Received: 22 September 2021 | Accepted: 29 June 2022

DOI: 10.1111/1365-2664.14247

Journal of Applied Ecology | BRITISH ECOLOGICAL SOCIETY

PRACTITIONER'S PERSPECTIVE

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

Filip Alimpić[1] | Jelena Milovanović[1] | Remigiusz Pielech[2] | Georgi Hinkov[3] | Roland Jansson[4] | Simon Dufour[5] | Marcin Beza[6] | Nebi Bilir[7] | Luis Santos del Blanco[8] | Gregor Božič[9] | Daniel Bruno[10] | Pier Mario Chiarabaglio[11] | Neli Doncheva[12] | Yaşar Selman Gültekin[13] | Mladen Ivanković[14] | Mary Kelly-Quinn[15] | Nicola La Porta[16] | Marina Nonić[17] | Eduardo Notivol[18] | Eva Papastergiadou[19] | Mirjana Šijačić-Nikolić[17] | Lorenzo Vietto[11] | Marc Villar[20] | Petar Zhelev[21] | Patricia María Rodríguez-González[22]

[1]Singidunum University—Environment and Sustainable Development, Belgrade, Serbia; [2]Department of Forest Biodiversity, Faculty of Forestry, University of Agriculture in Kraków, Kraków, Poland; [3]Forest Research Institute at the Bulgarian Academy of Sciences, Sofia, Bulgaria; [4]Umeå University, Umeå, Sweden; [5]Université Rennes 2/UMR LETG, Rennes, France; [6]The Kostrzyca Forest Gene Bank, Miłków, Poland; [7]Isparta University of Applied Sciences, Isparta, Turkey; [8]CSIC—INIA—CIFOR, Madrid, Spain; [9]Slovenian Forestry Institute, Ljubljana, Slovenia; [10]Pyrenean Institute of Ecology (Spanish National Research Council; IPE-CSIC), Zaragoza, Spain; [11]CREA—Research Centre for Forestry and Wood, Casale Monferrato AL, Italy; [12]WWF Bulgaria, Sofia, Bulgaria; [13]Forest Economics Department, Düzce University, Faculty of Forest, Düzce, Turkey; [14]Croatian Forest Research Institute, Jastrebarsko, Croatia; [15]School of Biology and Environmental Science, University College Dublin, Dublin, Ireland; [16]Edmund Mach Foundation, Trento, Italy; [17]University of Belgrade—Faculty of Forestry, Belgrade, Serbia; [18]CITA (Agricultural Research Centre), Aragon, Spain; [19]School of Natural Sciences—University of Patras, Rio, Greece; [20]INRAE—ONF—BioForA, Orléans, France; [21]University of Forestry, Sofia, Bulgaria and [22]Forest Research Centre—School of Agriculture—University of Lisbon, Lisbon, Portugal

Correspondence
Patricia María Rodríguez-González
Email: patri@isa.ulisboa.pt

Funding information
European Cooperation in Science and Technology, Grant/Award Number: CA16208; Forest Research Centre by the FCT, Grant/Award Number: UIDB/00239/2020; Ministarstvo Prosvete, Nauke i Tehnološkog Razvoja, Grant/Award Number: 0801-417/1; Narodowe Centrum Nauki, Grant/Award Number: 2019/35/B/NZ8/01901; Portuguese Foundation for Science and Technology (FCT), Grant/Award Number: 2020.03356.CEECIND; Portuguese Foundation for Science and Technology (FCT), Grant/Award Number: PTDC/ASP-SIL/28593/2017

Handling Editor: Thibault Datry

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

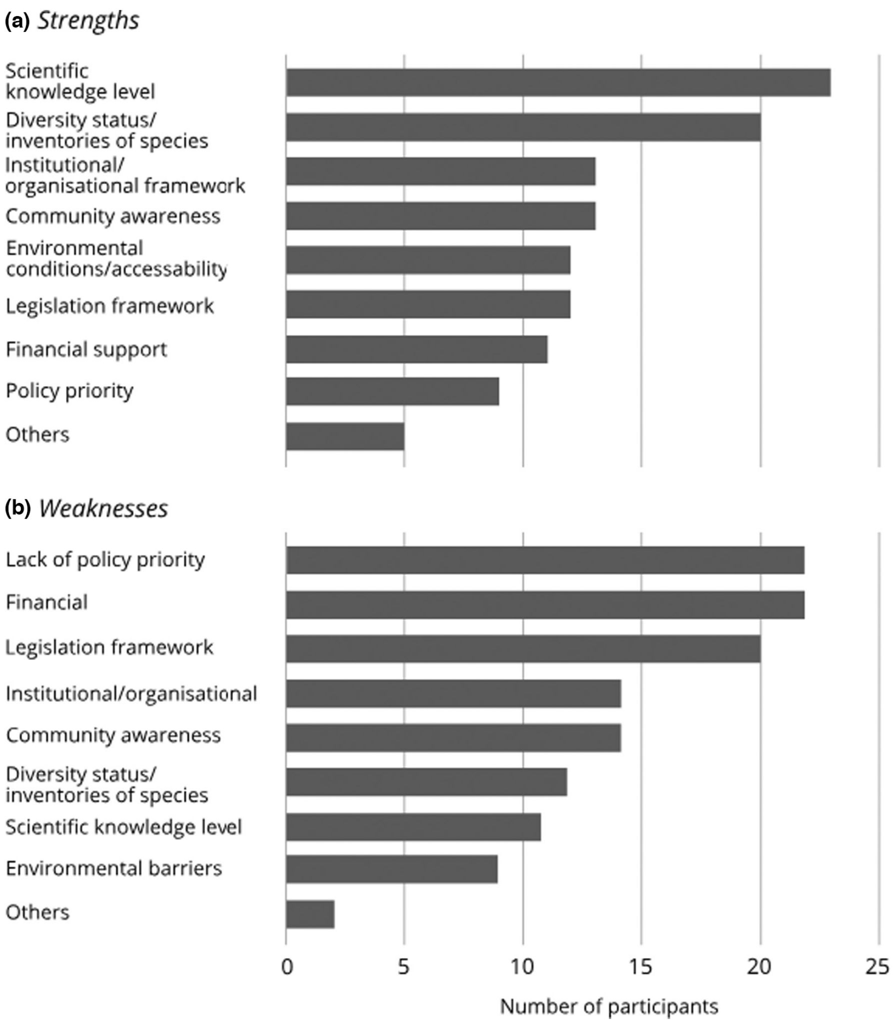

FIGURE 1 Strengths (a) and weaknesses (b) identified by participants that can be used to achieve effective riparian genetic resources conservation.

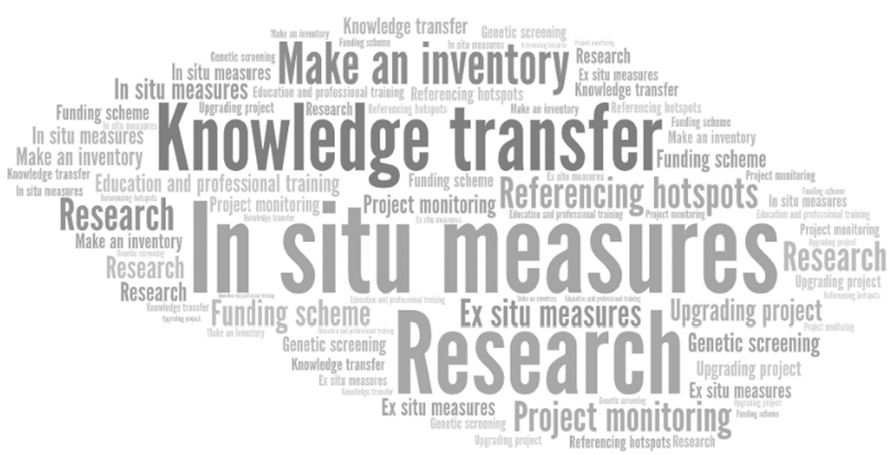

FIGURE 2 Major topics of the most beneficial project identified by respondents that aimed at riparian genetic resources conservation at the national level.

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.

ACKNOWLEDGEMENTS

The work leading to this paper was developed within the COST Action (CA16208)—CONVERGES (Knowledge Conversion for Enhancing Management of European Riparian Ecosystems and Services), supported by COST (European Cooperation in Science and Technology; www.cost.eu) and by the Horizon 2020 Framework Programme of the European Union. We thank three anonymous reviewers for comments and suggestions that greatly improved the paper. JM was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia, according to the agreement No. 0801-417/1. PMRG was supported by the Portuguese Foundation for Science and Technology (FCT) through the 2020.03356.CEECIND grant, and through PTDC/ASP-SIL/28593/2017 grant; and Forest Research Centre by the FCT (UIDB/00239/2020) grant. RP was supported by the grant from the National Science Centre, Poland (2019/35/B/NZ8/01901).

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).

ORCID

Filip Alimpić https://orcid.org/0000-0003-2083-8065
Patricia María Rodríguez-González https://orcid.org/0000-0001-8507-8429

REFERENCES

Alimpić, F., Milovanović, J., Pielech, R., Hinkov, G., Jansson, R., Dufour, S., Beza, M., Bilir, N., del Blanco, L. S., Božič, G., Bruno, D., Chiarabaglio, P. M., Doncheva, N., Gültekin, Y. S., Ivanković, M., Kelly-Quinn, M., La Porta, N., Nonić, M., Notivol, E., … Rodríguez-González, P.M. (2019). Data from: Riparian vegetation—Conservation and management of genetic diversity. Retrieved from https://converges.eu/resources/conservation-and-management-of-riparian-species-genetic-diversity/

Bjelke, U., Boberg, J., Oliva, J., Tattersdill, K., & McKie, B. G. (2016). Dieback of riparian alder caused by the Phytophthora alni complex: Projected consequences for stream ecosystems. *Freshwater Biology*, *61*(5), 565–579. https://doi.org/10.1111/fwb.12729

Breed, M. F., Harrison, P. A., Blyth, C., Byrne, M., Gaget, V., Gellie, N. J., Groom, S. V. C., Hodgson, R., Mills, J. G., Prowse, T. A. A., Steane, D. A., & Mohr, J. J. (2019). The potential of genomics for restoring ecosystems and biodiversity. *Nature Reviews Genetics*, *20*(10), 615–628. https://doi.org/10.1038/s41576-019-0152-0

Broadhurst, L. M., Lowe, A., Coates, D. J., Cunningham, S. A., McDonald, M., Vesk, P. A., & Yates, C. (2008). Seed supply for broadscale restoration: Maximizing evolutionary potential. *Evolutionary Applications*, *1*(4), 587–597. https://doi.org/10.1111/j.1752-4571.2008.00045.x

Chenault, N., Arnaud-Haond, S., Juteau, M., Valade, R., Almeida, J.-L., Villar, M., Bastien, C., & Dowkiw, A. (2011). SSR-based analysis of clonality, spatial genetic structure and introgression from the Lombardy poplar into a natural population of *Populus nigra* L. along the Loire River. *Tree Genetics & Genomes*, *7*(6), 1249–1262. https://doi.org/10.1007/s11295-011-0410-6

Cortina-Segarra, J., García-Sánchez, I., Grace, M., Andrés, P., Baker, S., Bullock, C., Decleer, K., Dicks, L. V., Fisher, J. L., Frouz, J., Klimkowska, A., Kyriazopoulos, A. P., Moreno-Mateos, D., Rodríguez-González, P. M., Sarkki, S., & Ventocilla, J. L. (2021). Barriers to ecological restoration in Europe: Expert perspectives. *Restoration Ecology*, *29*(4), e13346. https://doi.org/10.1111/rec.13346

Dufour, S., Rodríguez-González, P., & Laslier, M. (2019). Tracing the scientific trajectory of riparian vegetation studies: Main topics, approaches and needs in a globally changing world. *Science of The Total Environment*, *653*, 1168–1185. https://doi.org/10.1016/j.scitotenv.2018.10.383

European Environmental Agency. (2020). *European waters—Assessment of status and pressures 2018*. https://www.eea.europa.eu/themes/water/european-waters/water-quality-and-water-assessment/water-assessments

Fady, B., Aravanopoulos, F., Benavides, R., González-Martínez, S., Grivet, D., Lascoux, M., Lindner, M., Rellstab, C., Valladares, F., & Barbara, V. (2020). Genetics to the rescue: Managing forests sustainably in a changing world. *Tree Genetics & Genomes*, *16*, 80. https://doi.org/10.1007/s11295-020-01474-8

Faivre-Rampant, P., Zaina, G., Jorge, V., Giacomello, S., Segura, V., Scalabrin, S., Guérin, V., De Paoli, E., Aluome, C., Viger, M., Cattonaro, F., Payne, A., PaulStephenRaj, P., Le Paslier, M. C., Berard, A., Allwright, M. R., Villar, M., Taylor, G., Bastien, C., & Morgante, M. (2016). New resources for genetic studies in Populus nigra: Genome-wide SNP discovery and development of a 12k Infinium array. *Molecular Ecology Resources*, *16*(4), 1023–1036. https://doi.org/10.1111/1755-0998.12513

González del Tánago, M., Martínez-Fernández, V., Aguiar, F. C., Bertoldi, W., Dufour, S., García de Jalón, D., Garófano-Gómez, V., Mandzukovski, D., & Rodríguez-González, P. M. (2021). Improving river hydromorphological assessment through better integration of riparian vegetation: Scientific evidence and guidelines. *Journal of Environmental Management*, *292*, 112730. https://doi.org/10.1016/j.jenvman.2021.112730

Hoban, S., Archer, F., Bertola, L., Bragg, J., Breed, M., Bruford, M., Coleman, M., Ekblom, R., Funk, W. C., Grueber, C., Hand, B., Jaffé, R., Jensen, E., Johnson, J., Kershaw, F., Liggins, L., MacDonald, A., Mergeay, J., Miller, J., … Hunter, M. (2022). Global genetic diversity status and trends: Towards a suite of essential biodiversity variables (EBVs) for genetic composition. *Biological Reviews*, *97*, 1511–1538. https://doi.org/10.1111/brv.12852

Imbert, E., & Lefèvre, F. (2003). Dispersal and gene flow of *Populus nigra* (Salicaceae) along a dynamic river system. *Journal of Ecology*, *91*(3), 447–456. https://doi.org/10.1046/j.1365-2745.2003.00772.x

Labonne, J., Ravigné, V., Parisi, B., & Gaucherel, C. (2008). Linking dendritic network structures to population demogenetics: The downside of connectivity. *Oikos*, *117*(10), 1479–1490. https://doi.org/10.1111/j.0030-1299.2008.16976.x

Nilsson, C., Brown, R. L., Jansson, R., & Merritt, D. M. (2010). The role of hydrochory in structuring riparian and wetland vegetation. *Biological Reviews of the Cambridge Philosophical Society*, *85*(4), 837–858. https://doi.org/10.1111/j.1469-185X.2010.00129.x

Paz-Vinas, I., Loot, G., Stevens, V., & Blanchet, S. (2015). Evolutionary processes driving spatial patterns of intraspecific genetic diversity in river ecosystems. *Molecular Ecology*, *24*, 4586–4604. https://doi.org/10.1111/mec.13345

Riis, T., Kelly-Quinn, M., Aguiar, F. C., Manolaki, P., Bruno, D., Bejarano, M. D., Clerici, N., Fernandes, M. R., Franco, J. C., Pettit, N., Portela, A. P., Tammeorg, O., Tammeorg, P., Rodríguez-González, P. M., & Dufour, S. (2020). Global overview of ecosystem services provided by riparian vegetation. *Bioscience*, *70*(6), 501–514. https://doi.org/10.1093/biosci/biaa041

Rodríguez-González, P. M., García, C., Albuquerque, A., Monteiro-Henriques, T., Faria, C., Guimarães, J. B., Mendonça, D., Simões, F., Ferreira, M. T., Mendes, A., Matos, J., & Almeida, M. H. (2019). A spatial stream-network approach assists in managing the remnant genetic diversity of riparian forests. *Scientific Reports*, *9*(1), 6741. https://doi.org/10.1038/s41598-019-43132-7

Singh, R., Tiwari, A. K., & Singh, G. S. (2021). Managing riparian zones for river health improvement: An integrated approach. *Landscape and Ecological Engineering*, *17*(2), 195–223. https://doi.org/10.1007/s11355-020-00436-5

Smulders, M. J. M., Cottrell, J. E., Lefèvre, F., van der Schoot, J., Arens, P., Vosman, B., Tabbener, H. E., Grassi, F., Fossati, T., Castiglione, S., Krystufek, V., Fluch, S., Burg, K., Vornam, B., Pohl, A., Gebhardt, K., Alba, N., Agúndez, D., Maestro, C., … Boerjan, W. (2008). Structure of the genetic diversity in black poplar (*Populus nigra* L.) populations across European river systems: Consequences for conservation and restoration. *Forest Ecology and Management*, *255*(5), 1388–1399. https://doi.org/10.1016/j.foreco.2007.10.063

Storme, V., Vanden Broeck, A., Ivens, B., Halfmaerten, D., Van Slycken, J., Castiglione, S., Grassi, F., Fossati, T., Cottrell, J. E., Tabbener, H. E., Lefèvre, F., Saintagne, C., Fluch, S., Krystufek, V., Burg, K., Bordács, S., Borovics, A., Gebhardt, K., Vornam, B., … Smulders, M. J. M. (2004). Ex-situ conservation of black poplar in Europe: Genetic diversity in nine gene bank collections and their value for nature development. *TAG. Theoretical and Applied Genetics. Theoretische Und Angewandte Genetik*, *108*(6), 969–981. https://doi.org/10.1007/s00122-003-1523-6

Tinschert, E., Egger, G., Wendelgaß, J., Heinze, B., & Rood, S. (2020). Alternate reproductive strategies of *Populus nigra* influence diversity, structure and successional processes within riparian woodlands along the Allier River. *France. Journal of Hydro-Environment Research*, *30*, 100–108. https://doi.org/10.1016/j.jher.2020.03.004

UNEP & IUCN. (2021). *Nature-based solutions for climate change mitigation*. Retrieved from https://www.unep.org/resources/report/nature-based-solutions-climate-change-mitigation

Werth, S., Schödl, M., & Scheidegger, C. (2014). Dams and canyons disrupt gene flow among populations of a threatened riparian plant. *Freshwater Biology*, *2502–2515*, 2502–2515. https://doi.org/10.1111/fwb.12449

Wubs, E. R. J., Fraaije, R. G. A., de Groot, G. A., Erkens, R. H. J., Garssen, A. G., Kleyheeg, E., Raven, B. M., & Soons, M. B. (2016). Going against the flow: A case for upstream dispersal and detection of uncommon dispersal events. *Freshwater Biology*, *61*(5), 580–595. https://doi.org/10.1111/fwb.12736

BIOSKETCH

Filip Alimpić is a teaching associate at the Singidunum University in Belgrade, Serbia, working closely with the professors and students of the Environment and Sustainable Development Study Program. He was a COST (European Cooperation in Science and Technology) grantee for the Short-Term Scientific Mission (STSM) program at the University of Lisbon. More about his research and teaching activities can be seen at https://eng.singidunum.ac.rs/profile/falimpic.

Jelena Milovanović is a full-time professor at the Study Program Environment and Sustainable Development of the Singidunum University in Belgrade, Serbia. She has been involved in forest genetic resources conservation and climate change challenges research since 2005 and she has made significant scientific and expert achievements in this field. She is the author of many journal articles, chapters and books on forest genetic resources, conservation issues and environmental protection, including chapters in international series, and participates as an expert in many international and national projects. More about her references and projects can be seen at https://eng.singidunum.ac.rs/profile/jmilovanovic.

Remigiusz Pielech is an independent researcher at Department of Forest Biodiversity, Faculty of Forestry, University of Agriculture in Kraków, Poland. His main focus is to understand the functioning and diversity patterns in riparian ecosystems. He is leading a project on genetic structure and gene flow among riparian plant populations. Besides, he also works on the effects of large-scale disturbances, browsing pressure and management on forests. In addition, he is also involved in collaborative analyses of temperate forest dynamics as well as patterns of diversity in Palaearctic grasslands.

Georgi Hinkov has been a researcher for 25 years at the Forest Research Institute. His research work in the last 5 years is related to riparian forests, assessment and monitoring of invasive plant species, the impact of climate change on forests, old growth forests, forests in protected areas of the European ecological network Natura 2000.

Roland Jansson is professor of ecology at Umeå University, Sweden, focusing on the ecology of streams and rivers, and how climate change in the past has shaped macroecological patterns and processes. He leads several projects aiming at the ecological rehabilitation and restoration of riverine ecosystems affected by damming and flow regulation, specifically focusing on conserving biodiversity and to mitigate the effects of and adapt ecosystems to the effects of climate change.

Simon Dufour is a geographer at the Rennes university, France. His research focus on fluvial landscapes, especially on spatial patterns of riparian buffers at large scale, interactions between hydromorphological, biological and social processes, river and floodplain management and restoration and remote sensing uses. He participates and leads projects and research contracts, from local to international scale, dedicated to understand socio-ecological functioning of riparian systems and to enhance their management.

Marcin Beza is a Deputy Director of the Kostrzyca Forest Gene Bank (Poland) – an organizational unit of the State Forests National Forest Holding. He develops his activity on a multi-faceted effort to maintain the genetic resources of plants forming the native flora of Polish woods, including: preservation of gene pool of both the oldest indigenous forest stands and the individual conservation trees, preservation of gene pool of protected and endangered plants, implementation of individual species restitution programmes.

Nebi Bilir is a professor of forest genetics at the Department of Forest Engineering of Isparta University of Applied Sciences. He has long-term research interests in selection, improvement and establishment of seed sources in forest genetics. He was deputy Coordinator of WP 2.09.01 (Seed Orchards) from 2009 to 2019. He was the Chair of the international seed orchard and breeding theory conference to be held in Turkey, 2012. He has published international and national papers in forest genetics together with scientific board members in international meetings and journals.

Luis Santos del Blanco works as a postdoc in forest conservation genetics at the Spanish Forest Research Center. His research interests comprise evolutionary quantitative genetics, plant reproductive ecology, conservation genetics and ECM fungal ecology and cultivation.

Gregor Božič is senior researcher in the Slovenian Forestry Institute. He has more than 25 years experiences in forest genetics related to conservation of forest genetic resources in link to applications with practical forestry. He has experiences in adaptive forest regeneration to maintain biodiversity in riparian forests, and identification of plant material with boarder adaptive properties for ecosystem services. He was a Slovenian representative in EUFORGEN Pan-European conservation efforts for Populus nigra L.. Currently he is the representative of the National Poplar Commission of Slovenia in the FAO - International Poplar Commission governance body.

Daniel Bruno is a community ecologist specialized in riparian ecology and working as a postdoc at Pyrenean Institute of Ecology (Spanish National Research Council; IPE-CSIC) studying the 1) effects of global change on biodiversity and ecosystem functions and services in rivers with special emphasis in riparian vegetation and Mediterranean areas; 2) riparian management and restoration actions to mitigate anthropogenic impacts and 3) citizen science and environmental monitoring.

Pier Mario Chiarabaglio is a forestry scientist with experience on environmental ecology. He is involved in researches on agro-forestry systems, wood production, bio-economic models (growth, production and profitability comparisons), ecology (bioindicators, GHG balance, energy balance, LCA) and land recovery.

Neli Doncheva is a chief forest expert at WWF Bulgaria with over 20 years of experience in forest related topics: responsible forest management, restoration of riparian forest habitats, identification of high conservation values forests, incl. old growth forests, stakeholder engagement, protected areas management and forest biodiversity.

Yaşar Selman Gültekin has been a researcher at Düzce University, Faculty of Forest, Forest Economics Department since 2005 and is now an assistant professor. He earned his PhD in forest economics at Düzce University, Natural Science Institute Forest Engineering, in 2015. His research focuses on forest economics, stakeholder analysis and management, participation, ecotourism, and structural equation modelling.

Mladen Ivanković, Scientific Adviser, is Head of Division for Genetics, Forest Tree Breeding and Seed Husbandry at the Croatian Forest Research Institute, Jastrebarsko, Croatia. His research activities focus on forest genetics related to the conservation of forest genetic resources and seed science. He has experience in many national and international projects (COST E52, COST FP0905, REFOCuS, etc.), organization of workshops, mentoring doctoral students, reviewing scientific journals and projects. He is the author of scientific journal articles, chapters, and books (https://www.bib.irb.hr/pregled/profil/17245).

Mary Kelly-Quinn is an Associate Professor in the School of Biology and Environmental Science, University College Dublin, Ireland. Her research focuses on assessment of land-use and other anthropogenic activities on the physical, hydrochemical and ecological quality of surface waters with particular reference to multiple stressors and climate change. This includes identification of impact mitigation measures, some of which relate to riparian zone management. She is also engaged in research on operationalisation of ecosystem service science into policy and practice. Further details of her publications are available at https://people.ucd.ie/mary.kelly-quinn .

Nicola La Porta is a Senior scientist at Edmund Mach Foundation (Trento) in North-East Italy, where he is working in forest protection against biotic and abiotic stresses including evaluation of forest genetic resources and biodiversity to enhance resilience and adaptation to climate changes. This places his work at the intersection between forest pathology, microbiology, plant genetics, ecology and adaptation to climatic changes. His experience and interests are in forest dynamics, particularly in mountain forests in the Alps, including riparian forests.

Marina Nonić is an Assistant Professor at the University of Belgrade - Faculty of Forestry, Republic of Serbia. Her scientific work has been mainly focused on forest genetics, plant breeding and conservation of forest genetics resources, as well as plant production. Dr. Marina Nonić is author/co-author of more than 80 scientific journal and conference papers, including chapters in books published by Springer and CRC Press. She is one of three editors of book "Forests of Southeast Europe under a Changing Climate: Conservation of Genetic Resources", published by Springer.

Eduardo Notivol is a senior forest researcher at CITA (Agricultural Research Centre) of Aragon (Spain) since 1992 on applied forest genetics (quantitative genetics): Genetic variability, preservation and sustainable use of forest genetic resources, tree improvement, design and analysis of experiments, GIS, databases and information technologies. Deeply involved in EUFORGEN (European forest genetic resources conservation program) as Spanish national focal point of EUFGIS (European information system on forest genetic resources) and other projects related. Member of the scientific committee of a riparian Natural Reserve in Ebro river (Spain)

Eva Papastergiadou is a Professor of Ecology at the Department of Biology, University of Patras, Greece with an expertise on ecosystem-scale dynamics, riparian vegetation, aquatic macrophytes ecology, functional diversity patterns and processes of aquatic assemblages. She has experience as key partner and National representative of Greece and Cyprus in WFD 2000/60 Intercalibration process, in many national and international projects, organization of workshops, and coordination of scientific working teams. Editorial Board member of five international journals, and Editor of two journal special issues.

Mirjana Šijačić-Nikolić is a Full Professor at the University of Belgrade - Faculty of Forestry, Republic of Serbia. She published more than 300 scientific papers related to genetics of forest trees, plants breeding, conservation and sustainable utilization of forest genetic resources and plant production, co-authored the university textbook Conservation and Directed Utilization of Forest Genetic Resources and numerous chapters in national and international books published by Springer and CRC Press and is one of three editors of book "Forests of Southeast Europe under a Changing Climate: Conservation of Genetic Resources", published by Springer. She is national coordinator for Serbia in EUFORGEN.

Lorenzo Vietto is an agronomist and researcher at the Poplar Research Institute since 1996. Field of interest: coordinator for the poplar breeding and clonal selection program (veneer production, biomass, phytoremediation), conservation and characterization of poplar and willow genetic resources, river restoration activities, sustainable forestry management and environmental certification of poplar stands. He has been member of the P. nigra Network and of the Scattered Broadleaves Network (EUFORGEN Program). Technical Secretary of the Working Party ‘Nomenclature, Taxonomy and Registration (International Commission on Poplar and Other Fast-Growing Tree, FAO)

Marc Villar is Research Director at INRAE BioForA Research Unit in Orléans, France. He is in charge of the national programme of the conservation of genetic resources of the riparian tree Populus nigra L. In this context, his research activities focus on the study of genetic diversity at the national and local scales, of the impact of the environment (sediment texture, temperature, water resources) on the regeneration success and of the ecology of the riparian forest.

Petar Zhelev is a Professor of Forest genetics in the University of Forestry in Sofia, Bulgaria. His research interests and achievements encompass much broader area and include population genetics, biodiversity conservation (incl. gene conservation of plant and animal species), tree breeding, botany and dendrology. He served as a member of the COST Domain Committee (FPS) from 2006 to 2014 and chaired the international Group of Experts “Climate change and biodiversity”, affiliated with the Bern Convention, from 2010 to 2012.

Patricia María Rodríguez-González develops her research activity on riparian and wetland ecology, including characterization, modelling, assessment and monitoring of riparian vegetation. Along with research in the Forest Research Centre of the School of Agriculture (University of Lisbon), she collaborates with public administration in policy implementation (WFD, Habitat, Ramsar), in riparian vegetation management and restoration and best practices dissemination being co-Chair of CONVERGES COST Action and co-coordinator of the Portuguese Network of Ecological Restoration.

SUPPORTING INFORMATION

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

How to cite this article: Alimpić, F., Milovanović, J., Pielech, R., Hinkov, G., Jansson, R., Dufour, S., Beza, M., Bilir, N., del Blanco, L. S., Božič, G., Bruno, D., Chiarabaglio, P. M., Doncheva, N., Gültekin, Y. S., Ivanković, M., Kelly-Quinn, M., La Porta, N., Nonić, M., Notivol, E. ... Rodríguez-González, P. M. (2022). The status and role of genetic diversity of trees for the conservation and management of riparian ecosystems: A European experts' perspective. *Journal of Applied Ecology*, *59*, 2476–2485. https://doi.org/10.1111/1365-2664.14247