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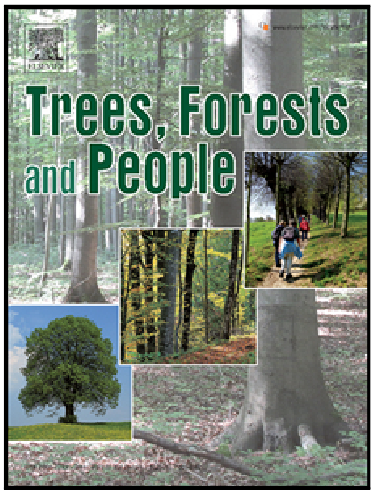

Participatory Mapping of the Forest Community Stakeholders in Europe Focusing on Forest Genetic Resources, Forest Reproductive Material, and Protected Forests

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Participatory Mapping of the Forest Community Stakeholders in Europe Focusing on Forest Genetic Resources, Forest Reproductive Material, and Protected Forests

1. Introduction

European forests cover around 160 million hectares (EU-27), with over 90 % of semi-natural forests. Primary and old-growth forests cover less than 4%, yet they “are of utmost importance for Europe’s biodiversity” as they are considered to be more resistant and adaptive to disturbances than modified forests (EEA, 2020). Protected forests, 5.68% of European forests, aim either to conserve forest biological diversity, or to protect landscapes (EEA, 2020). Plantations represent 6 percent of the planted forests and 0.4 percent of the total forest area in Europe (EEA, 2020). The genetic diversity of forest trees is most often conserved in old-growth and other forests where (close to nature) management considers genetic principles. Further on, the genetic diversity of about over 100 tree species and 4000 populations are partially conserved in about more than 3500 genetic conservation units with 4000 populations (portal.eufgis.org/).

Sustainable forest management warrants a careful consideration of both forest genetic resources (FGR) and forest reproductive material (FRM) (Lefèvre et al. 2020). FGR are the heritable materials maintained within and among tree and other woody plant species that are of actual or potential economic, environmental, scientific, or societal value (FAO, 2014). They include the genetic diversity of biological entities such as seeds, standing trees, and entire forests, within and between species (EUFORGEN, 2021). FGR are the result of the adaptation and evolution of forest tree species over time and space, forming the basis of forest biodiversity at the gene, species and ecosystem level (FAO, 2014). They are also fundamental to the long-term survival of species and the stability of forest ecosystems, sustaining a wide range of ecosystem services, such as terrestrial biodiversity, timber production, carbon sequestration and water regulation. (FAO, 2014, EUFORGEN, 2021; Muys et al., 2022; Storch et al., 2023). As such, FGR are a crucial part of climate change adaptation and mitigation (Fady et al., 2016). They face direct and indirect pressures (IPCC, 2023; Vacek, Vacek and Cukor, 2023) that threaten their functions and persistence by increasing their vulnerability to disturbances (Maes et al., 2020; Muys, 2021; Graudal et al, 2014; Alfaro et al., 2014). Forest reproductive material (FRM) - seeds, plants and plant parts of tree species - is crucial for establishing productive silvicultural systems (EUFORGEN, 2021, European Commission, 2023). FRM is also essential for reforestation programmes aiming to restore the genetic diversity of natural ecosystems. Thus, FGR and FRM are "valuable for present and future human use and therefore an invaluable asset and a cornerstone of sustainable forest management" (de Vries et al. 2015, p.v).

While FGR and FRM may include similar biological components (such as seeds, plant parts, or entire plants), their conceptual framing and practical uses differ. FGR refer broadly to the heritable genetic variation within and among tree populations and serves as the foundation for long-term conservation strategies aimed at preserving evolutionary potential and biodiversity. In contrast, FRM denotes the tangible products (seeds, seedlings, or cuttings) used directly in forest regeneration, afforestation, or breeding programs. Thus, FRM represents a functional output of FGR, derived through selection and propagation for specific goals (i.e. productivity, resilience, etc.). In conservation, FGR are managed both in situ (e.g., gene conservation units) and ex situ (e.g., seed banks), whereas FRM is used operationally in forestry and landscape restoration to ensure genetic suitability and adaptability of planted forests. This distinction underpins the need for separate but coordinated governance, management, and research approaches for each.

Despite their importance, the management and conservation of FGR and the production and deployment of FRM often remain understudied and lack the integration of diverse stakeholder perspectives (Pascual et al., 2023). Forests and forestry related-sectors encompass a broad range of stakeholders – including academia, industry, government, and civil society – whose decisions and activities directly or indirectly influence forest sustainability. These groups have overlapping, divergent, or conflicting priorities, complicating efforts to achieve sustainable outcomes (Ihemezie et al., 2021) and leading to poor implementation and enforcement of existing policies. Even when policies are in place, there are often gaps in implementation and enforcement, which undermines their effectiveness. These gaps result from a lack of resources and funding, inadequate monitoring and evaluation systems, closed data flows and limited stakeholder involvement, capacity and expertise (Nabuurs et al., 2022; Hazarika et al, 2021; Kramer et al., 2016; Koskela et al., 2016). For example, although the EU Forest Strategy and the EU Access and Benefit Sharing (ABS) Regulation provide a policy framework, the inadequate financial and human resources, limited stakeholder participation, and a lack of monitoring and evaluation mechanisms hamper their implementation (Pecurul-Botines et al., 2023; Graudal, et al., 2020). This often results in uneven or insufficient implementation and compliance with policy measures, which can further lead to unsustainable or inadequate management and use of FGR and FRM (Willer, Smith and Aldridge, 2019). Therefore, there is a rising need for greater awareness and engagement among policy- and decision-makers, forest managers, researchers, and the wider public (Hoban et al., 2021; Marcu et al., 2020; Harazika et al, 2021).

Yet, the absence of a comprehensive stakeholder analysis and mapping represents a significant gap in conservation and management of FGR, and production and deployment of FRM (Reed, 2008). Existing studies have predominantly addressed the ecological (i.e. de Vries et al., 2015; Storch et al., 2018; Vajana, et al, 2022), management (i.e. Lefèvre et al., 2013; Koskela, et al., 2013; Muys et al., 2022; Jandl et al, 2024) or policy (i.e. Lefèvre et al., 2020; Graudal et al., 2020; Hoban et al., 2021, Lovrić et al., 2023) dimensions of FGR and FRM, but there is a notable paucity of research focusing specifically on stakeholder analysis within this domain. This gap is significant because the success of FGR conservation and FRM deployment initiatives depends not only on scientific and technical considerations but also on the effective engagement and collaboration of diverse stakeholders, including local communities, policymakers, industry representatives, and conservation organizations (Fady et al., 2016).

Although studies addressing stakeholder interactions that influence FGR management and conservation and FRM production and deployment are rare, recent efforts have begun to acknowledge the importance of stakeholder perspectives in those fields. For instance, a study by Šijačić-Nikolić et al. (2018) examined the attitudes of key stakeholders in forestry and nature protection towards the conservation of FGR in Serbia. Vinceti et al. (2020) conducted research with 200 forest owners and managers from 15 European countries to understand, amongst others, their knowledge of FGR and their attitude toward actively managing these resources. They found that most of the respondents (86%) were aware of the potential offered by managing FGR, and preferred FRM of local origin. Yet, such studies are relatively scarce. There remains a critical need for comprehensive frameworks that integrate stakeholder analysis into FGR and FRM research and practice (Fady et al, 2022, Lefèvre et al, 2024). Addressing this gap is essential for developing holistic strategies that not only advance scientific understanding but also foster collaborative governance and sustainable management of forests.

This study addresses the identified research gap using a combination of approaches: a participatory stakeholder mapping, a systems thinking and quadruple helix model (Carayannis and Campbell, 2009; 2010). The general aim of this study is to improve the understanding of the stakeholder landscape surrounding the forest genetic resources (FGR) and forest reproductive material (FRM) domains in Europe, with the goal of supporting more effective and inclusive governance of these critical resources. To achieve this, the study pursues two specific objectives:

1. To systematically map and categorise the stakeholders involved in the conservation and management of FGR and the production and deployment of FRM
2. To analyse stakeholder relationships and perceptions**,** identifying key roles, synergies, and tensions between actors, to inform future strategies for integrated forest governance and sustainable resource use.

The significance of this study lies not only in providing an empirical stakeholder map for the European context, but also in offering a transferable framework for participatory stakeholder analysis that can inform forest governance more broadly. Many of the governance, coordination, and capacity challenges faced in Europe, such as fragmented responsibilities, conflicting stakeholder interests, and limited cross-sector dialogue, are shared by forest sectors globally. As such, this study offers a methodological and conceptual contribution that is relevant to researchers, practitioners, and policymakers concerned with genetic resource management, sustainable forestry, and participatory governance globally. The study highlights the importance of integrating local and global perspectives, ensuring that forest management strategies reflect the needs and priorities of diverse stakeholders while aligning with international commitments.

2. Conceptual framework

In this study, we view forests as complex socio-ecological systems, shaped by the interactions between ecological processes, human activities, and governance structures (Plummer and Armitage, 2007). From systems thinking approach the forest goals and outcomes (i.e. biodiversity conservation or climate resilience) emerge from dynamic, non-linear interactions among biological, institutional, and societal elements. It also highlights the importance of understanding forests not in isolation, but as embedded within wider land-use and socio-political systems, including agriculture, water, and energy (Nebasifu et al., 2024; Nocentini et al., 2017; Messier and Puettmann, 2011).

To address the complexities of forest governance under conditions of ecological uncertainty and stakeholder diversity, we drew on the concepts of adaptive governance and innovation systems (Armitage et al., 2009). These approaches highlight the importance of collaboration, learning, and experimentation among diverse actors to navigate trade-offs and respond to emerging challenges (Armitage et al., 2009; Carayannis and Campbell, 2009; 2010). Building on this, we adopted the quadruple helix model (Carayannis and Campbell, 2010) as both a theoretical and analytical tool for structuring stakeholder analysis. Originally developed in the context of innovation policy, the quadruple helix extends the triple helix model of academia, government, and industry (Etzkowitz and Leydesdorff, 2000) by adding civil society as a fourth pillar, thereby recognising the critical role of public values, community knowledge, and non-market contributions in shaping system outcomes (Carayannis and Campbell, 2009; 2010).

In our research, the quadruple helix model served two purposes. First, it provided a structured framework for categorising stakeholders involved in FGR, FRM, and protected forests, ensuring balanced attention to actors across research, regulatory, commercial, and civic domains (Carayannis et al., 2012). Second, it guided our interpretive analysis of stakeholder dynamics, allowing us to identify where synergies, tensions, and gaps exist across sectors. By integrating this model with participatory mapping, we were able to visualise how different types of stakeholders engage with forests in varying ways, and how their roles and relationships may influence conservation and sustainable use outcomes.

Stakeholder ("a stake = something to gain or lose") is anyone directly or indirectly influencing or being affected by a certain decision, project, program or process (Rietbergen-McCracken and Narayan, 1998). Stakeholders are individuals or organisations (fiscal persons or legal entities) that have a capacity to act. In our case of forest stakeholder community, stakeholder is anyone who is directly or indirectly affected by or have an influence on FGR, FRM and forests.

By adopting systems thinking, we define forest stakeholder community as a group of stakeholders who have a shared interest or concern in forests and forestry-related issues. Members are linked by social ties and may directly or indirectly influence, or be affected by, decisions and actions related to forests, FGR and/or FRM. Some stakeholders focus specifically on the conservation, management, or use of FGR and FRM, others are involved in broader forestry activities (i.e. policymaking, education, research, economic development, and environmental stewardship). Collectively, they engage in joint actions and decision-making that can both shape and respond to relevant challenges.

3. Research design

3.1. Methodology

This study was done under the Horizon Europe project "*Harnessing forest genetic resources for increasing options in the face of environmental and societal challenges (OptFORESTS[1])"*. The main aim of OptFORESTS project is to support the protection and sustainable use of FGR in Europe by strengthening cooperation and knowledge sharing for promoting climate change adaptation and biodiversity-friendly forestry practices (OptFORESTS, 2025).

Given the nascent state of stakeholder mapping for FGR and FRM in Europe, this study adopted a descriptive, exploratory approach without statistical hypothesis testing. Rather than generalising from sample-based data, we generated conceptual and structural insights through participatory expert consultation and thematic synthesis. Exploratory research is commonly employed when the phenomenon being studied is not well understood or when existing knowledge is fragmented (Creswell,

[1] https://www.optforests.eu/

2009). This approach allows researchers to identify patterns, generate new insights, and develop a conceptual framework that serves as a foundation for further hypotheses and research.

The research adopts an abductive reasoning process, which combines elements of deductive and inductive reasoning (Dubois and Gadde, 2002). Abduction focuses on iteratively moving between empirical observations and theoretical insights to refine understanding (Timmermans and Tavory, 2012). This abductive approach was particularly well-suited to this study, as it allowed the integration of theoretical frameworks (starting deductively from the quadruple helix model) with empirical insights derived from experts' interactions and diagrammatic analysis. Through this process, the research was able to both build upon existing knowledge and generate novel insights into the composition of forest stakeholders' community conceptualising it into three different sub-communities.

To ensure the research remains focused and actionable, we established clear boundaries to delineate the scope of inquiry. The study focuses on the forest stakeholder's community in Europe in its broadest sense, encompassing all relevant stakeholders and beneficiaries whose activities, decisions, or interests intersect with forest-related sectors. While the research takes a broad view of the forest stakeholders' community, it specifically targets FGR and FRM. While we initially conceptualised those two sub-communities, the third subcommunity (Protected forests) emerged later in research (see Methods section for more details). This boundary ensured that the research provided actionable insights for the management of FGR within the broader context of forest sustainability. This approach also acknowledges the interplay between local and global perspectives. While the research focuses on specific stakeholder groups and activities, it places these within the context of global challenges such as biodiversity loss, climate change, and sustainable development, by considering also stakeholders that are not directly engaged in forestry, but their activities might directly or indirectly impact it. This dual focus ensures that the findings are both locally grounded and globally relevant, addressing the needs of diverse stakeholders while contributing to broader policy and governance frameworks.

3.2. Methods

We employed participatory stakeholder mapping as the primary method to identify, categorise, and visualise the diverse stakeholders involved in forest management and conservation, with a specific focus on FGR and FRM. Stakeholder mapping is a widely recognised method for systematically identifying and analysing the roles, relationships, and influence of stakeholders in complex systems (Reed et al., 2009). Participatory stakeholder mapping emphasises the active engagement of stakeholders or their representatives in the mapping process, ensuring that diverse perspectives are integrated and that the resulting framework reflects shared understanding and priorities (Reed, 2008). This approach was particularly suited to the multi-functional nature of forests, where diverse stakeholder groups often hold overlapping or conflicting interests.

The identification process began with a workshop in 2022 involving nine OptFORESTS researchers. During this session, stakeholders were identified through collaborative brainstorming based on participants' disciplinary knowledge and professional experience. No structured interviews were conducted for this study. To guide this process we used the definition of stakeholder defined in section 2. Sub-groups were distinguished where actors had functionally or ontologically distinct roles – for instance, separating *students* from *universities* acknowledged that while students are part of academic institutions, their role as future practitioners and beneficiaries of forest education warranted separate consideration. Similarly, *breeding scientists* were distinguished from *seed bank managers* due to their differing positions in the FRM value chain. Guiding questions included:

- *Which individuals, groups, or institutions have the capacity to influence or are affected by the management, conservation, or use of FGR and FRM?*
- *How should we categorise these stakeholders across academia, industry, government, and civil society?*
- *Which stakeholders are primarily linked to FGR, FRM, or protected forests, and where do overlaps occur?*
- *Are there sub-groups within each stakeholder type that warrant separation based on function or orientation (e.g., students vs. universities, forest managers vs. seed producers)?*
- *Who is missing?*

The discussions were conducted in English, the working language of the project. Experts were not compensated beyond their role in the consortium, and participation was voluntary.

After the initial stakeholder categories were generated, a smaller team of six researchers (three from the original group and three additional consortium members) refined the map through four structured review rounds. These were conducted via digital collaboration using Miro – a visual workspace that allowed us to cluster, connect, and annotate stakeholder categories interactively (Miro, 2024). For example, early in the process, “forest users” was listed as a single group, but through iterative feedback and literature cross-referencing, this was divided into more specific actors (e.g., “tourist organisations,” “NTFP businesses,” “local communities”), recognising their different relationships to forests. In this process, a stakeholder category related to protected forests emerged inductively, as we gain better understanding of the stakeholders’ positions towards the conservation of FGR and use of FRM in forest management.

The use of Miro enabled theoretical integration by allowing real-time comparison of emergent stakeholder configurations with our conceptual frameworks, such as the quadruple helix model. For instance, stakeholders were colour-coded and spatially grouped according to their primary affiliation (academia, industry, government, or civil society), helping to ensure alignment with the model and encouraging reflection on ambiguities. A practical example of this was our debate over whether intergovernmental organisations belonged under government or academia – Miro helped visualise cross-cutting roles, prompting us to allow for dual affiliation depending on institutional function.

During an in-person consortium meeting, we distributed printed versions of the fourth iteration of the map to 40 experts (OptFORESTS project partners mostly with expertise in genetics, breeding, modelling, social and political forest science), who proposed modifications and shared feedback. While the detailed breakdown of panel is available in Annex A, the panel included a mix of experts in forest genetics, tree breeding, forest modelling, conservation biology, social and political sciences, and forest policy. The majority of participants came from academia and research institutions.

On this way, the definitions and groupings were cross-checked among researchers for consistency, with proposed changes requiring justification grounded in either empirical practice (e.g., professional mandates, project deliverables) or theoretical rationale (e.g., stakeholder theory, systems thinking). The relationships among stakeholder categories were derived through expert elicitation, based on domain knowledge and experience rather than empirical quantification. Interactions were defined in terms of typical roles, collaborative pathways, and flows of information, resources, or influence. We did not attempt to measure the intensity or frequency of these interactions, as such factors are highly context-specific and dependent on institutional arrangements, geographic scale, and specific forest-related objectives. Instead, we focused on identifying major connection points and relational patterns that shape forest genetic resource and reproductive material governance. These refinements collectively ensured that the final stakeholder map reflects both empirical realities and conceptual clarity.

4. Results: The Three Sub-Communities and Their Stakeholders

The stakeholder analysis revealed a total of 45 stakeholders' groups. We categorised them in three interconnected sub-communities – Forest Genetic Resources (FGR), Forest Reproductive Materials (FRM), and Protected Forests – each with its own priorities, stakeholder composition, and relationships with forests. In Section 4.1 we describe the stakeholders categorised using the quadruple helix framework (academia, industry, government, and civil society). In Section 4.2 we present the conceptualisation of three sub-communities.

4.1 Stakeholders and Their Roles within Each Sub-Community

4.1.1 Academia and Research

The academia category includes eight stakeholder groups: universities, students, research institutes, geneticists, biotechnologists, breeding scientists, gene/seed bank managers and other researchers (Annex B, Table 1). These stakeholders play a pivotal role across all three sub-communities. They create, advance and communicate knowledge, foster innovation, and prepare the next generation of forestry professionals.

Universities and research institutes supply scientific research and expertise (Wilson, Dyer and Cantore, 2024) to forest managers, operational breeders, seed banks, and government agencies, supporting forest management, breeding programs, and genetic conservation efforts. They offer training and capacity building to students, forest practitioners, and local communities, enhancing skills in biodiversity monitoring, FGR management, and sustainable forestry. Researchers, including geneticists, biotechnologists, breeding scientists and others (i.e. socio-economic researchers, political scientists, ecologists, etc.) advance scientific knowledge and collaborate with industry and business stakeholders by sharing knowledge and advancing genetic innovations. They also advise policymakers and decision-makers on policy development for forest governance. Gene and seed bank managers interact with breeders and forest agencies by providing FGR critical for breeding, restoration, and conservation initiatives (Wambugu, et al., 2023). In relation to FGR, academic stakeholders are key actors in identifying, conserving, and studying genetic variation through both in situ and ex situ approaches. Their work often underpins conservation policy and breeding strategies. When it comes to FRM, academia contributes to developing improved varieties, advising on selection protocols, and training forestry professionals who implement FRM-based practices.

Some international organisations (i.e European Forest Institute, the International Union of Forest Research Organizations) play a role in governance of FGR, FRM and PF they could facilitate knowledge transfer, shape international policy frameworks, and support coordination and funding across scales. Although their presence might be particularly relevant at the science-policy interface, it is cross-cutting as international organisations could also belong to industry, government or civil society categories, depending on their legal status and scope of work. Academia and research thus serve as a knowledge hub, linking scientific inquiry with practical applications and governance in the forest sector.

While efforts of academia stakeholders are often synergistic, competing priorities might arise. For example, while some universities and research institutes (or their branches) may focus on enhancing productivity and adaptability through genetic improvements, others might prioritise conservation, minimising human influence on genetic processes.

4.1.2 Businesses and Industry

The businesses and industry category comprises 15 diverse stakeholder groups, including forest managers, forest planners, forest-based industries, small and medium enterprises (SMEs), non-timber forest product (NTFP) businesses, pharmaceutical companies, tourist organisations, mining companies, seed processing laboratories, phytosanitary laboratories, breeders, seed producers, forest nurseries, FRM marketers and FRM traders (Annex B, Table 2). Their activities range from operational forest management and FRM production to the indirect benefits they derive from forest ecosystems.

Businesses and industry stakeholders contribute significantly to the forest stakeholder community through their operational, technological, and economic roles. They utilise advancements in FRM for increased wood production, restoration practices, and sustainable forest management. Business and industry stakeholders engage in dynamic interactions through the provision of products and services. Forest-based industries create demand for FRM from breeders, nurseries, and seed producers (Bett et al., 2021). Simultaneously they benefit from forest managers who apply FRM in forestry operations. SMEs offer specialised services to forest managers, nurseries, and conservation initiatives (Fugeray-Scarbel, et al., 2023). NTFP businesses rely on and collaborate with forest owners and local communities for sustainable resource use (Živojinović et al., 2017). Pharmaceutical companies depend on genetic resources maintained by researchers and gene banks, sometimes also funding biodiversity conservation (Rummun et al., 2020). Tourist organisations support conservation through eco-tourism initiatives interacting with forest managers and protected area agencies (Bell et al., 2007). Mining companies could collaborate with forest managers and nurseries for ecosystem restoration after extraction activities (Pietrzykowski, 2019). Seed processing and phytosanitary laboratories ensure quality assurance for FRM distributed to forest managers, nurseries, and restoration projects (Gömöry et al., 2016; Mataruga et al., 2023). FRM marketers connect producers with forest owners, restoration projects, and industries, ensuring the flow of materials across the forest stakeholder community (Fugeray-Scarbel et al., 2023). Business and industry stakeholders engage with FGR primarily as users or facilitators of genetic material, often indirectly through breeding or restoration inputs. Their primary role in FRM is more direct and operational—producing, marketing, and deploying reproductive material to meet forestry and commercial needs. Their influence is particularly strong in the practical application and scaling of genetic innovations.

While primary focus of business and industry stakeholders often lies in maximising productivity and efficiency, their activities are often interconnected with conservation efforts and forest sustainability. Business and industry’s innovative capacity, from genetic improvement technologies to sustainable resource management, positions it as a key player in addressing global challenges such as climate adaptation and biodiversity loss. Businesses and industry stakeholders thus contribute to forest sustainability but may also create tensions between conservation and production goals (Shelton et al., 2025).

4.1.3 Government

The government category includes 12 stakeholder groups: forest agencies, protected area agencies, agricultural agencies, energy agencies, water management agencies, local authorities, decision-makers, policymakers (politicians), the military, customs offices, FRM certifiers, and funding organisations (Annex B, Table 3). These stakeholders influence forest management and conservation across the FGR, FRM, and Protected Forests sub-communities through policymaking, regulation, enforcement, and funding.

Government stakeholders interact through regulatory frameworks, financial support, and (collaborative) governance with various actors. Intergovernmental agencies (e.g. Food and Agriculture Organization) supporting policy development, standard setting, and intergovernmental coordination. Forest agencies provide operational oversight to forest managers, breeders, nurseries, and conservation organizations by enforcing policies designed by decision-makers and supported by funding organisations (Schmithüsen, 1999). Decision-makers draft technical guidelines that shape the implementation of FGR and FRM policies (Pierini and Volpi, 2018) while policymakers approve and fund these initiatives (Raihan, 2023). Agricultural, energy, and water management agencies provide land-use planning and subsidies to farmers, forest owners, and bioenergy producers (Mekonnen, 2017; Navarro and Lopez-Bao, 2019; Favero et al., 2020). Often, they collaborate with local authorities. Customs offices and certifiers ensure that seed producers, nurseries, and forest managers comply with phytosanitary standards (Ronzhina et al., 2022; Mataruga et al., 2023). Funding organisations interact with research institutions, businesses and industry, NGOs, and local communities by channelling financial resources to implement conservation and management initiatives, creating a dynamic network of governance interactions (Ian et al., 2015). Government stakeholders shape both the regulatory and financial environments surrounding FGR and FRM. In the case of FGR, this includes establishing and maintaining gene conservation units, funding research, and creating legal frameworks for access and benefit-sharing. For FRM, governments regulate production, certification, and quality control, and often provide incentives or subsidies for use in forestry operations.

The government category often demonstrates synergies between stakeholders, such as collaboration between decision-makers, certifiers, and forest agencies. While the roles of governmental stakeholders often complement each other, conflicting priorities can emerge, particularly between agencies promoting productivity and those focused on conservation (Willer, Smith and Aldridge, 2019). Conflicts can particularly arise between policymakers emphasising short-term political gains and decision-makers advocating for long-term conservation goals. Similarly, competing priorities among agencies (e.g., agricultural expansion versus forest conservation) can create tensions, underscoring the need for integrated governance frameworks that balance conservation, productivity, and societal needs (Mc Culloch-Jones et al., 2021)

4.1.4 Civil Society

The civil society category encompasses ten stakeholders' groups, including forest owners, protected area owners, local communities and Indigenous peoples, hunters, farmers, NGOs, forest visitors/users, media, youth, and the general public (Annex B, Table 4). While some stakeholders actively engage in forest management and conservation activities, others act as beneficiaries, relying on ecosystem services, cultural values, and resources provided by forests. This dual role highlights both their contributions and dependencies within the forest stakeholder community.

Civil society stakeholders foster critical interactions within the forest stakeholder community through advocacy, participation, and resource management. NGOs provide policy advocacy, conservation support, and community engagement to local communities, forest agencies, local authorities, and business and industry stakeholders (Kaufer, 2023). Local communities and Indigenous peoples contribute traditional ecological knowledge to forest managers, conservation organisations, and research institutes (Molnár et al., 2023), yet often face restricted access to protected areas (Dawson et al., 2022). Simultaneously, they rely on government agencies and NGOs for support and resources. Forest owners collaborate with forest managers, nurseries, and business and industry stakeholders to ensure sustainable forest management while benefiting from technical assistance provided by research institutions (Tiebel et al., 2021). Youth organisations are indirect beneficiaries of forests and engage with universities, NGOs, and local authorities through education programs and advocacy campaigns (Zurba et al., 2024). Media disseminate information from researchers, policymakers, and conservation groups to the broader public, influencing opinions and policy decisions (Çupi, 2023; Słupińska et al, 2022). Civil society interacts with FGR through advocacy for biodiversity conservation, traditional knowledge systems, and participatory conservation practices. Their engagement with FRM is more varied – ranging from support for restoration using local material to critical perspectives on the risks of overly technocratic or industrial approaches. Their influence often reflects cultural values, local priorities, and societal trust in forest governance.

Civil society stakeholders bring a human-centred perspective to forest management, emphasising the cultural, social, recreative and ecological values of forests. Civil society acts as a conduit for public engagement, ensuring that forest strategies reflect community values and address local needs (Zoeller, et al. 2025). However, differing views and priorities, such as concerns over genetic innovations or access restrictions in protected areas, can create tensions within this category.

4.1.5 Stakeholders relationships

The interactions between stakeholder groups are facilitated through various mechanisms that create a dynamic and interdependent system (Figure 1)

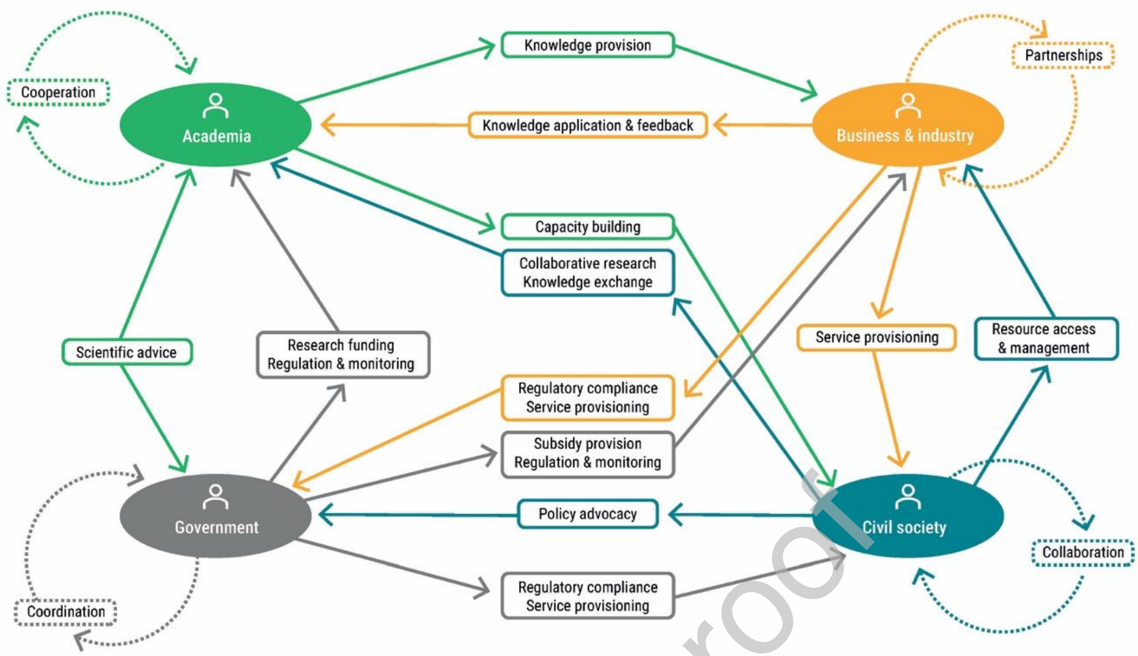

Figure 1. Illustration of major positive relationships between four stakeholders' categories (Source: Own elaboration; Design by Serena Cesca, 2025)

Figure 1 illustrates the major interactions between four stakeholders' categories of quadruple helix approach applied to the whole forest stakeholder community. It highlights key positive relationships such as knowledge provision, capacity building, financial support, regulatory compliance, and collaborative research. Each arrow represents the dynamic exchange of resources, services, and expertise, emphasising the interdependent nature of stakeholder roles in managing FGR, FRM, and protected forests. The figure underscores that these interactions should drive innovation, policy development, and sustainable forest management through continuous feedback, cooperation, and shared responsibilities across sectors. We dive deeper into these interactions in the following section (4.2), as well as in the Discussion (Section 5).

4.2 The Three Sub-Communities: Diverging but Complementary Values and Perceptions of Forests

The forest stakeholder community consists of three interconnected sub-communities: the Forest Genetic Resources (FGR) sub-community, the Forest Reproductive Materials (FRM) sub-community, and the

Protected Forests sub-community (Figure 2). Each sub-community represents distinct values, perceptions, and priorities that shape their approaches to forest management and conservation. While these perspectives sometimes align, differences can create challenges in fostering collaboration and finding common ground.

The FGR sub-community is grounded in the value of conserving and sustainably managing genetic diversity in forest ecosystems. This community bridges forestry conservation and productivity goals. It is characterised by low to medium intensity human influence. Perceptions of sustainable forest management conceptualised here are, in many European countries, characterised by closer-to-nature principles, and minimal genetic interference (i.e. natural regeneration, or reforestation with local provenances, species mixtures). The genetic diversity conserved by the FGR sub-community underpins forest resilience, enabling ecosystems to adapt to challenges such as climate change and invasive species. Stakeholders in this sub-community often perceive FGR and their diversity as critical to ensuring the long-term adaptability and resilience of forests in the face of global challenges, such as climate change and biodiversity loss. Their approach tends to combine scientific research with practical conservation efforts, emphasising the need for active management to conserve and manage genetic diversity. Many stakeholders in this sub-community see forests as dynamic systems that may benefit from targeted interventions to enhance their genetic and ecological integrity. However, perspectives within this group vary. While researchers and geneticists may advocate for maintaining as much genetic variation as possible to safeguard future adaptability, forest managers and planners might focus on the practical application of genetic diversity, narrowing this diversity through selection supporting specific genotypes, such as trees with straighter stems (Gömöry et al., 2021).

The FRM sub-community tends to emphasise the practical and economic benefits of forests, in particular development, production, and deployment of FRM to support forestry and restoration goals. It is characterised by high intensity human influence and medium to high genetic interference in forest ecosystems. Sustainable forest management here is characterised by practices such as planting improved material, from local or non-local species, use of hybrids etc. Stakeholders in this sub-community often value forests as renewable resources that can be optimised through scientific advances, such as tree breeding, nursing, planting, etc. Dominated by business and industry stakeholders (i.e. seed producers, nurseries, biotechnology researchers) the FRM sub-community focuses on developing and deploying genetically selected and /or improved materials for wood industry, forestry and restoration purposes. However, the perception of FRM as a tool for progress is not universal. While business and industry stakeholders often embrace FRM to increase efficiency and economic returns, some civil society actors, such as local communities, NGOs, or small-scale forest owners, might view the use of genetically improved materials with caution. Although genetic improvement is not necessarily genetic modification (which is absent in European forestry), concerns about the potential risks of genetic manipulation or the disruption of natural processes are sometimes expressed (Barnhill-Dilling and Delborne, 2021). The FRM sub-community, therefore, reflects a blend of innovation and pragmatism, but it must navigate differing opinions about the balance between technological solutions and ecological sensitivity.

The PF sub-community prioritises the intrinsic value of forests and biodiversity, often advocating for stricter conservation measures and minimal human intervention. It can be characterised by low to no human influence. This sub-community is increasingly aware of the importance of genetic diversity and its ability to generate adaptive novelty. Members of this sub-community advocate evo-centred conservation, where processes that create and foster genetic diversity (and thus the possibility of evolution) are to be protected (Sarrazin and Lecomte; 2016), perceiving forests primarily as natural habitats, cultural landscapes, and sources of ecosystem services that must be preserved for their inherent worth. Their emphasis is often on ecological integrity, which might lead to a preference for minimising activities like logging, breeding programs, or large-scale human interventions (corresponding to IUCN protection categories III to VI). Other stakeholders from this group give a preference to naturality of processes, which can result in the transformation of the ecosystem (corresponding to IUCN protection categories I and II). Overall, the Protected Nature sub-community provides a critical counterbalance to production-oriented approaches, ensuring that biodiversity and ecosystem values are not overshadowed by economic considerations.

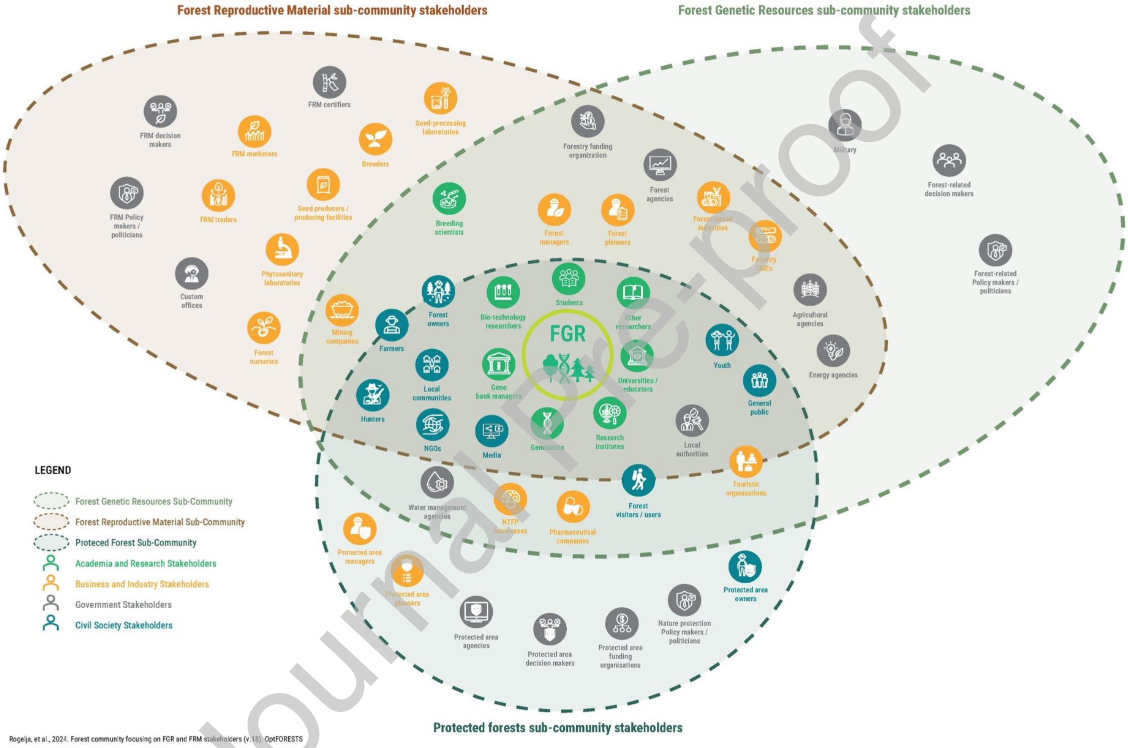

Figure 2. Forest stakeholder community focusing on Forest Genetic Resources (FGR), Forest Reproductive Material (FRM) and Protected Forests (PF) Stakeholders (Source: Own elaboration; Design by Serena Cesca, 2025)

The positioning of stakeholder groups within or across the three sub-communities reflects their primary or most typical roles, as assessed through expert consultation and literature review. While many stakeholders operate across multiple domains (e.g., policymakers influencing both FGR and FRM), they were placed according to the domain where their influence is most specific or direct. For example, gene and seed bank managers were situated within the FGR sub-community due to their core focus on genetic conservation, whereas breeding scientists were placed closer to FRM. Similarly, although the military may own or manage forest land, its involvement in FRM-related activities (e.g., seed procurement, nursery development) is typically limited, justifying its marginal placement.

It is important to note that the categorisation and positioning of stakeholder groups in this study are not intended to suggest internal homogeneity. On the contrary, each group likely encompasses a wide range of perspectives, motivations, and degrees of influence that can change over the time. For instance, forest owners may vary from small private landholders to institutional or corporate actors, each with distinct interests and capacities. Similarly, policymakers may operate at different administrative levels and with varying mandates. The stakeholder map should therefore be viewed as a high-level conceptualisation that captures dominant patterns rather than exhaustive realities. These groupings serve as an entry point for further investigation and refinement. Future research should build on this work by engaging directly with stakeholder groups through targeted surveys, interviews, or participatory workshops to uncover the diversity within each category and assess how internal variation may affect collaboration, conflict, and policy uptake.

5. Discussion

Building on the results of the stakeholder mapping and categorisation, in this section we critically reflect on the composition, structure, and relationships among the forest genetic stakeholder community, corresponding to the study's objectives. Section 5.1 reflects on the composition and diversity within stakeholder groups. Section 5.2 focuses on the interactions between these sub-communities, examining how different stakeholder priorities align or diverge, the trade-offs and synergies that emerge, and the role of governance complexity and spatial scale in shaping these dynamics. Section 5.3 concludes the discussion with a critical reflection on the conceptual framework and methodological approach.

5.1. Structuring the stakeholder landscape: categories, communities, and overlaps

This section addresses Objective 1 of the study. It reflects on the diversity and heterogeneity of stakeholder groups (5.1.1), as well as the conceptual and functional boundaries between the three identified sub-communities (5.1.2).

5.1.1 Diversity and heterogeneity within stakeholder groups

The stakeholder map shows the diversity of actors relevant for FGR and FRM and how these actors are related. The majority of stakeholders identified across all three sub-communities were linked to academia and research. This is not surprising given the strong role of research and monitoring in both the conservation and management of FGR, and the production and use of FRM. Actors from academia and research also engage in developing guidelines, delivering practical training, producing education material, and consulting national and international bodies, which increases their visibility across domains.

In addition to academia, the other stakeholder groups also display considerable internal diversity. Government stakeholders range from international policy institutions and national regulatory agencies to local forest administrations, each with varying mandates and jurisdictional authority. Business and industry actors span a broad spectrum, from small-scale nursery operators and private forest owners to transnational timber and seed companies, each with differing priorities and degrees of influence. Civil society stakeholders include both formal organisations (i.e environmental NGOs and conservation foundations) and more informal or loosely organised groups (i.e. recreational forest users or community advocates). Importantly, the prominence and functional roles of these actors vary significantly across national contexts, depending on governance structures, policy traditions, and forest ownership patterns (Hazarika,et al, 2022; Ferranti et al, 2014). In some countries, forest management may be highly centralised, while in others, non-state actors such as private forest owners or NGOs play a leading role in shaping conservation of FGR and FRM strategies (Kaufer, 2023). Additionally, stakeholder priorities are not static (Ihemezie et al, 2021). They may shift over time in response to policy changes, market trends, ecological crises, or emerging scientific insights. These distinctions and dynamics are important because they shape how different actors engage with FGR and FRM, and influence their capacity to participate in governance processes.

The stakeholder groups were located according to their dominant focus, with the understanding that most operate across multiple areas. For instance, many stakeholders in the FGR sub-community also work with FRM or contribute to conservation within protected areas. This overlapping of communities points to a shared interest in forest sustainability and interdependence between domains. Stakeholders such as researchers, policy developers, and NGOs were found to contribute across all three sub-communities, suggesting a high degree of functional and institutional interconnection. Nevertheless, some stakeholders were placed at the periphery of the map. For example, the military was included due to its ownership and management of forest land in some countries, but appears at the margin due to its limited direct involvement with FGR or FRM. Similarly, stakeholders like students were distinguished from universities to reflect their different institutional roles and influence pathways.

The map does not attempt to show the intensity of relationships between stakeholder groups, as these vary by national context, topic, and policy setting. Instead, it offers a structural overview that highlights where overlaps, underrepresented actors, or siloed responsibilities may exist. These patterns provide a foundation for examining stakeholder interactions and governance challenges, as explored in the following section.

5.1.2 Conceptual distinctions and interdependencies among sub-communities

The spatial positioning of the three sub-communities (FGR, FRM, and PF) illustrates their distinct but interconnected roles in the conservation, management and deployment of FGR and FRM. The three sub-communities are centred around different perceptions of management of FGR and the way genetic processes are considered (or not) during forest management. The division is not strict but reflects the continuum with varying degrees of human intervention in terms of genetic interference in forest ecosystems. Simultaneously, such division reflects the main values, perceptions, and priorities of the stakeholder groups within each sub-community. Spatial and governance scales (from local to national) further shape the dynamics and interactions between the three sub-communities, as further reflected in section 5.2.

We conceptualised FRM to applied practices and intensive human influence. Although FRM is an output of FGR (encompassing the broader conservation and management of genetic diversity), the decision to visually separate the FRM sub-community from the FGR sub-community in the diagram is purposeful. It reflects important distinctions, as it allows for clearer recognition of these distinct priorities and stakeholder dynamics. The diagram acknowledges the unique contributions and challenges of each group while preserving their interconnectedness. This distinction ensures that both the foundational goals of conserving FGR and the applied goals of developing productive and resilient FRM are appropriately recognised and supported. Regardless, it should be kept in mind that the boundaries between sub-communities are blurred. A protected forest, for example, with no human intervention, can very well be considered as an FGR. On the other hand, a seed orchard produces FRM, but is as such also an FGR and can contribute to conserve it. A Gene Conservation Unit, which is an FGR, can and should be managed to support evolution of the FGR, and is often used also for seed collection, and thus producing FRM.

The relationship between FGR and FRM sub-communities is rooted in their shared dependency on genetic diversity, yet their goals and methods have diverged significantly over time (Hoban et al., 2023; Kavaliauskas et al., 2018). Historically, forestry practices were closely tied to the natural genetic pool provided by forest ecosystems. Early foresters relied on natural seed harvest from wild populations to meet their needs, with little to no artificial selection or breeding (Andrew and Gillespie, 2017; Kavaliauskas et al., 2018). This placed FGR at the centre of both conservation and production efforts, as the genetic diversity of forest ecosystems directly supported human activities. Over time, as the demands on forests grew the need for more predictable and efficient forestry systems emerged (Pâques, 2013). The advent of scientific breeding programs marked a turning point in the evolution of FRM as a distinct sub-community (White et al., 2014; Pâques, 2013). Breeding programs, which initially drew directly from wild FGR, began selecting and enhancing specific traits, such as faster growth rates, pest resistance, and climate adaptability (Fugeray-Scarbel et al., 2024). This marked the beginning of applied genetics in forestry and restoration, differentiating FRM from the broader conservation-oriented goals of FGR.

The rise of FRM as a specialised sub-community did not diminish its dependency on FGR. Instead, it created a symbiotic relationship, where the genetic diversity of FGR, and PF serves as the foundation of FRM breeding programs. Without the broad genetic base provided by FGR, FRM would lack the variability necessary to respond to new challenges such as climate change or emerging pests and diseases (Hiemstra et al., 2022). This interdependence underscores the importance of continued investment in FGR conservation to ensure the long-term success of FRM. Conversely, FRM also contributes to FGR conservation by providing practical applications of conserved FGR trough FRM programmes. For example, FRM programmes often identify and highlight genetic traits of high ecological or economic value, such as drought tolerance or disease resistance. These traits can then inform FGR priorities, guiding decisions about which species or populations require conservation efforts. Breeding populations (at the base of breeding programmes) sometimes maintain extinct or endangered natural populations (e.g. some populations of *P. sylvestris* (France), *P. menziesii*, *P. nigra*) and hybridisation (between populations/or species) is a source of new diversity. This dynamic creates a feedback loop, where FGR supports FRM with genetic resources, and FRM provides data and applications that reinforce the importance of conserving those resources.

Our distinction between the values and roles of FGR and FRM sub-communities is crucial for policy, funding, and engagement. Policies must address their unique priorities, ensuring balanced attention and resources while at the same time support collaboration between the two sub-communities to promote sustainability. For instance, integrating FGR conservation with FRM breeding can align long-term genetic conservation with short-term productivity goals.

5.2 Interactions Among Forest Sub-Communities: Trade-offs, Synergies, and Multi-level Governance

This section addresses Objective 2 of the study. The following subsection examine intersections between each pair of sub-communities (5.2.1), followed by a synthesis of cross-cutting trade-offs and synergies (5.2.2), and an analysis of the governance complexity that shapes their interactions (5.2.3). Through this structure, we aim to highlight not only areas of conflict and tension but also latent opportunities for cooperation and system-level learning.

5.2.1 Intersections of sub-communities

The intersection between the FGR sub-community and the PF sub-community is characterised by prioritisation of conservation of genetic diversity. Protected forests act as vital *in situ* reservoirs of genetic material, contributing to global and regional biodiversity goals under frameworks such as the European Union Biodiversity Strategy for 2030 and the Natura 2000 network (European Commission, 2020; Secretariat of the Convention on Biological Diversity, 2021). Through research, academia plays a key role in facilitating collaboration between these two sub-communities. For instance, population genetic studies can inform about most important locations for conserving FGR (Matasci et al., 2016, Myking et al 2009, Stojnić et al 2019, Theraroz et al.) or the effect of management on genetic diversity (Westergren et al. 2015). Recent genetic monitoring developments have established standardised methods for tracking forest genetic resources across European protected areas (Aravanopoulos et al., 2015; Kavaliauskas et al., 2022). Universities and research institutes also collaborate with protected area managers to safeguard genetic corridors and ensure connectivity between fragmented forest patches (Alimpić et al 2022; Westergren, et al.., 2018). Traditional ecological knowledge, although less prominent in Europe then elsewhere contributes to conservation efforts. For example, transhumance is still observed in Southern Europe for maintaing semi-natural landscapes that act as buffer zones for protected forests (Plieninger and Bieling, 2012; Hartel, et al., 2013; García-Martínez Olaizola, and Bernués, 2009). The Sámi people (in Finland, Sweden, and Norway) practice reindeer husbandry which has great influence on nature and forests, while enjoying special protection for their traditional livelihoods. These practices create complex social-ecological systems that support biodiversity conservation while maintaining cultural heritage (Oteros-Rozas et al., 2013).

The FGR sub-community and the FRM sub-community share a reliance on genetic diversity to address challenges such as climate change, ecosystem resilience, and sustainable forest management. At the heart of this relationship lies the essential role of genetic diversity conserved by the FGR sub-community, which forms the foundation for FRM breeding programs. In turn FRM breeding programs conserve genetic diversity in their breeding populations. For example, EUFORGEN's efforts to coordinate conservation of populations of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) across Europe illustrate of efforts to supply FRM programs with of drought-tolerant or pest-resistant materials (Mátyás et al., 2004; Skrøppa, 2003). Conversely, FRM breeding programs reinforce the value of genetic conservation by demonstrating the practical performance of specific traits, such as faster growth or improved wood quality. For example, afforestation projects in Romania (Marcu et al., 2020), and in Finland (Ahtikoski et al., 2020) have successfully utilised improved FRM of Norway spruce with high growth rate.

The intersection between the FRM sub-community and the PF sub-community highlights both philosophical differences and opportunities for collaboration. While the FRM sub-community targets genetic improvements to enhance forest productivity and resilience, the PF sub-community prioritises conservation and the preservation of natural processes. Despite these differences, there is considerable potential for synergies, particularly in addressing shared challenges such as climate change, biodiversity loss, and landscape-scale restoration. Restoration (Higgs, 1997) probably represents a key area of collaboration between these sub-communities. Degraded landscapes, particularly those adjacent to protected forests, often require large-scale restoration efforts to stabilise ecosystems, sequester carbon, and create buffer zones (Kittur et al., 2023). These buffer zones and ecological corridors can enhance ecosystem connectivity, supporting the objectives of protected forests by maintaining biodiversity corridors (Kinnoume et al., 2024; Kremer et al., 2012).

5.2.2 Trade-offs and synergies across sub-communities

Tensions frequently arise within and between sub-communities due to differing priorities, values, goals and resource constraints. In the FGR sub-community, debates might arise over the merits of i*n situ* versus *ex situ* conservation (Jovani et al., 2024). While *in situ* conservation maintains genetic diversity within natural ecosystems, it requires large forest areas. Other researchers argue for *ex situ* strategies, such as seed banks, which may better safeguard genetic material against climate change and habitat loss (Mahanayak, 2024). Increasingly, integrated *in situ* and *ex situ* conservation are becoming favoured (Lefevre et al., 2024; Amancah et al., 2023; EUFORGEN, 2021)).). This divergence might particularly be evident in discussions about conserving rare species, where limited resources and strict regulations force difficult trade-offs.

Within the FRM sub-community tensions or competition stem from unequal access to genetic material, markets, and subsidies. For instance, breeding programmes have been and are faced with critical human resources and financial constraints which over time, leading to closure or disruption for many years. Nurseries in Europe have voiced concerns over unavailability of subsidies for FRM production (Haeler et al., 2023; Konrad et al., 2025), or market entry barriers imposed by high costs of certification, which results in narrowed diversity of available FRM and disadvantaged local economies (Lefèvre et al., 2024).

In protected forests, tensions emerge when researchers seek access to genetic material from protected forests for *ex situ* conservation or breeding purposes. Yet, strict conservation policies may restrict such activities, as demonstrated in German protected forests (Demant, 2022; Demant et al., 2019) or in strictly protected areas (IUCN protection categories I and II) (Parviainen et al., 2020; Lefèvre et al., 2013). Even in less strictly protected areas (IUCN categories III and IV) local communities can face limited access to resources such as firewood or non-timber forest products, leading to conflicts (Dawson et al., 2021). Similarly, stakeholders from business and industry or forestry sectors may view protection measures in forests under IUCN protection categories III to VI as potential constraints on land use and development opportunities.

Environmental NGOs such as WWF and BirdLife Europe advocate for expanding protected areas and minimising human intervention, opposing extracting genetic resources from protected forests for breeding programs (WWF, 2020). Media coverage, such as reporting on the controversial logging (i.e in Białowieża Forest in Poland (Bieńkowska et al., 2019), or in Romania (EIA, 2015)) amplifies these debates. Biodiversity conservation NGOs often support FRM as a tool for restoring degraded landscapes but concerns about the ecological and ethical implications of genetic manipulation persist. Public debate, such those in Germany around genetically modified organisms (GMOs) in forestry highlight broader societal scepticism about intensive genetic interventions, even when these are presented as solutions to climate adaptation (Barnhill-Dilling and Delborne, 2021). Controversies also arise around afforestation projects with non-native species, highlighting societal concerns about the balance between innovation and ecological preservation (Barnhill-Dilling and Delborne, 2021).

The core trade-offs shaping the FGR, FRM, and PF landscape revolve around how societies balance ecological integrity, production needs, and long-term adaptability in the face of uncertainty (Willer et al., 2019). At the most fundamental level, land itself is limited: allocating forest areas to strict conservation reduces availability for active management, restoration, or timber production, yet intensively managed forests often lack the structural and genetic complexity that support biodiversity and resilience. Similarly, decisions around species and provenance selection introduce a temporal trade-off (Olson et al., 2023). Some conservationists caution that intensive FRM production methods, such as selection and size sorting may erode forest genetic diversity (Gömöry et al., 2021). Selecting reproductive material based on current climate suitability may maximise short-term survival or yield, but risks maladaptation under future conditions, while favouring uncertain future climate scenarios could jeopardise present-day viability or ecological integrity and stability (Jacobs et al., 2023; Vanden Broeck et al,., 2021).

These tensions are compounded by divergent funding dynamics. Breeding and FRM deployment are often aligned with market-oriented, short-term forestry objectives and thus attract more consistent investment, while FGR conservation requires long-term commitment and is more vulnerable to political and economic cycles (Wu et al., 2021). Even within conservation, resource scarcity often forces difficult choices: should limited funds be used to conserve broad genetic variation across many species, or focused on targeted, marginal populations? These trade-offs are rarely technical alone—they are shaped by power asymmetries, institutional inertia, and differing values around what forests are for and who should benefit from them.

While tensions are persistent and trade-offs real, the forest governance system also holds untapped synergies that could be leveraged to meet the dual imperatives of resilience and sustainability. One of the most promising, yet underutilised, synergies lies in the temporal complementarity of the sub-communities: FRM efforts might tend to prioritise short- to medium-term forest performance, while FGR conservation provides long-term genetic insurance, and protected forests serve as reference ecosystems that anchor natural evolutionary processes. When linked strategically, these orientations offer a powerful basis for designing adaptive forest systems that remain resilient across ecological, economic, and generational timescales.

A second area of synergy stems from the plurality of knowledge systems embedded in each sub-community. Breeding programmes contribute detailed phenotypic and performance data; conservation scientists offer insight into evolutionary processes and gene flow; protected area managers understand social-ecological dynamics on the ground; and local or Indigenous knowledge holders bring place-based perspectives on long-term forest change. When these knowledge types are brought together in deliberate learning environments, they can drive not only better decisions but also innovation. For instance, the emergence of assisted gene flow and genetic enrichment strategies that blend natural regeneration with targeted FRM input reflects the kind of creative synthesis needed to respond to climate uncertainties and biodiversity loss. However, realising such innovations requires rigorous risk assessments, increasing stakeholders' knowledge, transparent communication and inclusive governance frameworks that balance genetic ecological and practical considerations (Fady et al., 2023; Crispo, Derry and Brady, 2021; Barnhill-Dilling et al., 2021).

Finally, the institutional diversity across the sub-communities – often seen as fragmented – can itself become a source of strength when supported by multi-level coordination. Mechanisms such as stakeholder platforms, cross-sectoral funding schemes, and co-developed policy instruments are essential to unlocking these latent synergies and aligning Europe's forest genetics landscape toward a more adaptive and socially legitimate future.

5.2.3 Governance complexity and spatial scale

Governance and spatial scale add another layer of complexity. In Europe, there is still large variation in the regulations directly influencing FGR, FRM and protected forests. European-level policies, such as those under the EU Forest Strategy, EU Biodiversity Strategy and others aim to harmonise restoration practices with conservation goals and production needs, but implementation varies significantly between countries, leading to inconsistencies and fragmented outcomes. For instance, while the EU's Natura 2000 network promotes harmonised conservation efforts across member states, national differences in implementation frequently result in inconsistencies that hinder cross-border collaboration (Ferranti et al., 2013).

There are also national, European, and international regulations, that indirectly impact FRM production, deployment and trade (Beuker et al., 2020). The European Commission (EC) is also in the process of revising the regulation of the production and marketing of FRM that has provoked debate within the FGR and FRM community (EUFORGEN, 2023). New proposal amends Regulations (EU) 2016/2031 and 2017/625 of the European Parliament and of the Council and repeals the Council Directive 1999/105/EC (Regulation on Forest Reproductive Material).

Regional and national differences create fragmentation, particularly when cross-border collaboration is required to address shared challenges such as pest outbreaks or climate adaptation. For example, the Nordic countries run large-scale breeding programs, while Mediterranean nations prioritise natural regeneration and smallholder-oriented FRM development (Koskela et al., 2013). At the local level, restoration projects often face competing land-use priorities, particularly in regions where land is scarce or highly contested. For example, in Romania, some reforestation efforts near Natura 2000 sites have encountered opposition from local communities concerned about restricted access to traditional resources such as firewood or grazing areas (Manolache et al., 2018). Opposite example would be Italy's Gran Paradiso National Park, where participatory governance models have been introduced to mediate these tensions, allowing limited access for traditional activities like grazing while ensuring the integrity of protected ecosystems (Borrini-Feyerabend et al., 2013).

These governance differences and mismatches create trade-offs. While harmonisation efforts seek to create common standards, they may overlook local needs and socio-cultural contexts. At the same time, decentralised governance can support place-based adaptation but may lack coordination across borders or between sectors. Synergies arise when multi-level governance structures enable both flexibility and alignment through stakeholder-inclusive planning, shared monitoring systems, or regionally tailored but legally coherent regulatory frameworks. Supporting cross-scale dialogue and piloting participatory governance models could bridge these divides and improve outcomes for both forest biodiversity and forest-based economies.

The diverging attitudes and values of close-to-nature forest management, intensive forestry, and strict protections, respectively, thus exist within same stakeholder groups, as well as among different ones, and are spanning all sub-communities. This underscores the need for transparent communication and inclusive stakeholder engagement (EFI et al., 2018). In general, much more knowledge exchange between various scientists (geneticist, conservationists, silviculturists, sociologists, economists), professionals, policy- and decision-makers and general public is needed to ensure ecologically adequate practices for FGR conservation as the decision making is becoming more urgent due to climate change progress.

5.3 Reflections on conceptual framework and methodology

In our research we used quadruple helix approach for stakeholder mapping and categorisation. A strength of this model lies in its ability to foster innovation, where stakeholders co-create knowledge, technologies, and solutions (Carayannis and Campbell, 2010). Participatory governance mechanisms such as living labs or stakeholder platforms embody the principles of the quadruple helix by promoting dialogue and joint decision-making across sectors. These arrangements can support trust-building and equitable management strategies, particularly when dealing with long-term and ethically sensitive issues like genetic conservation and breeding (Ansell and Gash, 2008). The inclusion of civil society extends the scope of innovation beyond technical solutions, embedding cultural and social values critical to sustainability.

This study demonstrates that applying the quadruple helix framework to forest genetic resource governance enables a structured yet flexible categorisation of stakeholders across sectors. However, our findings also suggest that this model may underrepresent power dynamics and internal diversity within stakeholder categories. For example, actors in the “civil society” helix range from individual forest visitors to well-resourced NGOs, highlighting a level of heterogeneity that the model does not explicitly address. While it supports macro-level mapping, its ability to guide micro-level engagement strategies is limited unless combined with more granular, context-specific methods such as stakeholder interviews or social network analysis.

The integration of systems thinking with the quadruple helix model allowed us to trace interactions and tensions across sectors while embedding them within the broader ecological and governance systems in which forests operate. This theoretical integration offers a novel contribution to stakeholder analysis in forestry, particularly for underexplored domains like FGR and FRM. It also advances the literature on stakeholder complexity in environmental governance by showing how high-level conceptual frameworks can be operationalised through participatory mapping.

A central methodological feature of this study was the use of participatory mapping, implemented through an iterative process involving a core team and broader expert consultations. The two-level process allowed for a more balanced synthesis of theoretical rigour and practical relevance. It also helped identify missing stakeholder groups, clarify overlaps, and improve the categorisation. Future applications could further enhance this approach by explicitly integrating deliberative techniques or structured feedback loops to address complex or contested stakeholder roles.

Despite these challenges, the quadruple helix approach offered unique opportunities for innovation and collaboration. By leveraging the expertise and resources of academia, business and industry, government, and civil society, it could create a pathway for integrating local knowledge with global science, balancing conservation and productivity goals, and fostering resilience in the face of climate change. Also, quadruple helix approach could support more equitable distribution of forest management costs and benefits among different stakeholders across the administrative and geographical scales.

This method also has certain limitations. The final map reflects the perspectives of the researchers and consortium partners involved, which means some stakeholder groups or categories may have been underrepresented or missed, particularly those outside the project's immediate scope. As such, the stakeholder map depicts mostly research and academia viewpoint on the stakeholder's community. Nonetheless, the iterative process and the diversity of expertise within the consortium minimised this risk of exclusion of certain stakeholders' categories, as special attention was given to the question "Who is missing?". Moving forward, the map can be further updated as new insights and perspectives emerge, ensuring its continued relevance and utility. Future research could enhance the method by combining other data collection methods, such as interviews of survey.

Overall, our findings contribute to a growing body of work that seeks to bridge ecological systems thinking with stakeholder governance. We show that while conceptual models are valuable tools for mapping complexity, their real utility lies in their capacity to be tested, adapted, and iteratively improved through engagement with real-world actors and institutional dynamics. Future research could build on this by combining the quadruple helix with adaptive co-management frameworks or actor-network theory to better capture shifting roles, emerging coalitions, and conflicts. Additionally, incorporating temporal dynamics to adress how stakeholder roles evolve with climate impacts, policy shifts, or market changes would help enhance the explanatory power of the framework.

6. Conclusions

This study offers the first comprehensive mapping of stakeholder groups relevant to FGR and FRM in Europe, integrating protected forests into the analysis. This study highlights the critical importance of understanding stakeholders of FGR and FRM in ensuring the sustainability and resilience of forest ecosystems amidst mounting pressures from climate change, biodiversity loss, and deforestation, among others. Using a participatory stakeholder mapping approach grounded in the quadruple helix framework, we identified and analysed the complex relations, synergies, and tensions among diverse stakeholder groups. The findings underscore the complex nature of FGR and FRM management with the critical need for inclusive frameworks that integrate stakeholder dynamics into governance and decision-making. By emphasising the need for collaboration and knowledge exchange among academia, business and industry, government, and civil society, this research provides a foundation for advancing sustainable and equitable forest management practices. Although our work (Fig. 2) demonstrates the complexity of the stakeholder community in the forestry sector, it also serves to disentangle its structure across subcommunities and simplify understanding its nature. Policymakers, practitioners, and researchers can directly benefit from the stakeholder map developed in this study as a tool for understanding and navigating the complex web of interactions in forest management. Policymakers can use it to design more inclusive and targeted policies that address the needs and priorities of diverse stakeholder groups. Practitioners can leverage the map to identify potential collaborators, anticipate or resolve tensions, and implement integrated forest management practices.

For researchers, the map serves as a starting point for further studies on stakeholder dynamics, fostering interdisciplinary approaches to address the social, ecological, and economic dimensions of FGR and FRM.

However, addressing the challenges identified in this study requires moving from theoretical frameworks to practical implementation. Stakeholder engagement must be strengthened through participatory governance mechanisms, and funding disparities must be addressed to ensure equitable resource allocation. Moreover, governance structures should integrate local and indigenous knowledge to enhance cultural and ecological relevance, while educational programs must prepare future professionals to navigate the complexities of FGR and FRM management. Aligning these efforts with international frameworks, such as the CBD and the Sustainable Development Goals (SDGs), will further amplify their impact, fostering coherence between local actions and global priorities.

This study is not without its limitations. While it provides valuable insights into stakeholder dynamics, future research should expand its scope to include perspectives of a broader range of stakeholders and regional contexts, as well as comparative analyses of governance models. Such efforts can deepen our understanding of how to operationalise inclusive frameworks across diverse socio-political and ecological landscapes.

Ultimately, this study underscores the potential of collective action and innovation to address global challenges. By fostering collaboration, building trust, and integrating diverse perspectives, stakeholders can create governance systems that balance conservation with productivity, meet the needs of current and future generations, and ensure the long-term sustainability of forest ecosystems. In particular, innovations at the intersections of communities are key to face new challenges for the forests. As forests face unprecedented pressures, this work serves as a call to action for all stakeholders to unite in safeguarding one of the planet's most vital resources.

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Declaration of generative AI in scientific writing

During the preparation of this work the authors used Chat GPT 4.0 in the writing process to improve the readability and language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: