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PRACTITIONER'S PERSPECTIVE

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The status and role of genetic diversity of trees for the conservation and management of riparian ecosystems: A European experts' perspective

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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 at various ecosystem levels, including decreasing ecosystem services, so identifying the current status of genetic diversity of riparian tree species is vital to improve the effectiveness of restoration efforts.
2. We aimed to elicit expert views on the status and importance of genetic diversity of tree species, and conservation needs across European riparian ecosystems. Sharing of such information among researchers, managers and policymakers has 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 where our identified experts were asked to answer questions related to the status and conservation of genetic diversity of riparian tree species in their

respective countries. Specifically, we asked about societal awareness, legislative tools, good practices and conservation or restoration projects accounting for intraspecific genetic diversity and differentiation of tree species in riparian ecosystems. Questionnaire responses were analysed and discussed in light of the scientific literature to define needs and priorities related to the management and conservation of genetic diversity of riparian tree species.

4. The experts recognized that a combination of in situ and ex situ measures and/or integrative conservation of riparian ecosystems is the most appropriate option for conserving the genetic diversity of riparian tree species. 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*. This study revealed the importance of recognizing the ecological processes that shape the genetic diversity of riparian tree species in hydrographic networks (dendritic spatial configuration, specific patterns of gene flow among riparian populations, fragmentation of river by dams) but also the need to overcome socio-economic barriers, such as lack of policy priority, deficiency in funding and weak legislation framework.

KEYWORDS
biodiversity conservation, genetic erosion, genetic resources conservation, knowledge transfer, management, riparian genetic diversity, 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, improving river water quality, regulating in-stream temperature, stabilizing river banks, sequestering carbon and producing biomass supporting cross-ecosystem food webs, as well as providing cultural and recreational services (Riis et al., 2020). While much research has been devoted to the importance of species richness for riparian ecosystem functioning and stability, 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 can lead to high gene flow and downstream increases in genetic diversity. In addition, riparian habitat continuity across river networks leads to low genetic divergence among sites (Nilsson et al., 2010). Moreover, riparian zones are subject to multiple pressures that might lead to reductions in genetic diversity. For example, fragmentation by dams (Werth et al., 2014) and hybridization with non-native populations threaten the genetic diversity of riparian plant species. This is specifically true for important foundation species like *Populus nigra* L. (Chenault et al., 2011), potentially leading to low resistance to biotic and abiotic threats and increased extinction risk (Fady et al., 2020). Focusing on the genetic component of riparian plants' biodiversity is therefore key to conserve and restore riparian ecosystems efficiently. For example, riparian vegetation has great potential for the deployment of nature-based solutions addressing 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 (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 the genetic diversity of riparian trees, including conservation needs across European riparian ecosystems. The research was conducted within the network of the 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 ecosystem management.

2 | METHODOLOGICAL FRAMEWORK

The main goal of CONVERGES is to synthesize existing knowledge about riparian vegetation across countries and disciplines, covering topics from riparian research to restoration and management. A subgroup was formed 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.

First, a *short questionnaire* (Appendix S1-A) was sent to relevant experts (researchers, stakeholders and practitioners) across the 39 COST participating countries to collect information relative to the research dimension of the actions conducted at the country level (available literature, relevant projects and target species). In total 22 responses were received from 15 countries (Appendix S2-A), which were all included in the analysis.

Second, we conducted *structured questionnaires* (Appendix S1-B) to collect 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 the structured questionnaires included numeric data and text data with open-ended questions (NVivo software was used to analyse open-ended questions https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home). There were 30 responses from 19 countries (Appendix S2-B), and they were all included in the analysis. Methodology details can be found in supporting document (Appendix S3). Finally, in order to discuss the results, three main dimensions of a sustainable management have been considered: research, management and policy.

This study did not require ethical approval.

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 propagules preventing loss due to genetic drift (Paz-Vinas et al., 2015). Yet, other patterns may apply, as in *Populus nigra* where (a) no significant upstream/downstream differences in genetic diversity occur (Imbert & Lefèvre, 2003) and (b) clonality and sexual regeneration can co-occur within the same natural stand (Tinschert et al., 2020). This results in high complexity in observed spatial and temporal patterns of genetic variation and requires extensive knowledge to implement adequate management measures.

In spite of the ecological importance and the recognized threats to riparian genetic diversity, the results of the structured questionnaires revealed both a lack of assessment of genetic diversity status and the general perception of a poor status of the genetic diversity of species in riparian ecosystems. For the question relating to changes in riparian genetic diversity over the past 10 years, three options were possible: 'no significant changes', 'improving status' or 'degrading'. Apart from France and the Czech Republic, respondents from all countries (18/30) perceived that riparian genetic diversity was degrading. The respondent from France stated that a large number of genetic conservation actions have been implemented which have expanded knowledge about the genetic diversity of riparian tree species such as *Populus nigra*. This has been achieved by using multilocus nuclear DNA markers (e.g. *single nucleotide polymorphism* [SNP], Faivre-Rampant et al., 2016). According to all respondents, there was no coordinated plan of actions addressing the status of the genetic diversity of riparian tree species.

It has been demonstrated that 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 loss of genetic diversity within species and lead to local extinctions (Labonne et al., 2008). Therefore, adequate assessments of genetic diversity in riparian ecosystems, especially within tree species, are urgently needed to contribute to effective conservation.

3.2 | Policy dimension

The long-term degradation of riparian ecosystems has intensified since the 1950s, contributing to reduced river health (Singh et al., 2021), low achievement of the objectives of the European Union Water Framework Directive and unfavourable status of floodplain forest habitats across Europe (European Environmental Agency, 2020). Cortina-Segarra et al. (2021) identified genetic considerations as a pending crucial element to enable the improvement of ecosystem restoration effectiveness. In this sense, conservation of riparian tree genetic resources 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.

When asked whether their country has plans or programmes 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 Genetic Resources* (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 (GCUs) across Europe (www.eufgis.org). Moreover, the *First Report on the State of* *the World's Forest Genetic Resources* (2014) calls for urgent action for better management of forests and forest genetic resources to ensure their long-term sustainable use for communities that depend on forest products.

When it comes to riparian vegetation plant species 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, riparian 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 monitor or measure genetic erosion within riparian species, 70% of respondents gave a negative answer. 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 information regarding specific monitoring of the state of riparian genetic resources was provided.

3.3 | Management dimension

Since it is not included in most policies, the genetic diversity of riparian tree species has been mostly disregarded in impact assessments, monitoring and restoration projects. When asked about the most effective approaches to conserving genetic diversity of riparian tree species, 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). Forty per cent of respondents concluded that '*in situ + ex situ*' approaches were most effective. A slightly lower proportion (37%) supported integrative conservation. Ex situ as a stand-alone approach was not selected by any respondent, showing agreement within the scientific community and practitioners that only ex situ would be ineffective as a conservation strategy.

While few riparian species have been studied genetically, extensive 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 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, are recommended for long-term conservation (Smulders et al., 2008). Using local provenances for revegetation is vital to conserve local adaptation and 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 measure failure (Storme et al., 2004). For example, in Italy, long-term ex situ collections (2500 poplars and willows) of *Consiglio per la Ricerca in Agricoltura e l'Economia Agraria* (www.crea.gov.it) have already been used in river restoration.

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

The results overall showed that the *ecosystem approach*, defined in the Convention of Biological Diversity (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 genetic diversity of riparian tree species. Among the existing examples of good practices in the integrative conservation of riparian genetic diversity, mentioned by the respondents, the REFOCuS project (http://www.interreg-danube.eu/approved-projects/refocus) aims to boost riparian forest resilience in the Mura–Drava–Danube biosphere reserve as ecological corridors.

4 | NEEDS AND PRIORITIES

The questionnaires revealed a general lack of an integrated strategy for the conservation of riparian 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 and adequately manage intraspecific genetic diversity.

Concerning *specificities* of conserving genetic diversity of riparian tree species in comparison with other ecosystems, answers fell under eight categories: biodiversity, gene flow, regeneration, ecosystem functioning, water regimes, legislation, water management and pressures. Identified *strengths* (Figure 1a) that can help achieve effective conservation of riparian genetic diversity 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.

Weaknesses (Figure 1b) 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.

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 genetic resources of riparian trees. Respondents highlighted that policy needs to give priority

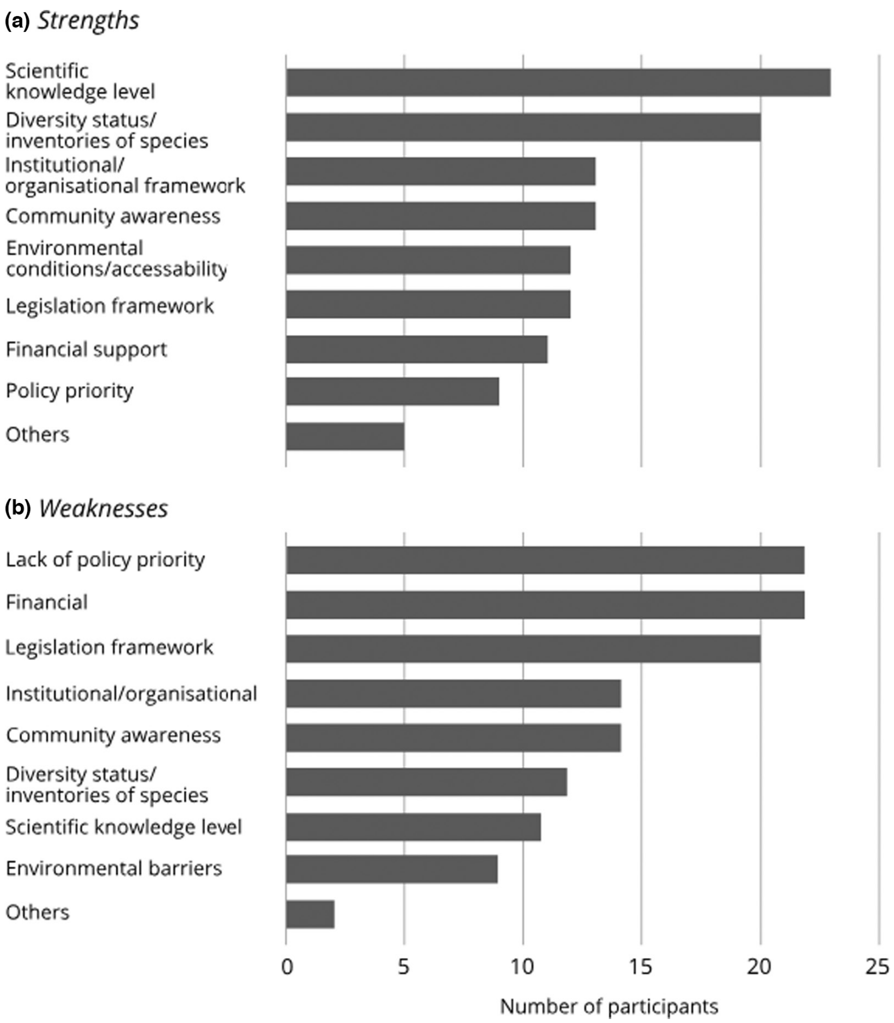

FIGURE 1 Strengths (a) and weaknesses (b) identified by participants that can be used to achieve effective riparian genetic resources conservation.

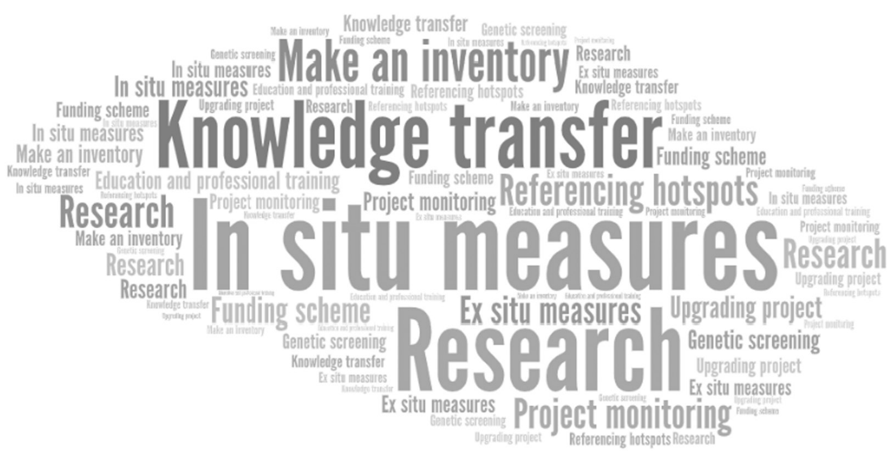

FIGURE 2 Major topics of the most beneficial project identified by respondents that aimed at riparian genetic resources conservation at the national level.

to genetic conservation to help design plans and develop projects that can be implemented in the short term.

Another question was to imagine the most beneficial project (Figure 2, Appendix S2-B) aimed at improving conservation of genetic diversity of riparian tree species at the national level. Answers covered a diversity of these topics: in situ measures, research, knowledge transfer, vegetation inventories, monitoring, referencing hotpots, ex situ measures, upgrading projects, funding scheme, genetic screening and education and professional training. The first four topics were most frequently mentioned by respondents (Figure 2).

Experts also identified a list of priority riparian tree species for the conservation of intraspecific genetic diversity. These included:

1. *Alnus glutinosa* (L.) Gaertner—mentioned in 14 countries as a functionally and economically important species, but also due to conservation aspects (i.e. priority habitat 91E0* according

to EU Directive 92/43/EEC), across different environmental conditions in Europe. An additional reason for prioritizing this species for conservation is its endangerment due to widespread population decline caused by the epidemic oomycete complex pathogen *Phytophthora × alni* (Bjelke et al., 2016).

2. *Salix alba* L.—mentioned in 10 countries. As with many other species in the Salicaceae family, it is found in the active channel and on floodplains, mostly as a functionally important species in typical dynamic riparian ecosystems.
3. *Populus nigra*—mentioned by the experts from nine 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. × euramericana* hybrids) and pure *P. nigra* varieties like the Lombardy poplar (Chenault et al., 2011).
4. *Ulmus laevis* Pall.—mentioned by the experts from eight countries as a conservation concern, due to reduction of its natural populations caused by Dutch Elm Disease and wetland degradation.

Other species of importance for genetic conservation in riparian ecosystems, according to respondents include: *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 respondents, we developed a framework for conducting surveys of the genetic status of species (Appendix S4), 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

Genetic resources assessment and conservation remains a global challenge (Hoban et al., 2022). In the case of riparian ecosystems, given the key role of riparian vegetation, the omission of genetic considerations in their management can potentially hamper efforts to conserve biodiversity and ensure ecosystem service provision. This omission needs to be addressed due to intensification of 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 the 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 resource 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, agricultural use of riparian zones, fragmentation of hydrographic networks, as well as global change, including potential geographic range shifts or maladaptation of populations at geographic range limits. In riparian restoration schemes involving seeding or planting it is vital that genetic diversity is ensured, and that locally adapted, native provenances are used. Furthermore, an understanding of the ecological processes that shape riparian ecosystems (Rodríguez-González 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. propagation of cuttings in the field having high genetic diversity; seedlings with identified and certified origin) is crucial. Inclusion of genetic diversity in assessments of the population status of native riparian tree species 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 identification of natural populations to serve as propagule sources. Due to the comparatively rapid dynamics of riparian forest species (i.e. 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, in species such as 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.

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.

AUTHORS' CONTRIBUTIONS

J.M., P.M.R.-G., R.P., G.H. and R.J. conceived the study; J.M. and P.M.R.-G. led the writing of the manuscript; F.A. analysed the data and prepared the figures. All authors contributed data and reviewed the manuscript.

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CONFLICT OF INTEREST

None of the authors have a conflict of interest in this study.

DATA AVAILABILITY STATEMENT

All data underlying the reported findings have been provided as part of the submitted article and are available via https://converges.eu/resources/conservation-and-management-of-riparian-species-genetic-diversity/ (Alimpić et al., 2019).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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