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Genetic Considerations in European Riparian Ecosystems Management: Experts View on Status and Needs

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Abstract

1. Riparian vegetation supports high biodiversity providing many services and is, therefore, an important landscape element. Riparian ecosystems are subject to numerous pressures leading to population decline and genetic erosion of riparian plants. This may have cascading effects on various ecosystem levels, decreasing services, so identifying the current status of riparian tree species genetic conservation needs is vital to improve the effectiveness of restoration efforts.

2. We aimed to identify expert views on the status and importance of tree species genetic diversity, including both adaptive (morphological) and neutral (molecular), and conservation needs across European riparian ecosystems. Sharing such information among researchers, managers and policymakers have the potential to enhance ecological restoration and management of riparian ecosystems.

3. We identified experts in riparian genetic resources conservation and management across Europe. These included stakeholders with different perspectives, ranging from researchers to practitioners. We designed a set of questionnaires that asked our identified experts to answer questions related to riparian tree species genetic conservation in their respective countries. Specifically, we asked about societal awareness, legislative tools, good practices and conservation or restoration projects taking account of tree species genetic resources in riparian ecosystems. Questionnaire responses were analyzed and discussed in light of scientific literature to define needs and priorities related to the management and conservation of riparian tree species genetic resources.

4. The experts recognized the *ecosystem approach,* as the most appropriate option for the conservation of tree species genetic diversity in riparian ecosystems applied through a combination of *in-situ* and *ex-situ* measures and/or *integrative conservation*. Simultaneous application of conservation measures at the level of priority species, identified by experts, and protection of riparian areas are required.

5. *Synthesis and applications.* The results of this study revealed the importance of recognizing the ecological processes that shape tree species genetic diversity in hydrographic networks (spatial patterns and gene flow, fragmentation) but also the need to overcome socio-economic barriers, such as lack of policy priority, deficiency in funding and weak legislation framework.

Key words: genetic erosion, genetic resources conservation, knowledge conversion, riparian genetic diversity, riparian vegetation

1 INTRODUCTION

Riparian ecosystems have been recognized as critically important elements in the landscape, providing multiple benefits to the environment and societies (Dufour et al. 2019). Riparian vegetation in general, and specifically riparian trees, are of special significance, contributing to multiple key ecosystem services, including filtering agricultural pollutants and improving river water quality, regulating instream temperature, stabilizing river banks, sequestering carbon and producing biomass, as well as providing cultural and recreational services (*R*iis et al. 2020). Whilst much research has been devoted to the importance of species richness for riparian ecosystem functioning and stability, relatively less is known about the potential ecosystem-level importance of genetic diversity of riparian tree species. Genetic diversity within riparian plant populations differs from other ecosystems in that downstream dispersal of propagules with flowing water leads to high gene flow and downstream increases in genetic diversity. Riparian habitat continuity across river networks leads to low genetic divergence among sites (Nilsson et al. 2010). Moreover they are subject to multiple pressures that lead to genetic diversity reduction. For example, fragmentation by dams (Werth et al. 2014) and hybridization with non-native populations threaten the genetic diversity and integrity of riparian plant species. This is true also for important foundation species like *Populus nigra* (Vanden-Broeck et al. 2005; Chenault et al. 2011; Vanden-Broeck et al. 2012), potentially leading to low resistance to pathogens and increased extinction risk (Fady et al. 2020). This genetic component is crucial for the many efforts to restore and recover riparian and floodplain vegetation. For example, riparian vegetation has great potential for the deployment of nature-based solutions which address the recovery of ecosystem structure and functioning (UNEP & IUCN, 2021), but the provenance of plant material used in planting and seeding can be critical for the success of projects (McKay et al. 2005; Breed et al. 2019). Despite these challenges, the genetic component is rarely integrated into the management and conservation of riparian ecosystems and no transnational vision has been developed on priorities in this domain.

The aim of this paper is to identify expert views on the status and importance of tree species genetic diversity, including both adaptive (morphological) and neutral (molecular), and conservation needs across European riparian ecosystems. The research was conducted within the network of COST Action CONVERGES (https://converges.eu/), which aims to improve knowledge conversion and technology transfer among researchers, practitioners and policymakers for the improvement of riparian ecosystems management.

2 METHODOLOGICAL FRAMEWORK

The main goal of CONVERGES is to synthesise existing knowledge about riparian vegetation across countries and disciplines, covering topics from riparian research to restoration and management. A subgroup named “Genetic conservation” (GC-WG2) was formed during the CONVERGES WG2 meeting (Iceland, 2018) to review the state-of-the-art in genetic conservation of riparian vegetation at the European level and to identify the main knowledge gaps, conservation barriers and future research and management needs.

Firstly, a *short questionnaire* (Appendix S1-A) was sent to relevant experts (researchers, stakeholders and practitioners) across the 39 COST participating countries, aimed at, collecting information on the research dimension (available literature, relevant projects), and identifying relevant riparian species. In total 22 responses were received from 15 countries (Appendix S2-A).

Secondly, *structured questionnaires* (Appendix S1-B) collected country reports covering strategies implemented so far, major barriers, current needs and potential solutions for improving the conservation of genetic resources across European riparian ecosystems. Analyses of structured questionnaires included numeric data and text data with open-ended questions (NVivo software https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home). There were 30 responses from 19 countries (Appendix S2-B).

3 STATUS OF GENETIC CONSERVATION OF RIPARIAN VEGETATION IN EUROPE

3.1 Research dimension

The genetic composition of riparian vegetation is influenced by several factors (biogeography, local conditions and species interactions), but what sets it apart from other plant communities is water flow as a vector for dispersal and the hierarchical structure of river networks (Nilsson et al. 2010). Water flow is the main agent of dispersal of propagules and therefore influences downstream gene flow among populations of riparian plants (Nilsson et al. 2010), while upstream gene flow mediated by wind, or animals occurs less frequently (Wubs et al. 2016). As a consequence of downstream-biased gene flow, upstream populations may experience higher loss of alleles, while downstream populations receive more alleles preventing loss due to genetic drift (Paz-Viñas et al. 2015). Yet, other patterns may apply, as in *Populus nigra* L. where (i) no significant upstream/downstream differences in genetic diversity occur (Imbert & Lefevre 2003) and (ii) clonality and sexual regeneration can co-occur within the same natural stand (Tinschert et al. 2020). This results in high complexity and requires extensive knowledge to implement adequate management measures.

In spite of the ecological importance and the recognized threats to riparian genetic diversity conservation, the results of the structured questionnaires revealed both a lack of assessment of genetic diversity status and changes in riparian tree species and the perception of a generally poor status of riparian ecosystems. For example, the view of respondents about changes in riparian genetic diversity in their country over the past ten years was that the situation is degrading. For this question, three options were possible: “no significant changes”, “improving status” or “degrading”. Apart from France and the Czech Republic, respondents from all countries (18/30) thought that riparian genetic diversity was degrading. The respondent from France stated that a large number of genetic conservation actions have been implemented and expanded knowledge about the genetic diversity of riparian tree species (e.g. *Populus nigra*) has been achieved by using new DNA markers (e.g. *Single Nucleotide Polymorphism* (SNP), Faivre-Rampant et al. 2016). According to the informants, there was no coordinated plan of actions addressing the status of riparian tree species genetic diversity.

Recently, several studies have demonstrated how anthropogenic barriers and habitat fragmentation affect the genetic structure of riverine plant populations (Werth et al. 2014). Such genetic isolation of rare and critically endangered plant populations can accelerate genetic erosion (the loss of genetic diversity within a species through a reduction in richness of alleles or alleles combination over time) and lead to local extinctions (Labonne et al. 2008). Therefore, adequate assessments of genetic diversity in riparian ecosystems, especially within tree species, contribute to efficient conservation.

3.2 Policy dimension

The long-term degradation of riparian ecosystems has continued to intensify since the 1950s, and has contributed to reduced river health (Singh et al. 2021), low achievement of the objectives of the Water Framework Directive, and the unfavourable status of floodplain forest habitats across Europe (EEA 2018). Cortina-Segarra et al. (2021) identified genetic considerations as a pending crucial element to enable the improvement of ecosystem restoration effectiveness. In this sense, riparian tree genetic resources conservation lies in an undefined gap between the policies addressing nature conservation and forestry. Genetic considerations are not treated as a separate issue in forestry legislation. National-level forestry-planning documents refer to forest genetic resources in different contexts, but without defining methods for their management in the context of genetic conservation.

To the question, does your countries have plans or programs to assess the state of genetic diversity of riparian tree species, 63% of respondents gave a negative answer. Respondents who gave a positive answer (33%) cited plans and programmes concerning biodiversity protection and forest genetic resources conservation in general, sometimes mentioning specific riparian tree species. Indeed, for forest tree species, a step forward has been the adoption of the *Global Plan of Action for the Conservation, Sustainable Use and Development of Forest GR* (2014), and its implementation strategy (http://www.fao.org/3/i3849e/i3849e.pdf), an outcome of the EUFORGEN programme, that encourages countries to upgrade the system of collecting genetic data and to establish a core network of dynamic genetic conservation units (GCU) across Europe (www.eufgis.org). Moreover the *First Report on the State of the World's Forest GR* (2014) calls for urgent action for better management of forests and forest genetic resources to ensure their long-term sustainable use for the local community that depends on forest products.

When it comes to riparian vegetation plant species (beyond other than trees), genetic issues are even more neglected. Riparian zones are subject to multiple legal instruments such as those related to land ownership, flood control or nature conservation. Yet, monitoring and assessment are not mandatory in European countries (González del Tánago et al. 2021), and the genetic component of riparian diversity is not addressed. Thus, when asked if there are procedures in place to moitor or measure genetic erosion within riparian tree species R 70% of respondents gave a negative answer.

These results reflect the neglect of riparian genetic resourcesand the disparity in planning the assessment and monitoring Respondents (23%) who gave a positive answer provided only information on procedures for monitoring the state of forests and forest genetic resources in general No iIformation regarding tpecific monitoring of the state of riparian genetic resources was nrovided. Riparian zones are subject to multiple legal instruments related to land ownership, flood control or nature conservation. Yet, monitoring and assessment of riparian tree species genetic diversity and connectivity are not mandatory in European countries (González del Tánago et al. 2021) .

3.3 Management dimension

Since it is not included in most policies, riparian tree species genetic diversity has been mostly disregarded in impact assessments, monitoring and restoration projects. When asked about the most effective approaches to conserving riparian tree species genetic resources, participants were given four options: *in-situ*, *ex-situ*, combination (*ex situ* and *in situ*) and integrative approaches (i.e. conservation that includes stakeholder engagement to achieve sustainable management of natural resources, González et al. 2017). Forty percent of respondents concluded that "*in-situ* + *ex-situ*" approaches were most effective. A slightly lower proportion (37%) supported integrative conservation. *Ex-situ* as a separate approach was not selected by any respondent which indicates that the majority of the respondents (both from the scientific community and practitioners) agrees upon that pure *ex-situ* is not effective for conserving riparian tree species genetic diversity. While few riparian species have been studied genetically, the research on the genetic structure of black poplar (*Populus nigra*), one of the most threatened tree species in Europe, provides a basis for recommendations on management of black popular and other riparian tree species. Restoring and re-instating the natural dynamics of floodplains, in combination with having sufficiently sized and spaced natural populations as seed sources, is recommended for long-term conservation (Smulders et al. 2008). Using local provenances for revegetation is vital to avoid introgression from exotic cultivars (Chenault et al. 2011). This requires identification of natural populations as propagule sources (e.g. 46 genetic conservation units across Europe for *P. nigra*; www.eufgis.org). These "*in-situ*" conservation actions should be supported by "*ex-situ*" measures to preserve indigenous genetic material, in case of *in-situ* measures failure (Storme et al. 2004). For example, in Italy, the CREA (www.crea.gov.it) long-term *ex-situ* collections (2500 poplars and willows), have been already used in river restoration.

According to the results of the structured questionnaires, the main benefit of conserving riparian tree species genetic diversity highlighted by 28 of the 30 respondents is *freshwater ecosystem* *conservation*. Also, 27 of them recognised *scientific interest* as another main benefit. *Filtering water pollutants*, *social importance,* and *economic benefits* were also highly ranked. Six out of 30 respondents recognized *food security* as one of the main benefits.

The results overall showed that the *ecosystem approach,* defined by the COP 5 Decision V/6 as *"a* strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way", is recognized as the most appropriate option for the conservation of riparian tree species genetic diversity. Among the existing examples of good practices in the integrative conservation of riparian tree species genetic diversity, mentioned by the respondents, is the REFOCuS project (http://www.interreg-danube.eu/approved-projects/refocus) that aims to boost riparian forest resilience in the Mura-Drava-Danube biosphere reserve as ecological corridors.

4 NEEDS AND PRIORITIES

The structured questionnaires revealed a general lack of an integrated strategy for the conservation of riparian tree species genetic diversity across European countries. Existing efforts in specific countries have focused on a few flagship species, often integrated into forestry programmes, but offering limited progress from an ecosystem perspective. Thus, it is urgent to integrate the genetic dimension in riparian vegetation management and to integrate riparian tree species in genetic resource conservation strategies. Understanding ecological processes (e.g. gene flow) and pressures (e.g. river fragmentation) in hydrographic networks is essential to conserve intraspecific genetic diversity and adequately manage riparian tree genetic resources .

In the last part of the structured questionnaire, respondents were asked to identify specificities, strengths and weaknesses of riparian tree species genetic diversityconservation as well as to propose and describe the most beneficial project at the national level. According to the results, four groups of answers were identified as follows:

Specificities of conserving riparian tree species genetic diversity in comparison with other ecosystems fell under eight categories: biodiversity, gene flow, regeneration, ecosystem functioning, water regimes, legislation, water management and pressures.

Identified *strengths* (*Figure 1*) that can help achieve effective riparian tree species genetic diversity conservation, were: scientific knowledge, diversity status (inventories of the species), institutional/organizational framework, community awareness, environmental conditions/accessibility, legislation framework, financial support, policy priority and others.

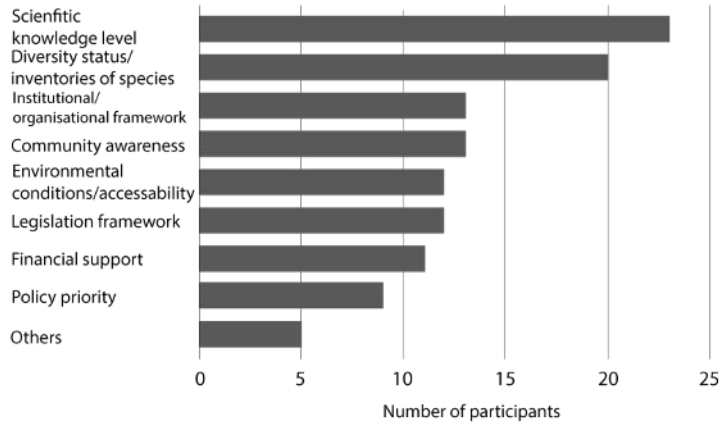

FIGURE 1

Strengths identified by participants that can be used to achieve effective riparian GR conservation

Weaknesses (*Figure 2*) that should be alleviated and/or eliminated were classified in the following categories: lack of policy priority, financial, legislation framework, institutional/organizational framework, community awareness, diversity status/inventories of species, scientific knowledge level, environmental barriers, and others.

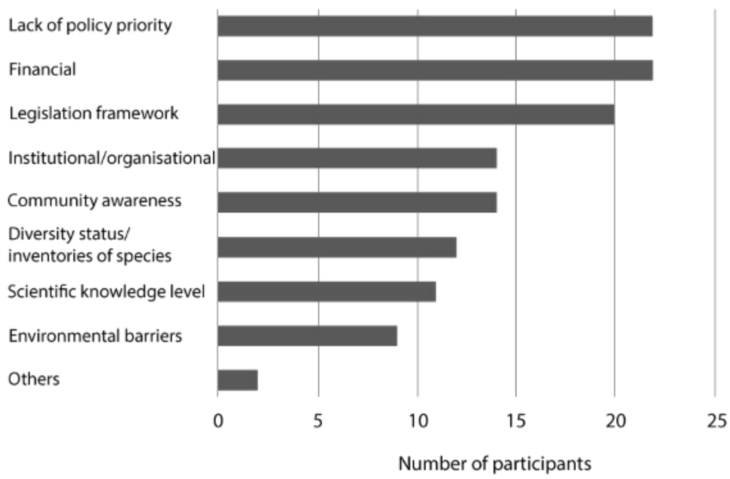

FIGURE 2

Weaknesses identified by participants that should be alleviated or eliminated to achieve effective riparian GR conservation

The top weaknesses identified were *lack of policy priority* and *financial support*, followed by *legislation framework*, which suggests a need for better governance to conserve riparian tree genetic resources. Respondents were of the opinion that policy needs to be given priority to riparian tree species genetic diversity conservation to help design plans and develop projects that can be implemented in short term.

The fourth question was to imagine the most beneficial project (Figure 3, Appendix S2-B) aimed at riparian tree genetic resources conservation at the national level. Their answers covered diverse topics: *in-situ* measures, research, knowledge transfer, vegetationinventories, monitoring, referencing hotspots, *ex-situ* measures, upgrading projects, funding scheme, genetic screening and education and professional training. The first four topics were most frequently mentioned by respondents as illustrated in Figure 3.

FIGURE 3

Major topics of the most beneficial project identified by respondents that aimed at riparian GR conservation at the national level

The short questionnaire made it possible to define identify a list of priority riparian tree species for the conservation of intraspecific genetic diversity. The species that were most highly often cited by the experts and practitioners are:

1. *Alnus glutinosa* (L.) Gaertner – mentioned in as many as 14 countries as a functionally and economically important species, but also due to conservation aspects. The conservation importance of this species is recognized in countries with very different environmental conditions throughout Europe (i.e. priority habitat 91E0*). An additional reason for prioritizing this species for conservation is its endangerment due to widespread population decline caused by the epidemic fungal pathogen *Phytophthora* x *alni* (Bjelke et al. 2016).

2. *Salix alba* L. – mentioned in 10 countries. Similar to many other species in the Salicaceae family, it is found living in the active channel and floodplains, mostly as a functionally important species within in the typical dynamics of riparian ecosystems (Karrenberg et al. 2002; Degirmenci 2019).

3. *Populus nigra* L. – mentioned by the experts from 9 countries (mostly the Central-South-East European countries), primarily as a conservation concern but also a functionally and economically important species. Genetic diversity of the species is highly endangered due to introgression and gene flow with both hybrid cultivars (especially *P.* x *euramericana* hybrids) and pure *P. nigra* varieties like the Lombardy poplar (Vanden-Broeck et al. 2005; Chenault et al. 2011; Vanden-Broeck et al. 2012).

4. *Ulmus laevis* Pall. – mentioned by the experts from 8 countries as a conservation concern, due to reduction of its natural populations caused by Dutch Elm Disease and wetland degradation (Devetaković et al. 2016).

Other species of importance for the genetic conservation of RE, according to respondents, are as follows: *Quercus robur* L., *Populus alba* L., *Fraxinus angustifolia* Vahl, *Ulmus minor* Mill., *Salix* spp. (*S.* × *rubens*, *S. fragilis*, *S. atrocinerea* Brot., *S. eleagnos* Scop., *S. salviifolia* Brot.), *Fraxinus excelsior* L., *Populus* spp. (*P.* × *canescens*, *P. tremula*), *Platanus orientalis* L., *Alnus incana* (L.) Moench, *Betula pubescens* L., *Carpinus betulus* L., *Liquidambar orientalis* Mill. and *Prunus padus* L.

Based on issues highlighted by the questionnaire respondents, we developed a framework for conducting surveys of the genetic status of species (Appendix S3), encompassing (1) Mapping of current status; (2) Species-level plans; (3) Funding; (4) Monitoring; (5) Knowledge transfer and dissemination; and (6) Evaluation. We envision that if the framework is applied to the species highlighted above, this can in turn inspire work on additional taxa.

5 CONCLUSIONS/PROSPECTS

The omission of genetic considerations in riparian management can potentially hamper efforts to manage river ecosystems to conserve biodiversity and ensure ecosystem service provision, given the key role of riparian vegetation and specific tree species at risk of genetic erosion. This omission needs to be addressed due to intensification of human [biotic and abiotic] pressures on riparian ecosystems, such as biological invasions, emerging alien diseases, and genetic pollution, that are leading to critical biodiversity loss.

Despite shortcomings in terms of representativeness of the respondents consulted, this study represents (to our best knowledge) the first pan-European survey that offers a broad view of the issues of genetic resources management for riparian tree species on a continental scale. Future research would benefit from addressing riparian genetic patterns and ecological processes such as gene flow, impacts caused by human alteration, such as agricultural use of riparian zones, fragmentation of hydrographic networks, as well as global change, including potential geographic range shifts or maladaptation of populations at the geographic range limits. In riparian restoration schemes involving seeding or planting it is vital that genetic diversity is ensured, and that locally adapted, native species are used. Furthermore, an understanding of the ecological processes that shape riparian ecosystems (Rodríguez-Gonzalez et al. 2019) is required.

Research needs to be followed by adequate knowledge transfer both to managers and decision-makers to better inform legislation and implementation. Incorporating and improving policies on genetic considerations are especially crucial as most species are non-commercial and binding regulations are required to control/certify the origin of the plant material that is made available in nurseries. In the context of increasing promotion of ecosystem restoration, guidance on best practice in the management of plant reproductive material from local native populations (e.g. cuttings propagation in the field with an adequate and large genetic diversity; seedlings with identified and certified origin) is crucial. Inclusion of genetic diversity in assessments of the native riparian tree species population status and recognition of trajectories in long-term monitoring are needed to ensure ecological integrity of riparian genetic resources in the future.

Genetic diversity is important both to ensure current population fitness and to maintain their adaptive potential to respond to environmental change (Fady et al. 2020). Restoration guidelines strongly recommend considering among-habitat genetic differentiation, and using local propagule sources to ensure evolutionary potential (Broadhurst et al. 2008), which requires identifying natural populations to serve as propagule sources. Due to the comparatively rapid dynamics of riparian forest species (rate of founding and extinction of populations), genetic conservation measures need to be streamlined to enable their rapid adaptation. Resistance to emerging pathogens will be critical, requiring selection of multiple individuals with resistance to pathogens, such as in elms, ash and alder (Bjelke et al. 2016). *In-situ* conservation and restoration should be supported by *ex-situ* conservation in seed orchards, clone collections, seed collections, arboreta, botanical gardens and gene banks, that adequately represent the genetic diversity of natural populations (Storme et al. 2004).

Improved integration of ecological processes that shape genetic resources in hydrographic networks (spatial patterns and gene flow, fragmentation) into management is required. Overcoming socio-economic barriers, such as the lack of policy priority and funding, and the weak legislation framework would help adoption of an ecosystem approach for sustainable conservation of riparian genetic resources within present and future climatic and land-use scenarios.

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AUTHORS' CONTRIBUTIONS

JM, PMRG, RP, GH and RJ conceived the study. JM and PMRG led the writing of the manuscript. FA analysed data and prepared figures. All authors FA, JM, RP, GH, RJ, SD, MB, NB, LSB, GB, DB, PMC, ND, YSG, MI, MKQ, NLP, MN, EN, EP, MŠN, LV, MV, PZ and PMRG contributed data and reviewed the manuscript.

DATA ACCESSIBILITY

"Data is accessible upon request to the corresponding author"

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