



From lab to forest: overcoming barriers to in vitro propagation of forest trees

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Abstract Reforestation initiatives are often limited by insufficient seeds, a problem exacerbated by natural variability in tree flowering and seed production and climate change and other environmental challenges. Innovative and adaptive solutions such as in vitro propagation are thus needed. Tissue culture can provide high-quality propagation material for tree conservation and mass propagation, but faces technical, economic, regulatory, and social barriers. Obstacles related to the academia–industry interface and to stakeholder concerns are discussed and actions suggested to overcome these barriers to realize the full potential of tree micropropagation. These include refining techniques to improve efficiency and reduce costs; establishing collaborations among researchers, industry, and foresters; and reducing points of contention and misinformation regarding genetic diversity and public perception. International collaborative initiatives, exemplified by the EU COST Action CA21157 COPYTREE, are elementary for achieving these goals.

Keywords Commercialization · Forest reproductive material · Technology transfer · Tissue culture

Introduction

Forest tree populations are declining due to habitat loss, climate change, and overexploitation, threatening biodiversity and human livelihoods (Curtis et al. 2018; Betts et al. 2022; FAO 2022; Zhou et al. 2023). The spread of invasive pests and diseases is exacerbated by global trade and climate change, presenting significant risks to tree health worldwide (Lovett et al. 2016). Loss of tree cover reduces carbon storage and weakens climate regulation capacity (Pan et al. 2011), leading to habitat loss for numerous other species and disrupting ecological balances (Lindenmayer et al. 2012) and human livelihoods (Chhatre and Agrawal 2009; Brancalion et al. 2020). At the same time, wood continues to be a valuable resource and is important for sustainable development.

For over 50 years, planted forests established with seed-raised plants have been the backbone of commercial forestry

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and wood production for human needs (Carle et al. 2020). The production of forest reproductive material (FRM) is facing growing limitations as impacts of climate change and demands within the timber market increase (Mataruga et al. 2023). FRM production is well-established in Europe, but frequently limited by a shortage of seed (Lelu-Walter et al. 2013), and there are worldwide problems with seed supply in terms of quantity, genetic diversity, and quality (Haase and Davis 2017; Jalonen et al. 2018). Seed production depends on the natural variation in trees flowering (Lelu-Walter et al. 2013) and seed set (Stoehr and El-Kassaby 2011). Further, increasing pest and pathogen problems, the effects of climate change and other environmental challenges negatively impact seed production, quality, and storage viability (Ascoli-Morrete et al. 2019; Marshet and Fekadu 2019; Hacket-Pain and Bogdziewicz 2021; Kijowska-Oberc et al. 2021; Mantilla Contreras et al. 2023; Bicho et al. 2024). Overcoming the lack of seed production capacity requires new adaptive strategies.

“Target seedling production” is a concept aimed to produce plants with specific traits adapted to their intended planting environment and represents a shift toward a more strategic and pragmatic approach to reforestation, using the most suitable planting material for each site (Landis 2011; Tsakalimi et al. 2013; Dumroese et al. 2016; Andivia et al. 2021). In the foreseeable future, it is likely that FRM may also be selected with consideration of its epigenetic and non-inheritable traits plus priming ability that confer superior field performance of trees as the environment becomes even more challenging (Bonduriansky et al. 2011; Amaral et al. 2020; Klupczyńska and Ratajczak 2021).

Tissue culture can provide the means to fill the gap in tree conservation and mass propagation; disease-free plantlets can be produced throughout the year for reforestation, breeding purposes, and germplasm storage and for multiplying endangered species (Fay 1992; Montalbán et al. 2020). In vitro techniques can be used to mass produce any number of genetically different clones, which is especially important for species that are recalcitrant or grow slowly, poor seed producers, or have rare mast years. In addition, tissue culture has the potential to reduce some disease and pest risks associated with traditional propagation methods.

In vitro propagation techniques, including tissue culture, are particularly valuable for producing FRM independent of seed availability and quality, addressing seed shortages and facilitating the clonal propagation of desirable genotypes (Lelu-Walter et al. 2013). Methodologies such as somatic embryogenesis (SE) offer the potential for accelerated and improved transfer of genetic gains achieved by breeding to practical forestry, bypassing the need for traditional seed orchards (Rosvall et al. 2019; Grattapaglia 2022), or stabilizing FRM production by complementing annual fluctuation in seed yields. Further, they can also provide means for

utilizing priming and epigenetics for improved resilience and other purposes (Puentes et al. 2018; Berggren et al. 2023; Viejo et al. 2023).

While tissue culture and in vitro multiplication have enormous potential, their general acceptance for large-scale FRM production faces technical, economic, regulatory, and social barriers (Lelu-Walter et al. 2013). Resolving these problems requires collaboration between researchers, breeders, nursery managers, investors, policymakers, and forestry practitioners. Objections and concerns regarding the potential impact of clonal FRM on biodiversity must be addressed. However, using clonal FRM that are propagated in vitro aligns with objectives for climate change mitigation and carbon neutrality. Superior growing stock in production forests can also help to reduce pressure on existing wild and old forests.

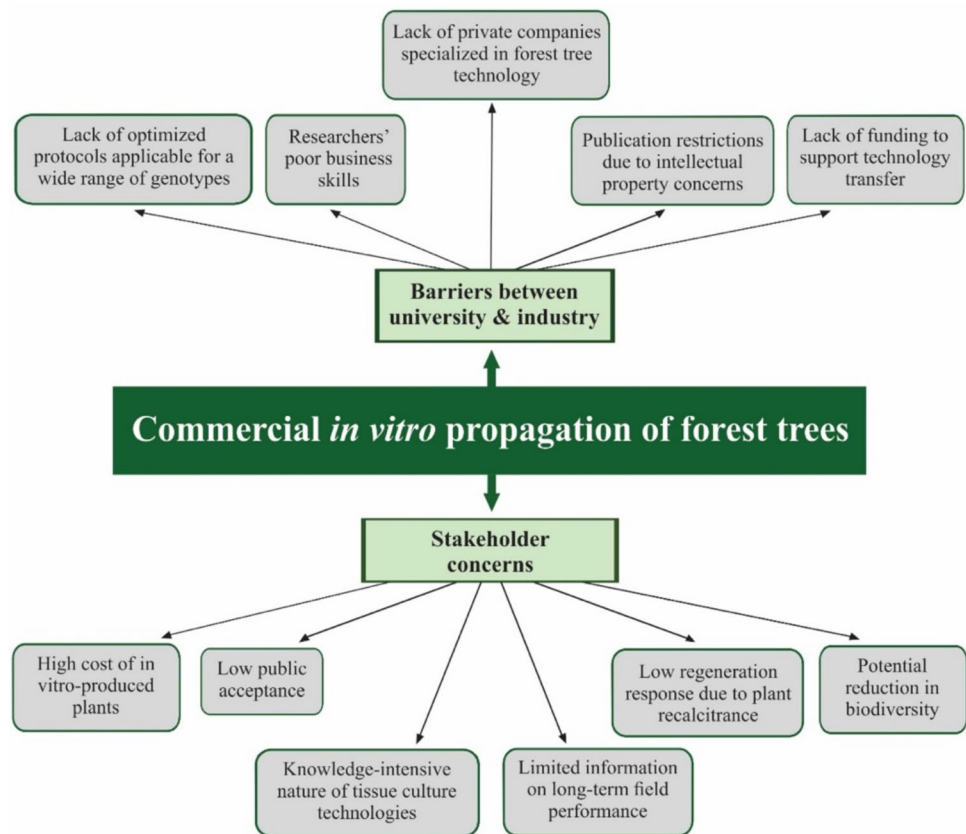
A recent study found that many tree species widely dispersed in Europe retain their evolutionary potential for survival over very long periods of time despite strong environmental changes (Milesi et al. 2024). By providing genetically superior FRM and this natural resilience in vitro propagation can also contribute to the future of ecological and economic sustainability in highly productive forests. This perspective paper examines technical and non-technical barriers for broader adoption of in vitro propagation of forest trees and outlines practical steps to address challenges. By integrating insights from research, commercial practice, and policy, exemplified by initiatives such as EU COST Action CA21157 COPYTREE, we aim to promote wider application of tissue culture technologies in forestry.

Recognizing the factors limiting commercial in vitro propagation of forest trees and some ideas on how to bridge the gap

Overview

The potential gains from large-scale propagation using plant tissue culture, are enormous, but the large-scale application of this technology to woody species remains challenging (Wu 2019; Aronen et al. 2025b). As summarized in Fig. 1, there are obstacles in the academia–industry interface and concerns for practical forestry. Mass propagation of FRM in vitro, with production volumes ranging from millions to tens of millions of plants, requires significant financial investment and the resolution of key biological, economic, and societal challenges, including regulatory compliance and public perception. Smaller-scale in vitro propagation is more readily achievable for breeding programs, genetic conservation efforts,

Fig. 1 Factors identified limiting commercialization of forest tree tissue culture



and commercial production of special trees (Find 2016; Stuepp et al. 2018; Merkle et al. 2022; Cardi et al. 2023). Although production volumes are smaller than for conventional FRM, the economic return per tree is higher.

Overcoming barriers between academia and industry

Although the recognized obstacles related to the academia-industry interface (Fig. 1) include technical issues such as lack of optimized tissue culture protocols, the issues are mostly related to differences among academic and business cultures, or they are structural in nature. Key issues include insufficient knowledge of markets, lack of specialized companies, researchers' poor business skills and potential conflicts between advancing a scientific career and developing a business, together with difficulties in treating all companies equitably and recognizing interests of competing partners. Acquisition of funding for technology transfer is also a critical issue. To overcome these barriers, it is essential to implement a combination of targeted strategies, as explained below.

Establishing generically applicable protocols and controlling contamination and solving physiological and developmental challenges are paramount and problems of concern even before upscaling plant production in the laboratory (Bairu and Kane 2011; Cassells 2012; Abdalla et al. 2022;

Balo 2023; Kumari et al. 2023). In addition, both research and industry developers need a very clear idea of what product specifications and expectations must be fulfilled, how to produce the plants, and how to get them to thrive long-term in the field. This process has many steps, from the location of initial research and development to the final production facility. Some issues will change over time, vary in relative importance or be more challenging than others, requiring external consultants with a specific skill or expertise. In the end, each problem must be solved or accepted that it is not solvable, e.g. developing generic media formulations. The road to successful technology transfer requires close cooperation and collaboration with regular face-to-face meetings between all participating groups (O'Dwyer et al. 2023).

Traditional FRM production methods based on seed collection and seed orchards with limited asexual propagation facilities or expertise have quite a different skill set and facility requirements for handling in vitro micropropagated plants. The lack of private companies specializing in this forest tree technology presents a significant obstacle to its implementation, hindering the potential for innovation and economic growth within the forestry sector. Creating new start-up companies and training new staff (who have open minds ready to accept and implement the new technology) could be viable options but may be outside the experience of most researchers and require the input of some business

acumen or developing relationships with existing commercial *in vitro* laboratories currently focused on horticultural crops but that could accommodate these new forestry products.

Transitioning from academia to the business world can be challenging for scientists, who likely lack commercialization or business expertise. Funding aimed at supporting technology transfer and commercialization of innovations can facilitate new business development and provide valuable connections to business coaches. Institutions can proactively create opportunities for their staff to gain practical business experience, resulting in a mutually beneficial situation for both the employer and the staff. In addition, establishing trust between researchers and industry partners, by starting with smaller collaborative projects, can help overcome the inherent cultural differences and build long-term partnerships that benefit both sides (Rossoni et al. 2024).

Research institutions often encourage staff to undertake projects with private companies; this practice looks good in principle but can create problems for researchers. These projects may offer valuable scientific challenges, but publication restrictions related to protecting intellectual property, for example, can limit career advancement for scientists who rely on publications for promotion. The vision for the project may be an issue with researchers wanting to focus on long-term scientific goals and companies needing to prioritize short-term commercial outcomes. The EU has an Innovation Procurement Fund (IF 2021) that could be useful at the technology transfer stage.

Publicly funded research is subject to national and European Union legislation that demands equitable treatment of all companies and impartiality from researchers, prohibiting preferential treatment. Navigating these regulations, particularly with limited legal support, can be challenging and hamper knowledge and material transfer. Clear guidelines and support structures are required to manage intellectual property rights issues and comply with regulations.

Collaborations with multiple companies can be even more complicated when they share a common interest in a novel technique. These companies are often competitors and can be reluctant to share information to protect their intellectual property and economic interests, interfering with effective collaboration and technology transfer. Lack of transparency and trust can also impede the development and widespread adoption of promising technologies such as *in vitro* propagation. Overcoming these challenges through open communication, clearly defined objectives, and mutually beneficial cooperation models is vital to realizing the full potential of tissue culture techniques and applying innovation within the forestry sector.

Beyond cost: addressing stakeholder concerns

Several factors contribute to the lack of stakeholder involvement in adopting *in vitro* propagation for forest tree production (Fig. 1), making its commercialization a very challenging process. The relatively high cost of plants produced *in vitro*, stemming from the labor- and knowledge-intensive nature of tissue culture technologies, is a significant deterrent for stakeholders (Senyange et al. 2024). Another significant concern is the potential reduction in biodiversity associated with clonal propagation, a critical factor in all ecological processes including forest establishment (Cardinale et al. 2012), managed by legislative requirements for vegetatively propagated FRM as discussed below. Biological recalcitrance, defined as the inability to propagate a species or a substantial proportion of its genotypes through *in vitro* techniques, is an ongoing problem for many tree species, which may result in unintentional selection for specific traits and reduced genetic diversity. Commitment to long-term research is required to avoid future plantation management problems relating to biodiversity and long-term field performance of the tissue-cultured trees. These issues, in turn, might influence stakeholders and public acceptance of the technology. To address the stakeholders' concerns, we suggest the following actions.

Robust methodologies that are applicable to a wide range of genotypes for each species need to be developed by testing a wide range of genotypes. Expanding the available genetic stock enhances the feasibility of addressing other difficulties concurrently (Aronen et al. 2025a, b).

The primary obstacle to the widespread forestry application of tissue cultured plants is their higher cost than seedlings. While benefits like greater productivity, shortened rotation cycles, and enhanced pest and pathogen resistance could offset these costs, forest owners face an immediate expenditure for planting stock. Still, returns are realized only at the end of the rotation period, sometimes spanning up to 60–80 years. A recent survey by Tikkinen et al. (2021) revealed that forest owners may be willing to pay up to a 24% premium for improved planting material. However, current *in vitro* propagation costs frequently exceed this threshold. Achieving an acceptable price requires innovation that promotes enhanced cost efficiency in all labor-intensive propagation phases, e.g., through integrating robotics and automation (Egertsdotter et al. 2019). Also, a larger pool of genetic material facilitates the selection of genotypes exhibiting both favorable propagation characteristics and desired traits; these are often unrelated. The costs of rigorous selection and testing are easily underestimated (Aronen et al. 2025a).

Successful innovation in forestry with long rotation times (up to 100 years), especially in the northern hemisphere, requires a long-term focus with enduring partnerships

and trust, in marked contrast to the prevailing short-term focus in research and funding, with normal projects typically spanning 2–5 years that is insufficient for establishing the viability of in vitro materials as FRM. Given the long rotation times of many tree species and the extensive field testing required within breeding programs, obtaining reliable data on growth characteristics and morphological traits can take 10–15 years. In contrast, wood quality assessments may need even longer durations. Another problem is that many research laboratories cannot conduct essential nursery performance and long-term field trials. Consequently, long-term commitment and collaboration among nurseries, forest research institutions, and tree breeders are crucial for establishing trials and pilot plantations with in vitro FRM. These joint efforts are essential for building confidence with legislative authorities, forest professionals, forest owners, and the public, who require evidence of the efficacy and environmental safety of the plant material before large-scale implementation.

While private companies can invest in research and development (Dean 2008; Adams et al. 2016), collaboration between companies and the wider scientific community remains limited, and the companies typically do not publish their results in scientific journals. Long-term testing of in vitro propagated materials is still largely confined to the research phase for most species, except for some fast-growing species such as eucalyptus, paulownia, poplars, some pines, and spruces.

Genetic diversity and regulatory compliance

International and national regulations and forest certification schemes influence the marketing and utilization of FRM, including tissue-cultured material. While national regulatory frameworks vary, all EU countries adhere to a common legislative framework for FRM marketing. Although these regulations are sometimes perceived as a challenge for tissue culture technologies, when considered proactively, they provide guidelines rather than obstacles for sustainable production.

Close collaboration with breeding programs capable of furnishing accurate genetic data on the propagated material is essential for regulatory compliance. Within the EU, FRM marketing is contingent upon registration (Council of European Union 1999), and the OECD has established similar provisions for international trade. In vitro propagated materials can be registered as basic material under the categories “Parents of family/ies”, “Clone” or “Clone mixture.” The “Parents of family” option bases FRM evaluation on parental characteristics, while “Clone” options assess the propagated genotypes directly. Furthermore, basic materials are classified as either “Qualified” or “Tested.” National regulations may also stipulate requirements such as the

minimum number of genotypes to be propagated, the maximum number of plants derived from a single genotype, and the maximum planting area (Lelu-Walter et al. 2013).

These regulations aim to mitigate risks associated with vegetatively propagated materials and to address numerous concerns, primarily the depletion of genetic diversity but also information gaps, prejudices, and economic considerations (Lelu-Walter et al. 2013; Tikkinen et al. 2021). Reduced genetic diversity raises concerns about susceptibility to novel pests and diseases, particularly in the context of climate change. Other concerns include increased resource competition among plantation trees with similar resource utilization patterns, potentially leading to yield losses, reduced support for other species, and diminished recreational value in multi-use forests. Many of these concerns are influenced not only by the genetic diversity of the planting stock, but also by forest management practices and can be minimized through rigorous field testing.

Although vegetative propagation inherently involves fewer genotypes compared to seed propagation, maintaining a sufficiently high number of genotypes from unrelated families can ensure relatively high allelic diversity. Recommended numbers generally range from 5 to 30, with 15 to 25 suggested for northern regions with extended rotation times (Rosvall et al. 2019). Finland has implemented a strategy to address diversity concerns, with registered SE-derived Norway spruce FRMs comprising 12 full-sib families, each represented by up to 10 genotypes in propagation batches. These propagated SE batches evolve due to breeding advancements and are assigned specific deployment areas. This approach ensures the periodic replacement of SE batches with improved versions and prevents ubiquitous cultivation of identical genotypes (Aronen et al. 2025a). Combining SE plants and seedlings can also enhance stand diversity and reduce establishment costs.

Cultivating public acceptance for forest biotechnology

Public acceptance is crucial to successfully integrate in vitro propagation in forestry. This implies proactive and transparent communication strategies that address public concerns and explain the technology’s potential benefits and challenges (Aronen et al. 2025a). Effective communication should emphasize the role of such techniques, focusing on acute environmental issues such as climate change and biodiversity loss while ensuring the long-term health and sustainability of forests; clear up misconceptions between clonal propagation and genetic engineering; plus provide accessible, scientifically sound information on the performance, benefits, and potential risks of tissue cultured materials.

This information can be conveyed through various channels, including online resources and demonstration sites,

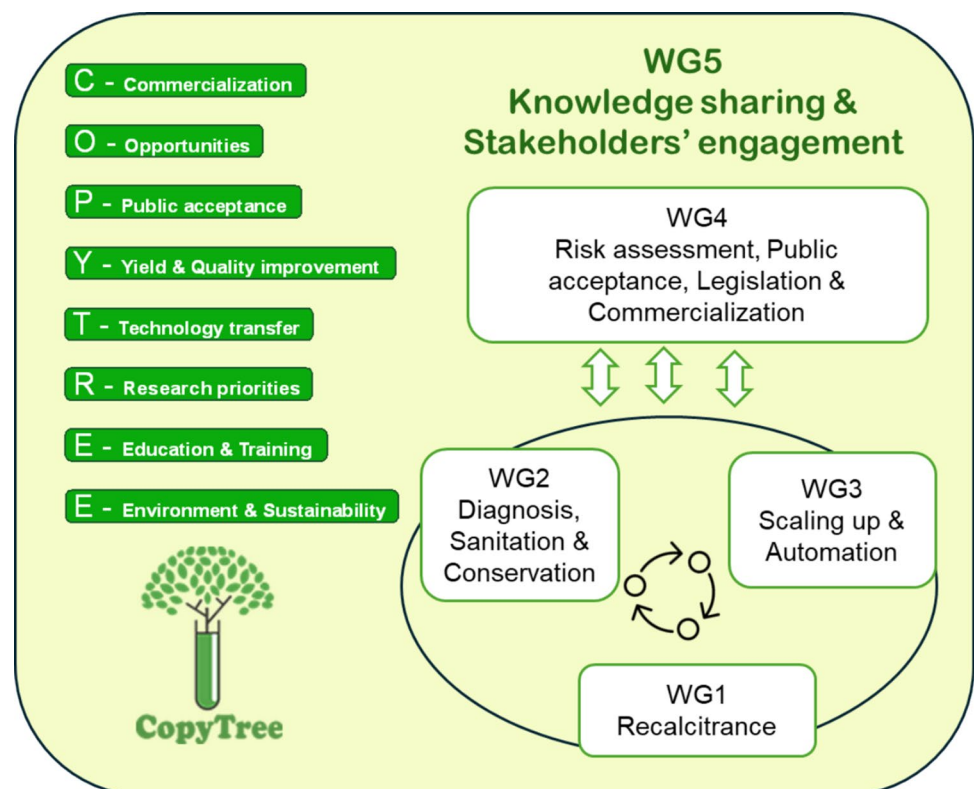
allowing greater public access to information. Furthermore, public–private associations can ease knowledge transfer and empower stakeholders across sectors to effectively disseminate information. By acknowledging the public’s influence on policy and market demand and actively engaging them in discussions about in vitro propagation, the forestry sector can acquire trust and support for this valuable technology. It is important to note that moving from science or knowledge to practical actions is often a cumulative and stepwise process, demanding several iterations and coevolution (Räsänen et al. 2024).

Partnering of industry and academia for knowledge transfer: the COST Action COPYTREE

The COST Action COPYTREE is advancing in vitro propagation, particularly for woody plants, focusing on collaboration and knowledge transfer among researchers and companies across Europe. This network brings together researchers, innovators and industry leaders from 50 countries and has over 370 members. Launched in 2022, the initiative seeks to establish collaborative innovation by connecting in vitro technology experts of fruit and forest trees, working together to reach important objectives (Fig. 2) to facilitate the transition of knowledge from laboratory research to commercial production.

This network successfully shares best practices, standardized protocols, and the latest research findings, essential for overcoming challenges such as recalcitrance, diagnosis and sanitation, and scaling up and automation. By evaluating new technologies and tools, e.g., through collaborative testing of new compounds, COPYTREE can identify the most effective and reliable methods for various woody species. COPYTREE contributes to risk assessment and public acceptance by disseminating knowledge about this technology’s potential risks and benefits in the EU. This proactive initiative helps to reduce prejudices and misunderstandings to promote informed decision-making. COPYTREE is not only about today’s innovation, but also the definition of the future by guiding the new generations of scientists and innovators in cutting-edge in vitro technologies for fruit and forest plants. Finally, COPYTREE stimulates commercialization by connecting researchers with industry partners and providing information about the opportunities and economic advantages of in vitro propagation, which encourages investment and facilitates technology transfer from the lab to the marketplace. By supporting network ideas, knowledge sharing, and innovation, COPYTREE is helping to unlock the full potential of novel propagation technologies and pave the way for a more sustainable future for our forests and the green sector.

Fig. 2 COPYTREE network and objectives



Conclusion

The increasing threats to global forests require innovative and adaptive solutions. In vitro propagation, with its potential to conserve endangered species, enhance reforestation efforts, and consider seed-related challenges, emerges as an essential tool to ensure a sustainable future for our forests. However, realizing the full potential of these novel technologies requires addressing fundamental obstacles and objections. These include refining techniques to improve efficiency and reduce costs, establishing contact and collaborations between researchers, industry, and foresters, and reducing points of critique and misinformation regarding genetic diversity and public perception. By actively involving stakeholders, promoting knowledge transfer, and supporting long-term research and development, we can prepare the forestry industry for the widespread adoption of in vitro propagation. The use of this technology will not only aid in conserving and restoring our invaluable forest resources but also contribute to handling the impact of climate change and preserving biodiversity for future generations.

Initiatives like the COST Action COPYTREE are important because they actively assist collaboration and knowledge transfer to advance tissue culture applications in woody plant species. It shares best practices, standardized protocols, and research findings to reduce drawbacks in the field. COPYTREE evaluates new technologies and tools, contributes to risk assessment, and stimulates commercialization. By encouraging network formation, knowledge sharing, and innovation, COPYTREE is helping to unlock the full potential of in vitro propagation and prepare the way for a more sustainable future in our forests and the green sector.

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