot height, root length and especially root collar diameter (Tillotson 1917, Kittredge 1929, Wakeley 1935). Later, in the mid-20th century, many researchers also recognized the importance of plant physiology for understanding seedling field performance. With the advent after mass production of containerized seedlings In the 1970 s, researchers evidenced that the physiology of seedlings can be manipulated with nursery practices and thus change the quality of seedlings (Lavender and Cleary 1974). In addition to morphological and physiological attributes, the selection of forest species and provenances also became part of the seedling quality discussion (Tinus 1974). More recently, forest practitioners understood that no single plant attribute can predict outplanting success (Lavender 1988, Puttonen 1997, Davis and Jacobs 2005). Instead, an integration of different functional attributes is required to predict seedling performance (Hawkins and Binder 1990, Mattsson 1997, Grossnickle and MacDonald 2018b). However, measuring a wide array of seedling attributes is impractical (Omi 1991).

The idea that plant quality is defined according to the planting site and not the nursery site is one of the pillars of the "target seedling concept" (Landis, 2011). The target seedling concept was initially developed in North America to define specific morphological and physiological seedling attributes that can be linked to the reforestation success in a specific site (Rose et al., 1990). This concept has become a standard of nursery and reforestation jargon (Landis, 2011). The target seedling concept expanded to the "target plant concept" to include all types of plant materials (e.g., trees, shrubs, grasses), reproductive materials (seeds or cuttings), as well as traditional nursery stock (Landis, 2011). Although this concept has been used by researchers for more than three decades, we lack an overview of its implementation in forestry practice in Europe.

The European forest sector will face important challenges in the near future: 1) expected more frequent extreme weather conditions for planted seedlings, 2) increasing demand for more areas to be planted, 3) limited seed availability that may hinder the seedling production of many forest tree species, and 4) maladaptation of forest tree species and populations to novel conditions. For all these reasons, European forest plantations and reforestation system needs to improve its efficiency and decrease establishment cost by increasing the proportion of seeds that result in seedlings in the nursery and survive after outplanting.

The importance of seedling quality control in the European forestry sector is supported by several European Union (EU) directives (e.g., Council Directive 66/404/EEC, 71/161/EEC, 1999/105/EC). The most recent directive, 1999/105/EC, establishes the framework for the quality control of Forest Reproductive Material (FRM) in the EU countries, with emphasis on the FRM origin. However, this directive does not specify any morphological or physiological criteria on the quality of planting material, except for two cases: the external quality standards for *Populus* spp. propagated by stem cuttings and the seedlings intended to be marketed in the Mediterranean climate regions.

The attributes and tests used to measure forest seedling quality can vary among countries. These differences may reflect the specificities of each country such as the size of the forestry sector and the forested area, prevalent forest management and silvicultural practices, forestry research, forest land ownership, and nursery cultivation methods. There is no general overview of the practices, regulations and standards for seedling quality applied across European countries. Conducting a pan-European comparison would provide a valuable starting point for updating and improving seedling quality monitoring and nursery production in Europe.

The aims of this study are: i) to review the state-of-the-art of forest seedling quality control across Europe, focusing on regulations, seedling attributes, testing standards, and the application of the target plant concept, and ii) to identify the main deficiencies and propose measures to improve seedling quality control. This knowledge will be useful for forest practitioners including nurseries, forest managers, and landowners, as well as decision-makers and researchers. particularly in the face of climate change and the increasing need for seedlings to support forest restoration efforts.

2. Methodology

We designed a questionnaire with 14 questions grouped into five main topics (see below). The questionnaire was designed after preliminary discussions among forest scientists and several representatives of public forest administrations of European countries enrolled in the Cost action PEN-CAFoRR (Pan-European Network for Climate Adaptive Forest Restoration and Reforestation- https://www.pen-caforr.org/). The members of each country compiled information using different sources of information: statistical, legislation and general information on the topic available in government and company websites (see Table S1), direct communication with forest officers of the public administrations and members of nursery associations, scientific and technical published literature, and the academic community. In some countries where the official information was not available, specific surveys among specific stakeholders of the forest sector were prepared.

The questions were:

A) *Nurseries and seedling production*

Number of nurseries that produce forest seedlings, the main stock type (container or bare root) and nursery ownership (state or regional government, company, private, city, others)?

Annual seedling production for the main tree species in the last 5 years?

B) *Legislation and standards of seedling quality*

What are the basic parameters of seedling quality (divide all parameters into three categories: genetic, morphological, physiological), at the level of major species?

Are the “latest research results” applied to improve seedling production and the definition of the quality of seedlings, especially concerning drought tolerance, cold hardiness, nitrogen content, new fertilizers, or other?

Describe the legislation that defines seedling quality in your country.

How do the “regulations” of your country define the quality of seedlings at the level of species, origin, method of production, type of seedlings, etc.?

Do you apply “standards” of seedling quality and how old are the standards? Who is in charge of standard improvement (e.g., nurseries, foresters, forest policy-makers, all of these…) Here, “standards” mean the characteristics of planting material defined by the state (or any institution) that is used to evaluate planting material.

C) *Procedures and institutions in charge of determining seedling quality*

Who controls the quality of seedlings (eg. institutions or it is done by producers and/or end-users)?

When is the quality of seedlings determined (e.g., in the nursery during production, at the delivery, after planting in the field or at another time)?

What cultivation techniques do you use to improve the quality of planting material?

D) *Seedling quality and survival after planting*

Do you control the quality of planting material based on field success (survival, growth, resistance to hazards), and how is it done?

Are nursery production methods designed to adjust seedling quality traits with field conditions (target plant concept)? Is the field performance of seedling (survival, growth, damage by hazards) controlled after planting? How is it done?

E) *Relevant literature and personal observations*

Which is the relevant literature about this topic in your country?

Your personal observations (problems) in terms of necessary corrections, activities and better monitoring of seedling quality?

Comments and other relevant information

Experts from each country were asked to review the information in their country and reply to each question (in the period 2021–2022). We received responses from 23 countries and the quantitative and qualitative synthesis of the information is presented below.

3. Results

3.1. Nurseries and seedling production

The number of forest nurseries per country strongly varied among countries, ranging from three in Montenegro to 1165 in Romania. Iceland, Montenegro, Norway, and Slovenia reported less than 10 nurseries while 10 countries had more than 100 nurseries. The other nine surveyed countries reported between 10 and 100 nurseries. All forest nurseries are private in Belgium, Iceland, and Slovenia, while only (or predominantly) public nurseries can be currently found in Bosnia and Herzegovina (B&H), North Macedonia, Montenegro, Greece, and Turkey. In the rest of the countries, both public (state or regional ownership) and private nurseries coexist.

According to the annual seedling production in the period 2015–2020, seedling production increases from the south to the north of Europe, except Turkey. Poland had the highest production rate (greater than712 million seedlings year^{-1}), followed by Sweden, Turkey, Slovakia, Finland, Germany, and Czech Republic, all with an annual production exceeding 100 million seedlings (Fig. 1). France, Norway, Romania, Portugal, Estonia, and Spain have an annual production between 10 and 100 million seedlings. Other countries such as Bulgaria, B&H, North Macedonia, Iceland, Italy, Serbia, Greece, Slovenia and Montenegro produce less than 10 million seedlings year^{-1}. Countries with larger seedling production also tend to have bigger nurseries according to the ratio between the seedling production and the number of nurseries. The five most cultivated forest species are (in millions of plants per year): *Pinus sylvestris* L. (600), *Picea abies* (L) Karst. (500), *Quercus robur* L. (200), *Quercus petraea* (Matt.) Liebl (100), and *Fagus sylvatica* L. (100). Data on seedling production for Belgium was not available because seedlings are produced by private nurseries, which do not provide information to third parties due to data protection regulations.

3.2. Legislation and standards of seedling quality

European countries show large differences in the use of basic attributes to control seedling quality. Regulations do not differ across countries in several cases, while in other countries such as Bosnia and Herzegovina, Belgium, Germany, Italy, or Spain, they depend on the region within the country. In several cases these intra-country differences are determined by climatic variability within the country. Since the attributes of seedling quality are usually divided into three groups, (1) genetic or FRM origin, (2) quantitative and qualitative morphological, and (3) physiological and performance attributes, we have analyzed the results separately for each attribute group (Table 1).

Table 1. Table 1. Attributes used in different countries as indicators of seedling quality under operational conditions. + = used attribute; - = not used attribute; +- = not used in practice despite it is mandatory;

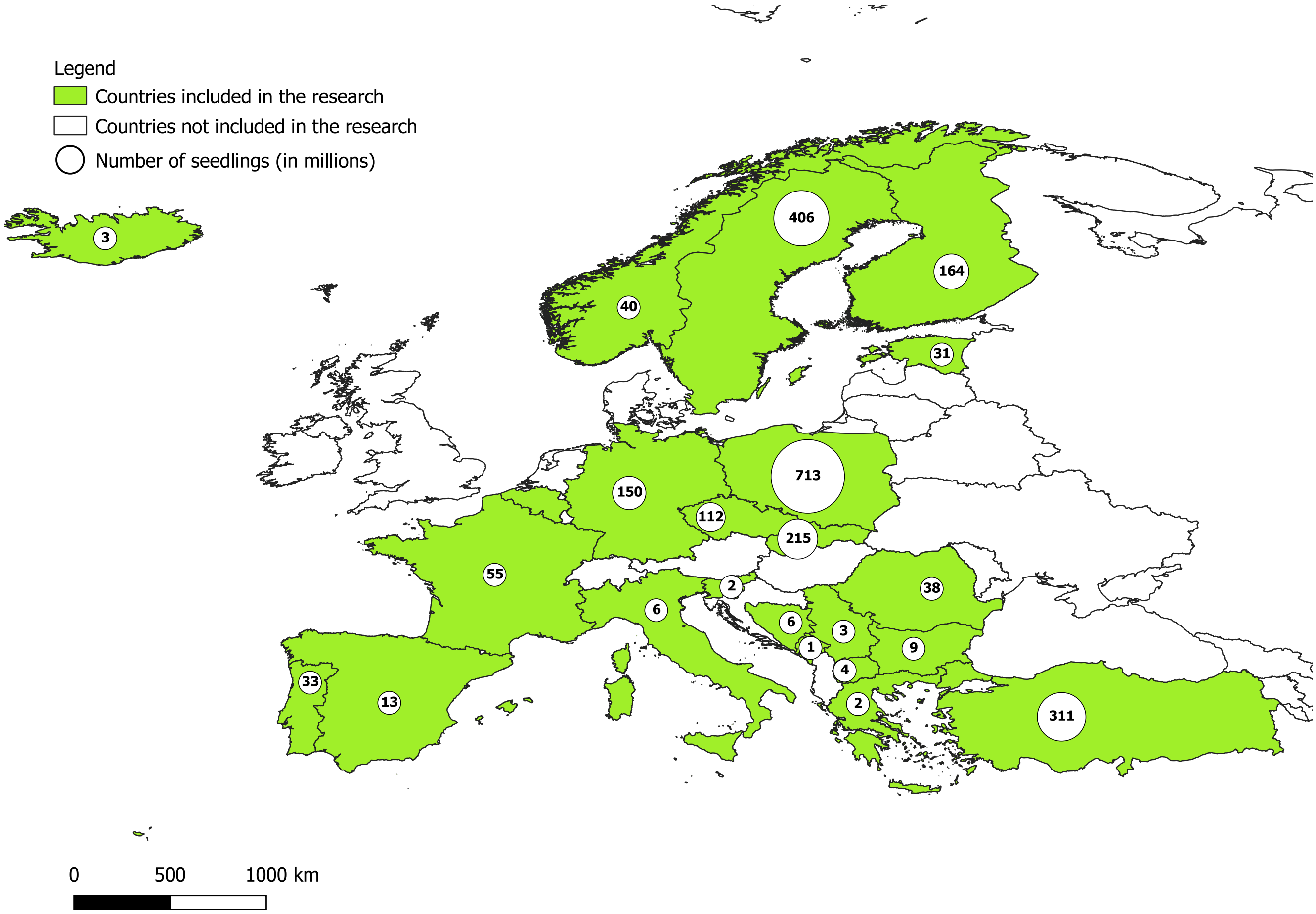

Fig. 1. Number of seedlings (in millions) in the 23 countries covered by the study (annual seedling production in the period 2015–2020).

B&H = Bosnia and Hercegovina; BD = Bud dormancy; RP = resistance to specific pathogens.

FRM origin is a key quality attribute of planting material in all countries. The legislation of the EU members and EØS (EEA) countries such as Norway is based on the EU Directive 1999/105/EC on the marketing of FRM. According to this legislation, knowledge of FRM origin is compulsory, and in most cases geographical seed zones or provenances have been defined for the main tree species (Berlin et al., 2019). Most countries have a "National Register" or"Catalogue" where the identity of FRM at seed collection, seedling production and finally at planting must be guaranteed. In B&H, Serbia, North Macedonia, and Montenegro, the FRM law defines the obligation to monitor the origin of FRM, but in practice this is not always implemented.

All countries use morphological attributes to evaluate seedling quality. Height and root collar diameter in relation to seedling age are the main quantitative morphological attributes in all countries (except Estonia which does not use the root collar diameter). The control of pest and pathogen presence is mandatory in all countries, while visible damage to buds, needles or roots are used as qualitative attributes in many countries (except Italy, Poland, Sweden, and Turkey). The presence of multiple stems is used to discard seedlings in 12 countries, basal stem curvature is considered in eight countries and fine root structure and the presence of marked root deformations is used in 11 out of the 23 analyzed countries. In addition, nine countries use morphological ratios such as the slenderness index (seedling height/root collar diameter) (Table 1). Seedling height and root collar diameter standards depend on container size (i.e. root volume) in Norway. Morphological attribute standards in Sweden depend on the latitude of the planting region with the emphasis on bud set and the lack of insect diseases.

Physiological attributes are only used in Fennoscandia, Iceland, and Estonia. Seedling nutrient concentration and frost tolerance is determined in Estonia, Finland, Germany, Norway, and Sweden, while root growth capacity is also used in Iceland and Sweden but only for conifers. The date of bud burst/dormancy is registered in France for some species such as *Pseudotsuga menziesii* (Mirbel) Franco. Seedling water status is analyzed in Estonia and needle electrolyte leakage in Finland, while the resistance to specific pathogens is analyzed in Belgium and France. Non-structural carbohydrate concentration is not analyzed in any country (Table 1). Researchers have proposed other physiological and performance attributes in Finland (Rikala 2002, Rikala 2012) and Norway (Fløistad 2014), but they are not currently used at the operational level.

In B&H, Belgium, Bulgaria, Czechia, France, Greece, Iceland, Italy, Montenegro, North Macedonia, Romania, Serbia, Slovakia, and Slovenia knowledge transfer for improving seedling production and quality attributes is low or non-existent at present. Most countries follow traditional "know-how" to grow seedlings and to define a high-quality seedling, and generally have not updated their practices according to new knowledge and paradigm changes. In a few countries (e.g. Spain, Turkey) knowledge transfer is mainly related to improving pest control and fertilization, growing media selection, and to a lesser extent to hardening and container selection.

Notably, plant production in north European countries such as Estonia, Norway, and Sweden is partly based on the latest knowledge (Gruffman et al., 2012, Jäärats et al., 2016, Jäärats and Tullus 2018). In Finland, the transfer of research-based knowledge to forest nurseries has been systematic since the 1990′s, when the Information service for nurseries was established at the Finnish Forest Research Institute unit. Knowledge transfer through different initiatives (journals, guidebooks, professional magazines, seminars, workshops, etc.) has been carried out on a customer-oriented basis. A similar system has been adopted in

Table 1
Attributes used in different countries as indicators of seedling quality under operational conditions. + = used attribute; - = not used attribute; +- = not used in practice despite it is mandatory; B&H = Bosnia and Hercegovina; BD = Bud dormancy; RP = resistance to specific pathogens.

Country	FRM origin	Quantitative morphological attributes				Qualitative morphological attributes				Physiological attributes					Performance attributes		Presence of pests or pathogens
		Age	Shoot height	Root collar diameter	Strong unbalance between shoot and root size	Damage of buds, stems, roots, foliage	Multiple stems	Stemcurvature	Poor root structure/ Strong root deformations	Nutrient concentration	Non-structural carbohydrate concentration	Water status	Electrolyte leakage	Other	Root growth capacity / potential	Frost ordrought tolerance	
1. B&H	+ -	+	+	+	–	+	–	–	–	–	–	–	–	–	–	–	+
2. Belgium	+	+	+	+	+	+	+	+	–	–	–	–	–	RP	–	–	+
3. Bulgaria	+	+	+	+	–	+	–	–	–	–	–	–	–	–	–	–	+
4. Czechia	+	–	+	+	+	+	+	+	+	–	–	–	–	–	–	–	+
5. Estonia	+	+	+	–	+	+	+	–	+	+	–	+	–	–	+	–	+
6. Finland	+	–	+	+	+	+	+	+	+	+	–	–	+	–	+	+	+
7. France	+	+	+	+	–	+	+	+	+	–	–	–	–	BD, RP	–	–	+
8. Germany	+	+	+	+	+	+	+	+	+	+	–	–	–	–	+	–	+
9. Greece	+	+	+	+	–	+	–	–	+	–	–	–	–	–	–	–	+
10. Iceland	+	+	+	+	–	+	–	–	–	–	–	–	–	–	+	+	+
11. Italy	+	+	+	+	+	–	+	–	+	–	–	–	–	–	–	–	+
12. N. Macedonia	+ -	+	+	+	–	+	–	–	–	–	–	–	–	–	–	–	+
13. Montenegro	+ -	+	+	+	–	+	–	–	–	–	–	–	–	–	–	–	+
14. Norway	+	+	+	+	–	+	+	–	+	+	–	–	–	–	–	+	+
15. Poland	+	–	+	+	–	–	–	–	–	–	–	–	–	–	–	–	+
16. Portugal	+	+	+	+	+	+	+	+	+	–	–	–	–	–	–	–	+
17. Romania	+	+	+	+	–	+	–	–	–	–	–	–	–	–	–	–	+
18. Serbia	+ -	+	+	+	–	+	–	–	–	–	–	–	–	–	–	–	+
19. Slovakia	+	+	+	+	+	+	+	+	+	–	–	–	–	–	–	–	+
20. Slovenia	+	+	+	+	–	+	+	+	–	–	–	–	–	–	–	–	+
21. Spain	+	+	+	+	–	+	+	–	+	–	–	–	–	–	–	–	+
22. Sweden	+	+	+	+	+	–	–	–	–	+	–	–	–	–	–	–	+
23. Turkey	+	+	+	+	–	–	–		–	–	–	–	–	–	–	–	+

Norway, and the consulting service for forest nurseries cooperates closely with forest research. The institutions such as the *Bayerisches Amt für Waldgenetik* (Bavarian Institution for Forest Genetics) (AWG, 2021) in Germany conduct their own field research or in cooperation with other research agencies like The Bavarian State Institute of Forestry (LWF) or some universities (e.g. Technical University of Munich, Georg-August-University of Göttingen). In Portugal, research is practically carried out only in nurseries linked to pulp companies (Navigator and Altri). In Poland, the results of the research carried out mainly by the Forest Research Institute and faculties of forestry are implemented in the nurseries of the State Forest Enterprise. Guidelines for forest nursery are developed and the Principles of Silviculture are revised (last edition 2012, currently updated). Their application in state-owned forest nurseries is mandatory.

All countries regulate the production of FRM by one or more laws and bylaws (see Table S1, supplementary material). However, these legislations only partially define the quality of seedlings. All countries establish the obligation of "genetic" quality of FRM or the identity of seed origin. Legislations also define the tree species subject to the law, provenance regions, method of provenance establishment, the characteristics of provenance regions, rules for FRM transfer within and between regions, etc. In contrast, only a few countries have laws that establish morphological and physiological attributes and standards on seedling quality. In Finland, forest tree seedlings will not be accepted if they are below a defined quality level which is based on several attributes. In Spain and Portugal, marketed seedling lots must fulfill several sanitary and specific qualitative and quantitative morphological attributes, which depend on the seedling age. Such requirements must be met by at least 95% of the plants in a seedling batch, which is also a requirement in most countries. In Italy, the quality requirements for seedlings to be marketed to the end user in the Mediterranean regions are indicated.

Almost all countries have quality standards or guidelines mainly based on seedling size and age. The Yugoslav standards (YUS) defined in 1964 are still used for the most common tree species in some countries of the former Yugoslavia (compulsory in B&H, Serbia, North Macedonia, Montenegro, but not in Slovenia). These standards define the minimum seedling height and root collar diameter depending on seedling age and species. They also define two seedling classes (I and II), while seedlings below standard cannot be traded or planted. Božič (1995) showed that the Council Directive from 1971 on the external quality standards for FRM marketed within the European Economic Community (71/161/EEC and its Annex 3 in 1974 (both no longer valid) were stricter and more detailed than ex-Yugoslav standards (YUS, 1964 and 1967). Furthermore, the Czech Republic is going to set the requirements for the quality of propagating material. Finally, in Romania, the quality of forest seedlings is defined based on National Standard *STAS 1347/2004.*

Some new standards require that plants should be labeled with a growth formula (the number of growing seasons from seeding to transplanting/the number of growing seasons in forest nursery before planting) and the specific requirements for the quality of seedling (Czech Republic). Some countries, such as B&H, Serbia, Macedonia and Greece have old guidelines, which have not been updated for a long time. Some attributes such as foliar nutrient concentration, frost hardiness and seedling height related to growing density have been proposed to update current regulations in Norway (Fløistad 2014). Sweden has had its standards for 20 years and there is a constant information exchange between researchers and plant nurseries. Research is performed by companies, Swedish University of Agricultural Sciences and Skogforsk (Forestry Research Institute of Sweden), often in collaboration with stakeholders. Similar national standards have been compulsory in Poland for over 30 years and include specific quality attribute requirements. In Finland, Germany, Czech Republic, and Poland seedling quality standards are a part of the law on FRM and their application is mandatory. In other countries these standards are not *a priori* applied in practice (e.g. B&H, Serbia, Montenegro, North Macedonia, Belgium, Bulgaria, Greece, Estonia, Slovakia). Morphological qualitative standards in Spain are not detailed, while seedling size relating to its age for the Mediterranean tree species is quite detailed. These size standards, however, are not defined for the Atlantic-climate trees. In Serbia, there are initiatives to change standards (Devetaković, pers. comm). More details about laws, standards and the institutions responsible for quality control and the links to the available literature in each country are shown in Table S1.

3.3. Procedures and institutions in charge of determining seedling quality

Most countries have public institutions in charge of seedling quality control (Table S1), with differences in the manner, intensity, and procedures. In general, FRM laws establish the institutions (authorities) in charge of determining seedling quality.

In Belgium, Czech Republic, Slovakia, Finland, France, and Slovenia the control is shared by different institutions; one institution is responsible for controlling the origin of FRM, another institution controls seedling quality, while the third party is in charge of disease issues or even outplanting success control. Norway, Poland, Sweden and Spain have a simple control procedure, where only nurseries and end users control the quality.

In Finland, self-control of plant quality has to be carried out by nurseries that are certified and registered as plant passport providers. Nursery staff in charge has to be trained and they need to deliver self-control plans to the Finnish Food Authority, which is the main organization in charge of seedling quality.

Countries can be divided into three groups according to the stage at which seedling quality is determined:

1. In the nursery during production and while seedlings remain dormant: Estonia, Montenegro and North Macedonia.
2. In the nursery and upon delivery: B&H, Czech Republic, Belgium, Germany, France, Iceland, Italy, Norway, Portugal, Romania, Serbia, Spain.
3. In the nursery, upon delivery and after planting: Bulgaria, Finland, Greece, Germany (if the planting has been funded with state subsidies), Poland, Slovenia, Slovakia, Sweden, Turkey. Survival after planting is assessed for seedling quality evaluation and/or for evaluating planting success (seedlings quality, damage by game, insects, and pathogens).

A common problem in many surveyed countries is that seedling quality decreases due to unsuitable seedling transport and handling during seedling shipping and planting.

Overall, legislation does not rule seedling cultivation standards or protocols to ensure the quality of seedlings. Some south European countries, however, establish a minimum container volume of 200 ml for cultivating tree species to be planted in the Mediterranean climate sites. Many nurseries follow their own protocols, which are partly trade secrets. These protocols relate to watering, shading, fertilization (based on monitoring the physical, chemical and biological soil properties), adequate growing media (not only in container production), root pruning, weed control, seedling storage and transport to the planting site or short day treatment. In some countries such as Czech Republic, Finland, Slovenia and Norway there are guidelines or manuals for seedling producers on proper seedling handling (Jurásek et al., 2010; ZGS, GIS, 2020a; ZGS, GIS., 2020b), the optimization of fertilization and soil management (Nárovcová et al., 2016), handbooks for tree nurseries and service providers (Rikala 2002, Rikala 2012, Pemán et al., 2013, Dietz 2019) or for planting material with specific needs such as seedling production for riparian forests (Božič et al., 2021).

3.4. Seedling quality and survival after planting

Regarding the control of plantation success, countries can be divided into three groups:

- Estonia and Italy do not survey seedling performance after planting to control or improve seedling quality.
- Most countries routinely measure the survival of planted seedlings and usually it must exceed 80–90% for a plant batch to be considered of fair marketable quality. However, this control is used as a measure of the success of afforestation and reforestation rather than an indicator of seedling quality:
  - B&H, North Macedonia, Iceland, Portugal, Romania, Serbia, Slovenia and Spain – 1st year after planting
  - Portugal, Romania, Greece and Montenegro – 2 years after planting
  - Norway – 3 years after planting
  - Poland, Czech Republic, Germany (Bavaria) – 5 years after planting
  - Belgium (private forestland) and France planting must be successful, regardless of measured year
- Seedling growth and health condition are also monitored in a few countries. In Belgium (state forests), Bulgaria, Sweden, Slovakia and Turkey they are measured 2–10 years after planting, depending on the environmental conditions of the planting sites.

Finland stands out from certain service providers which monitor the quality of planted seedlings as part of the quality management inventory tool developed in the 1990′s to measure forest regeneration. These quality measurements have evolved as a cost-efficient and effective part of the quality management system (Kalland 2004, Kankaanhuhta et al., 2009, Kankaanhuhta et al., 2010, Kankaanhuhta 2014).

Nurseries from Finland and some nurseries from Iceland, Norway, Spain, and Sweden modify seedling production according to the principle of "target plant concept" to fit seedling phenotype to site planting conditions and/or customer requirements. In the rest of European countries, nursery production does not seem to be designed to adjust seedling phenotypes to site conditions. The complexity of the internal socio-political organization in certain countries such as Bosnia and Herzegovina or Germany limits data availability and favors diverse intra-state approaches to monitoring seedling quality and the success of plantings at the national level. This further complicates the comparative analysis across countries.

4. Discussion

European countries have important differences in both the number of produced seedlings and the control seedling quality. North European countries tend to have higher seedling production than south Europe countries, except for Turkey. These differences among European countries also have implications for the production, transfer and trade of FRM within European regions (Konnert et al., 2015). The diversity of forest types, climate regions, national forest area, forest management methods, land tenure systems, forestry practices and national forest policies influences nursery production, and the procedures and standards for seedling quality assessment. Moreover, European countries show notable differences in the number of nurseries. Countries with higher seedling production tend to have fewer but larger nurseries than countries with lower production. The increase in nursery size facilitates enhanced technification and productivity gains (Landis 1995, Timpanaro et al., 2018).

Many countries lack reliable seedling production inventories, which hampers the analysis of production levels and seedling quality, and accurate bilateral trade statistics (Jansen et al., 2019). Several reasons limit the compilation of data on seedling production, including decentralization of nursery production across regions in some countries, private ownership where companies produce exclusively for their own use, the absence of official registers, the failure of national statistics to collect such data, deliberate concealment of production volume, protection regulations restricting data access to third parties, inconsistent criteria for categorizing "forest planting material", and discrepancies on which species are included in official seedling production data.

All countries included in the survey have legislations to regulate the genetic quality and the origin of FRM. This indicates a recognition of the importance of genetic quality in forestation. The adoption of the EU directive on the trade and utilization of FRM (European Council Directive 1999/105/EC), has resulted in the use of local seed provenances of native tree species in forest practices following the principle of "local is the best" (MCPFE 1993, Alizoti et al., 2019, Gömöry et al., 2021, Dimitrova et al. 2022). The same paradigm underlies the legislation of European countries that are not part of the EU as well as the "Scheme for the Control of FRM Moving in International Trade" by the Organization for Economic Cooperation and Development (OECD, 2012). Despite the awareness of the potential benefits of genetic diversity and the use of non-local FRM as an adaptive management strategy to address climate change, research conducted by Vinceti et al. (2020) reveals that forest owners and managers generally prefer local FRM over foreign alternatives. However, research is needed to enhance our understanding of the impact of genetic origin on seedling performances. It is important to recommend FRM suitable for a given site, especially considering the improved selection capacity and the potential for traceability of southern provenances that exhibit greater resistance to dry conditions in projected climate change scenarios (Bolte et al., 2016; Stojnić et al., 2018).

Morphological attributes determine the outplanting performance of seedlings, especially if they are not damaged or severely stressed (Larsen et al., 1986, Bayley and Kietzka 1997, Stone et al., 2003, Bayala et al., 2009, Li et al., 2011, Tsakaldimi et al., 2013). Consequently, these attributes have been used to discard poor-quality seedling batches. However, in many cases, qualitative attributes are ambiguous and imprecise. For instance, legislation in many countries stipulates that seedlings with a strong imbalance, i.e. they have a disproportionally large shoot relative to the root system, should not be used. However, the legislation does not provide clear criteria for defining such imbalances, species differences and measuring them. Consequently, these end-users may subjectively interpret this norm based on their own background or opinion. A similar issue arises with seedling size standards, where the range of shoot height considered to be of "suitable" quality is often so wide that virtually all types of seedlings can *de facto* be classified as marketable. We consider that many of the current standards have little utility and require redefinition based on updated research and quantitative reviews of published scientific literature (Grossnickle and El-Kassaby 2016, Andivia et al., 2021).

Monitoring of seedling quality standards vary between and within countries. For example, some reforestation managers and nursery staff thoroughly assess seedling quality on an annual basis, while others conduct evaluations only when issues arise (Haase 2008). These differences in perspective also appear to exist among some European countries. However, there is a need to improve standards for both morphological and physiological attributes. While some countries, such as Slovenia (Božič 1995), Turkey (Dilaver et al., 2015), and Norway (Fløistad 2014), have proposed revisions to quality standards, concerns have been raised that excessive standardization may negatively impact genetic diversity (Gömöry et al., 2021), thereby limiting their acceptance within national regulatory systems. Furthermore, upgrading some standards and legislation to include specific seedling cultivation methods and protocols should also be considered (Wallin et al., 2021).

The importance of seedling quality is widely acknowledged, yet there are evident discrepancies regarding what constitutes a high-quality seedling (Ivetić et al., 2016). Currently, there is no clearly defined and widely agreed and applied uniform methodology, laws, standards or protocols in the production of seedlings that explicitly aims to improve their quality. The few efforts for improving seedling quality and productivity have primarily focused on standardizing production processes, analyzing uncontrolled statistical variation, utilizing systematically measured data and learning from the results of continuous improvement activities (Deming 1986, Ishikawa 1985, Juran and Gryna 1993). Furthermore, this study confirms previous research (Hazarika et al. 2021) on critical uncertainties in the awareness of the existing national-level and European-level policies and their likely effects on the quality standard utilization of FRM (pers. comm. between authors).

Knowledge transfer among researchers, nursery staff, and other end-users is generally limited in most European countries, except for Fennoscandia. In many countries, insufficient research, practical experience, and lack of long-term experiments on plant quality hinder the capacity to provide empirical support and recommendations to enhance seedling production and quality. This lack of knowledge limits the modernization of plant production, the evolution of plant quality criteria and the training of nursery staff. Two reasons explain this situation. First, low revenues from forestry discourages research and innovation and hinders the recognition by society of the value of forestry sector (e.g. B&H, Bulgaria, Greece, Italy, Montenegro, North Macedonia, Romania, Serbia, Spain). Second, some countries rely more on natural regeneration than on forestation for forest regeneration. Thus, although research information is available in the language of each country, it is not implemented into regulations or transferred to improve nursery practices. Moreover, there is a division of opinions regarding the usefulness of "traditional knowledge" on nursery cultivation for improving seedling quality. For instance, authors from countries with low seedling production often believe that sticking to "tradition" limits improvement in seedling quality and advocate for the introduction of new cultivation methods and paradigms in the forestry sector (based on personal communication between authors). Finally, in many countries, practices are influenced not only by the law, but also by incentives and subsidies (public or private) that come with additional obligations. Although these incentives and subsidies do not have the force of a law, they strongly influence practices.

We could not assess confidently whether the data collected in the field after planting seedlings are used to improve nursery production and other processes that affect the quality of seedlings or if they are only used as indicators of outplanting success. Therefore, some results for several countries related to monitoring the survival of seedlings may be presented here as a basis for quality control, while they are used only as an indicator of the quality of work on planting seedlings.

The Target Plant Concept provides a framework for defining, producing, and handling seedlings and other types of plant material based on specific functional characteristics suitable for specific sites. These characteristics are often derived from research that tests factors linked to outplanting success, such as seedling morphology and physiology, genetic origin, and the capacity of plants to overcome limiting factors at the planting sites (Davis and Pinto 2021). Since plant attributes drive outplanting success, cultivation practices should be designed to produce seedling phenotypes that match the specific conditions of the planting site.

Nursery growers and field managers should work together to identify plant attributes that drive seedling survival (Dumroese et al., 2016). Users are expected to provide more information to nursery staff about the characteristics of the forestation habitats, as well as the feedback on the success of forestation and the success of different types of seedlings. Manufacturers can then improve the quality of seedlings by listening to users, considering their results and recommendations (pers. comm. between authors).

The implementation of the Target Plant Concept has been little implemented in Europe, mainly on selecting the appropriate provenances and, in some northern European countries, assessing frost hardiness prior to planting. Implementing the Target Plant Concept implies that nurseries need to produce several batches of phenotypically different plants and of different origin. This is difficult to implement in many European countries due to 1) inadequate advance planning of plant production; 2) low profitability of nurseries, limiting their capacity to produce multiple stock types; 3) insufficient technical skills of nursery staff are; 4) limited knowledge on the phenotypes that best perform under different planting conditions; and 5) the high ecologically diversity of forest habitats in Southeastern Europe and Mediterranean countries.

Planted forest focused on restoring degraded ecosystems or enhancing ecosystem services are generally less profitable than those aiming at timber management. However, where forest restoration is crucial for the mitigation of the effects and adaptation of ecosystems to global change, it is important to demonstrate the society the relevance of investing in planted forests. One key aspect of this investment should be directed to improve seedling quality. Certain countries cannot achieve the same high standards as countries with a strong timber sector, unless both society and European governments recognize the non-financial returns and high value of ecosystem services provided by these planted forests and restored ecosystems.

Finally, countries across Europe need to keep their specificity in the production of FRM. This is a consequence of different habitat conditions, different techniques of growing and regenerating forests, different ownership of forests and nurseries and different nursery production. However, they should learn from the experience of other countries, to improve their practice. It is therefore important that countries across Europe increase the exchange of knowledge, innovation and practical experience so that we can take advantage of the diversity between countries in habitat conditions and local practices.

5. Conclusions

Procedures, standards and attributes used to control seedling quality and the relationship between seedling producers, end-users and researchers vary significantly across Europe. In countries with high plant production, seedling quality monitoring is less stringent and relies more on agreements between producers and users. The differences in seedling quality monitoring between countries across Europe can be partially attributed to differences in regional forest productivity, which are linked by climate type, forest management practices, and the different forest policies.

All countries monitor the origin of FRM as an indicator of potential genetic quality, which is a consequence of the implementation of European Directive 1999/105/EC. Standards for morphological standards differ among countries, and the use of physiological attributes is limited to a few countries in northern Europe. In some countries, seedling quality monitoring is conducted by producers and users, while others have institutions responsible for monitoring and certification of plant material is carried out by institutions.

In general, European countries do not widely adopt the "target plant concept", except for considering the origin of FRM. However, there are recommendations on the most suitable provenances for different planting regions. Traditional practices and habits in seedling production present challenges in implementing new research findings and paradigm changes. In addition, the transfer of new knowledge on seedling production and quality based on research to producers is slow in practice.

This highlights the need to review seedling quality attributes and standards based on scientific knowledge and harmonize some of them among EU countries, while taking into account the specific environmental conditions and habitat characteristics across European regions. Furthermore, the introduction of the main principles of quality management and improvement tools, along national systematic data collection and sharing the best practices of the different forestation stages would improve the production and the transfer of FRM to meet present and future needs considering climate change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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