BRINGING THE MARGIN TO THE FOCUS: 10 CHALLENGES FOR RIPARIAN VEGETATION SCIENCE AND MANAGEMENT

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Abstract

Riparian zones are the paragon of transitional ecosystems, providing critical habitat and ecosystem services that are especially threatened by global change. Following consultation with experts, 10 key challenges were identified to be addressed for riparian vegetation science and management improvement: 1) Create a distinct scientific community by establishing stronger bridges between disciplines; 2) Make riparian vegetation more visible and appreciated in society and policies; 3) Improve knowledge regarding biodiversity - ecosystem functioning links; 4) Manage spatial scale and context-based issues; 5) Improve knowledge on social dimensions of riparian vegetation; 6) Anticipate responses to emergent issues and future trajectories; 7) Enhance tools to quantify and prioritize ecosystem services; 8) Improve numerical modeling and simulation tools; 9) Calibrate methods and increase data availability for better indicators and monitoring practices and transferability; 10) Undertake scientific validation of best management practices. These challenges are discussed and critiqued here, to guide future research into riparian vegetation.

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1. Introduction

Riparian ecosystems encompass the physical environment and biological communities of the inland-freshwater interface and are recognized as highly diverse relative to surrounding areas . They contain specialist ecological communities and provide crucial ecosystem services while occupying a relatively small landscape area (Sabo *et al*. 2005; Riis *et al.* 2020,). Riparian vegetation in particular is critical to the structure and function of streamside and aquatic ecosystems, yet it is often underemphasized in science and management in favour of abiotic processes (e.g. hydrology, channel and sediment dynamics) and other biotic communities of concern (e.g. aquatic species and food webs).

Throughout history, riparian areas have been subjected to multiple pressures and have consequently experienced widespread degradation (MEA 2005; Stella and Bendix 2019). Ecological restoration of riparian ecosystems is therefore increasingly recognized as essential to mitigate multiple environmental pressures. The protection and restoration of these transitional socio-ecosystems (see for example European Biodiversity Strategy to 2030) represent an effective way, in both monetary and spatial terms, of synergistically addressing international ambitions. For instance, functional riparian zones increase biodiversity, carbon storage, and freshwater system resilience to climate change and associated hydrological impacts (e.g. Dybala *et al.* 2018). At the global scale, protecting and restoring the functionality of riparian ecosystems thus contributes to several United Nations (UN) Sustainable Development Goals (e.g. SDG 6 "Clean water and sanitation"; 15, "Life on Land") and the UN Decade on Ecosystem Restoration 2021-2030. This also contributes to transnational, national, and regional initiatives and policies (e.g. the European Green Deal or EU Water Framework Directive (WFD), the Australian Murray-Darling Plan and various US legal frameworks including the Federal Clean Water Act and Endangered Species Act, inter-state river basin commissions, multistate river compacts, and state and regional regulations). Recognizing the importance of riparian ecosystems has resulted in much research worldwide, notably focused on riparian vegetation (Gregory *et al.* 1991; Naiman *et al.* 2005). Indeed, riparian vegetation properties provide useful information on underlying processes and regular robust quantitative monitoring could provide a reliable basis to understand and track the condition of the fluvial system (González del Tánago *et al.* 2021). Despite research effort and policy motivation, progress in improving the condition of riparian vegetation varies greatly among basins, regions, and countries and, in many cases, it remains limited (e.g. EEA 2020). The goal of this paper is to compile a synthesis of the current main challenges and potential solutions to advance progress in riparian vegetation research and management.

2. IDENTIFYING THE CHALLENGES

To identify the main challenges for riparian vegetation science and management, we mobilized the COST Action CONVERGES, which is a large international collaboration funded by the EU. This network, launched in 2017, brings together the diverse body of knowledge that exists across Europe and beyond on all aspects of riparian vegetation, from physical and biological processes to applied issues, including management and restoration practices. Currently, it consists of about 200 expert members from 39 countries, and covers a large range of academic disciplines such as biological sciences, earth and related environmental sciences, agriculture, forestry, aquatic ecology, fisheries sciences, environmental engineering, and social sciences. In this paper, we gathered the main outputs generated by three CONVERGES working groups which include discussion meetings, status reports, and scientific articles (see: www.converges.eu). In addition, we conducted an online survey from 10th to 20th March 2021 using the Google Forms tool with two open questions (ie "What are the 3 main challenges to enhance riparian vegetation (A) science and (B) management and policies?"), which participants could concisely answer with a maximum of 150 words each. Contributions were requested from all 200 members of the CONVERGES network. We received 62 responses for both questions from 33 countries in various geographical contexts, with at least five answers for each European region (i.e. Balkan Peninsula, Central Europe, Eastern Europe, Scandinavia, Southern Europe, and Western Europe) and four answers outside Europe (Australia, USA, and two from Turkey). Due to the composition of the network, the European region was over-represented. This inevitable geographical bias, which has already been highlighted by other studies (Dufour *et al*. 2019), is a challenge that is also discussed in the present review (see Challenge 4). We analyzed responses qualitatively using a coding approach (Kuckartz 2014) which includes: (1) reading the answers; (2) identifying repeating categories; (3) tagging and counting the frequency of these repeating answers; and (4) second reading of the answers to merge and/or to split the categories if necessary. This resulted in a list of categories for each question (Figure 1). Following this, the answers were clustered by challenges based on our expertise with no presupposed fixed number of challenges, The analysis showed that some challenges were mainly related to the "science" dimension, some to the "management" dimension and some appeared to belongito both dimension, so it was decided to group them in 3 main themes to provide a more pedagogical overview (Figure 2). At last, the first two identified challenges related to the need for unifying the field of research, and the associated epistemic community (i.e. a network of professionals with recognized expertise and competence and an authoritative claim to policy-relevant knowledge; Haas 1992) as a crucial initial step to make riparian vegetation more visible and to tackle the other challenges. We grouped these two challenges under the theme "Reinforcing a transdisciplinary field of knowledge". Challenges 3 to 6 were related with several issues at the frontiers of science and to a holistic consideration of riparian vegetation as a highly dynamic component co-constructed by biophysical and social processes, and as a part of living environments influencing and influenced by humans. These four challenges were grouped under the theme "Progressing scientific knowledge on riparian vegetation understanding". The last group of challenges related to relationships between science and environmental management. There is a long tradition in riparian vegetation studies considering applied issues but improvement is needed. These challenges were grouped under the theme "Aligning riparian vegetation science with management demands".

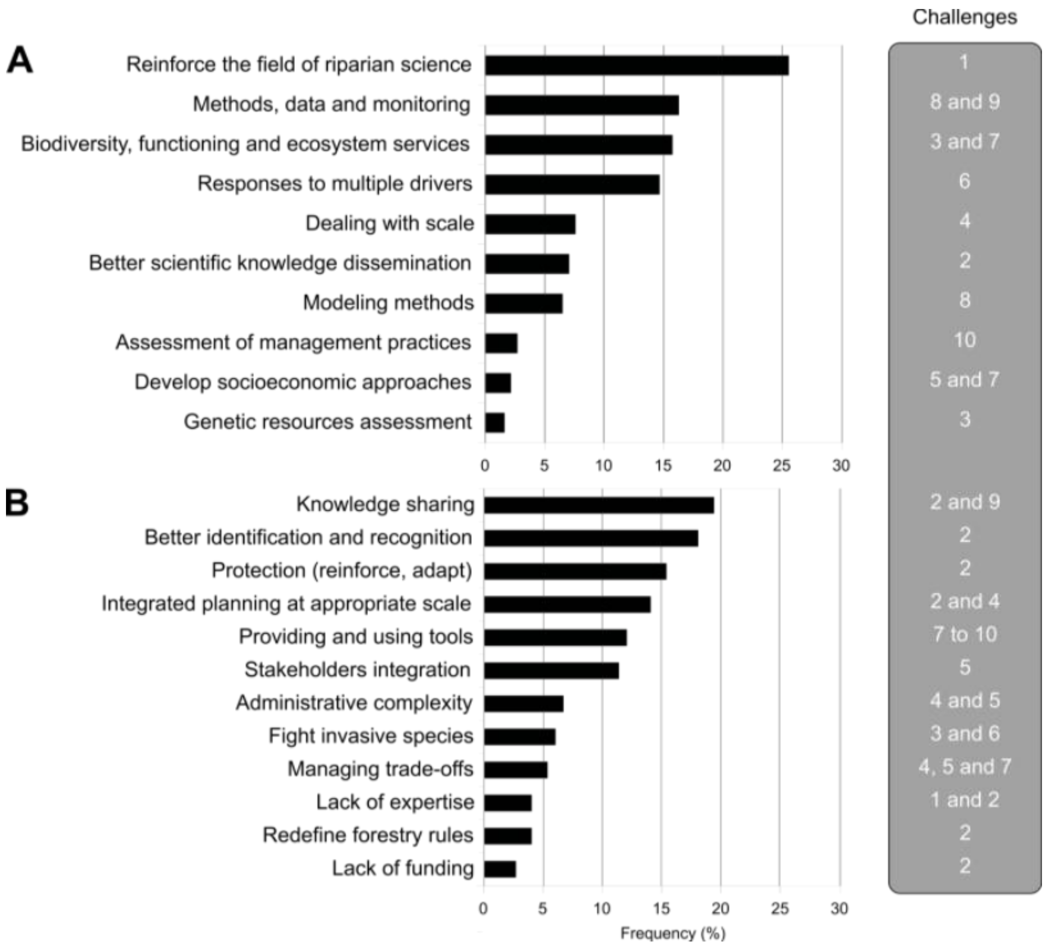

Figure 1. Main answers to the questions "What are the 3 main challenges to enhance riparian vegetation (A) science and (B) management and policies?" Frequency calculated based on the 62 responses to the online questionnaire launched in the CONVERGES network. The column "challenges" indicate to which one each answer belongs.

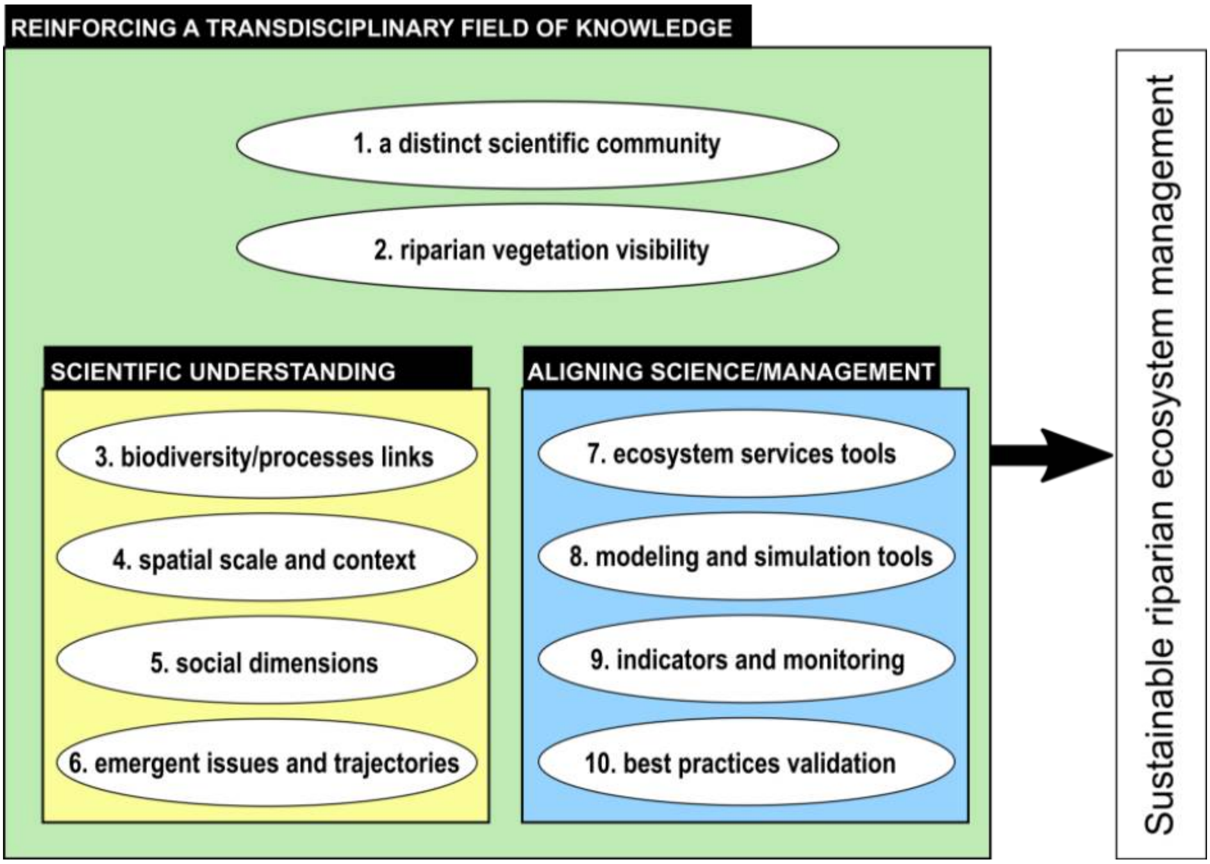

Figure 2 : Main challenges to enhance riparian vegetation science and management.

3. Reinforcing a transdisciplinary field of knowledge

3.1 Challenge 1: Bring to life a distinct scientific community

In spite of numerous scientific studies and reviews dedicated to riparian vegetation (e.g. Stella et al. 2013; González et al. 2015; Riis et al. 2020), Dufour et al. (2019) showed the lack of a united and well-identified worldwide scientific community focusing on riparian vegetation (eg with specific conferences and/or dedicated journals). This is probably due to its transitional nature : riparian vegetation is part of a dynamic interface system influenced by the river channel, the groundwater, the surrounding area, the upstream catchment, and the atmosphere (Petts and Amoros 1996). Thus, it has been investigated so far by diverse fields of (applied) science (e.g. hydrogeomorphology, hydraulics, ecology, agriculture, forestry, water management, landscape planning, restoration) and, more recently through, interdisciplinary scientific approaches (e.g. biogeomorphological studies).

The role of riparian zones in biogeochemical cycling (Dosskey et al. 2010), the effect of riparian vegetation on flood risk (e.g. Darby 1999) or biotic issues, such as genetic resources management or plant pathogen-related problems (Bjelke et al. 2016), provide good examples of the scattered nature of scientific works. In these three cases, much of the work, while often extremely specialized, does not integrate the complexity of the riparian vegetation patterns and functioning. It is not a question of the quality and relevance of studies, but rather that they are carried out independently without effective integration across disciplines. Given the multifaceted nature of riparian vegetation, and its connections with physical processes and society, these research lines would benefit from more collaboration within the biophysical and engineering disciplines, and strengthened even more by incorporating social sciences. This is crucial not only for a better understanding of riparian ecosystem functioning but also for management issues, given that riparian zones are often an area of conflicting interests (Arnold et al. 2012). Indeed, riparian vegetation conservation has been in permanent conflict with water resources management (e.g., flood protection, dam and reservoir operation, groundwater overexploitation) and floodplain land use change (e.g., urbanization, agriculture, commercial forestry).

The study of riverine ecosystems requires some level of interdisciplinary knowledge as the components of riparian, aquatic and terrestrial ecosystems are interdependent. The efforts made in recent decades to integrate scientific disciplines should be continued by encouraging transdisciplinary networking activities: (1) dedicated support of publication (e.g. specific journal); (2) the creation of specific sections in scientific associations; and (3) creation of a global riparian expert network with a good representation of disciplines, bioclimatic regions, and perspectives.

3.2 Challenge 2: Increase riparian vegetation visibility and emphasis in society and policies

From a broader perspective, riparian vegetation ecosystems are not well known, understood or appreciated by the general public. Like many "non-charismatic" plant species, riparian areas do not benefit from specific visibility as is the case for emblematic animal species (e.g. charismatic megafauna) or ecosystems (e.g. tropical forests, coral reefs) (Allen 2003). The scientific community fails to provide enough evidence or examples for effective communication about, for instance, how riparian vegetation protection and restoration can explicitly help vulnerable regions and communities to improve their resilience in response to rapid changes in climate and environment, economies, and social conditions. This low profile has tangible impacts because it hampers the mobilization of stakeholders (including general public and policymakers) and resources (i.e. funds). Thus, in some regions or countries, riparian vegetation is not identified in related environmental policies. For example, in Europe, the WFD does not explicitly mention it as a core element for the ecological status designation of rivers and thus its monitoring and assessment are not mandatory (González del Tánago et al. 2021). In the United States, federal environmental laws that mandate delineation of wetlands, stream water quality protection, and conservation of endangered species within river corridors do not specifically cover the riparian vegetation communities that support them, nor do they require their assessment and monitoring (Opperman et al. 2017). Nevertheless, several countries and regions have included riparian vegetation in their official or routine assessment protocols, as is the case of South Africa and South Korea (Feio et al. 2021).

The visibility and priority of riparian vegetation in environmental conservation policy and practice can be rectified by putting more effort in communication towards different public audiences, through more diverse channels (e.g. school and university, local newspapers, stakeholder meetings, NGO campaigns and professional communication training for river managers) and emphasizing all the different forms of traditional knowledge (González et al. 2017). Communication should concern both the values (e.g. using the Ecosystem Services (ES) approach, including influence on water quality or flood risk), and the biodiversity of riparian vegetation in ways that are recognized and appreciated by a broad audience. Additionally, enlarging the role of citizens in riparian monitoring and management would increase their awareness and ecological knowledge about the importance of riparian vegetation, best-management practices, and protection needs. Updating policies with a more explicit integration of riparian vegetation, notably in rural and urban planning regulations, is also needed (as found in the riparian strategy of Calgary, Canada, https://www.calgary.ca/uep/water/watersheds-and-rivers/riparian-areas.html). Legislation should include the multiple ecological functions and services that riparian vegetation provides in order to enable management approaches beyond merely protection from flooding.

4. Progressing scientific knowledge on riparian vegetation understanding4.1 Challenge 3: Improve our understanding of biodiversity - ecosystem processes links

This challenge embraces at least four issues. First, the need for better integration of the different levels of biodiversity beyond the species approach is especially crucial in riparian ecosystems (i.e. genetic, functional and landscape diversity). For example, in terms of the sex structure in the common, dominant dioecious riparian taxa (e.g. Salicaceae), further understanding of the differentiation of male and female roles at community and ecosystem levels is required. Also, the pool of genetic diversity within riparian ecosystems urgently requires more research, both theoretical (e.g. specificity of gene flow processes), and applied (e.g. genetic considerations in riparian restoration and conservation) (Whitham *et al.* 2006). Second, the development of geographically generalizable riparian functional-trait approaches should be accelerated toward a more mechanistic and regionally independent understanding of the community assembly processes (e.g. Merritt *et al.* 2010; O'Hare *et al.* 2016; Aguiar *et al.* 2018). Such an approach would help to establish the functional linkages between plant trait selection, phenotypic plasticity, and community assemblages that drive riparian ecosystem dynamics. The third issue involves achieving a better understanding of the influence that regeneration and persistence strategies of riparian plants may have on the formation of riparian corridors (e.g. modality of propagule dispersal; biomechanical tolerance and avoidance traits; physiological resistance to submersion or drought; Bornette *et al.* 2008). The formalization of a biogeomorphological paradigm has already recognized the active role of plants in fluvial-vegetation interactions (Corenblit *et al.* 2015) but the ecological processes have not been fully described in systems exposed to multiple stressors (e.g. Stella and Bendix 2019). The fourth issue relates to the need to improve our knowledge of plant interactions and the links between vegetation and other biota occurring in the riparian zone (e.g. microbiota and animals), as well as less-studied abiotic factors (e.g. links with groundwater hydrology). Indeed, in a restoration context, the focus should be not only the plant community but also their associated microbiome, crucial for an integral restoration of structure and processes (Koziol *et al.* 2018).

4.2 Challenge 4: Manage spatial scale and context-based issues in research

Traditionally, a large part of riparian vegetation science is based on reach-scale studies of a limited number of sites and contexts (e.g. Bendix and Stella 2013; González et al. 2015), which hinders upscaling and the application of well-informed, context-specific measures. There is overwhelming empirical evidence of the positive effects of riparian buffers at the reach scale on functions such as retention of pollutants, shading effects on water temperature, primary production, river morphology, inputs of organic material (leaves, large wood), and habitat for terrestrial species (Sweeney and Newbold 2014). However, more studies at the river-network or catchment scale are needed to assess if and how local reach-scale effects can be upscaled, especially because there is some indication that confounding stressors including catchment land use, impoundments or tile drainage may limit the effect of riparian buffers at larger scales (Marteau et al. 2022). This is of vital importance because current challenges in protecting the world's freshwater resources include establishing the feasibility and justification for broad-scale protection and restoration measures. For example, the EU Biodiversity Strategy for 2030 aims to restore at least 25,000 km of rivers and plant more than 3 billion trees. The success of such strategies depends on the ability to implement local restoration measures but also to assess the cumulative effects at larger spatial scales.

Furthermore, research results indicate that the functions of riparian vegetation listed above are context-specific and depend on vegetation and river characteristics as well as nature and intensity of stressor conditions. Vegetation characteristics including vegetation type (herbaceous, shrubs, trees) and stock age influence the retention of pollutants and shading effects. Furthermore, functions depend on river characteristics (eg shading effects are higher in small streams at low discharges). Moreover, the relative importance of the different functions depends on the specific stressor conditions (e.g. solubility of specific pesticides applied) and future climate change (e.g. increasing importance of shading in regions with high temperature increase). Most studies have been conducted in highly degraded small streams in temperate forested ecoregions. Specifically, comparative studies are scarce but are needed to better understand how the functions of riparian vegetation differ between ecoregions, river types and under different stressor conditions (Bendix and Stella 2013).

4.3 Challenge 5: Improve knowledge on the social dimensions of riparian vegetation

While the main levers to improve riparian vegetation management are socio-economic (e.g. Sher et al. 2020), the social dimensions are largely absent in the scientific literature (Dufour et al. 2019). The recent efforts to analyze riparian vegetation services partially address this gap, however, it is symptomatic of the naive way the scientific community considers social issues since, for example, cultural ecosystem services are not systematically assessed in detail (Riis et al. 2020). Thus, the social dimensions need further investigation, including legal, cultural, political, economic, and psychological issues (among others). Riparian vegetation is not only shaped by direct and indirect human drivers, it also contributes to the sense of place for people (Masterson et al. 2017). Thus, an appropriate understanding of local people's perceptions, roles, values, needs and interests and an effective engagement with them are needed for real integrative management (Fliervoet et al. 2016). For example, we need to identify who are the stakeholders, and what are their stakes; what are the balances of power and interests; how does this vary and what are the factors of influence? This challenge includes a deeper reflection on how to study those social elements (e.g. which indicators, which methods) but also on the nature of the knowledge and practices that drive riparian vegetation use, management and understanding, as well as gaps between the expectations of managers and the scientific vision, place given to traditional knowledges and other ontologies (more broadly to the decolonisation of ideas), etc. (e.g. Parsons et al., 2021). This challenge can be considered part of Challenge 1 but is worthy of its own place because the lack of specific knowledge of the social dimensions of riparian vegetation is much higher than any other scientific field.

4.4 Challenge 6: Anticipate responses to emergent issues and future trajectories

There is a need to incorporate a trajectory paradigm in forecasting riparian changes (Hughes et al. 2005, Wohl 2019). Global environmental changes present a considerable challenge for predicting riparian vegetation responses, assessing future responses, and thus, informing sustainable management. This challenge includes an accelerated velocity of environmental transformation that is already affecting both the nature and the intensity of interactions among the multiple stressors (Stella and Bendix 2019). For example, flow regulation is a major stressor along many rivers (Stella et al. 2010; Tonkin et al. 2018; Belletti et al. 2021) and a good understanding of associated processes is crucial to develop realistic environmental flows and restoration strategies (González et al 2018). Biotic threats include invasive species, pests and diseases (Hobbs 2000). Many studies have shown that riparian ecosystems are especially prone to biological invasions (Pyšek et al. 2010). The strategies, methodologies and techniques to prevent, eradicate, limit, or manage the spreading of these species, as well as emerging diseases (Bjelke et al. 2016), should integrate a clear understanding of the expected effects on future ecosystems. Despite recurrent calls for holistic and integrated management, this has seldom been realized and many riparian restoration projects across the world address a single driver, hampering the assessment of their transferability in a multi-pressures context. Longer-term monitoring and research projects collecting empirical data over decades (e.g. using Long-Term Ecosystem Research sites) are required to capture such interactions and provide the data to inform and validate modeling and management approaches.

5. Aligning riparian vegetation science with management demands

5.1 Challenge 7: Enhance tools to quantify and prioritize ecosystem services

Many ecological functions and ecosystem services are recognized for riparian vegetation, yet their quantification and prioritization have not been fully achieved (Hanna et al. 2018). Research is needed on qualitative environmental value assessment, quantification of service supply, and economic impact analysis of service use, maintenance, and conservation in different management scenarios (e.g. Dybala et al. 2019). A recent review identified the existence of understudied ecosystem services and the lack of a ranking among them across key riparian vegetation types as major research gaps (Riis et al. 2020). General issues related to all ecosystem services remain to be addressed including scale of analysis, spatial lags between service supply and demand, and synergies and trade-offs among services and disservices (Van Looy et al. 2013, Hanna et al. 2018). For example, how much area of forested banks is needed for effectively influencing temperature balance or ecological quality, and where in the catchment? (see Challenge 4) (Kail et al. 2020).

Providing key indicators for all the riparian ecosystem services and setting up open databases and toolboxes on ecosystem services measurements and values could be the first steps to address this challenge (e.g. the river ecosystem service index (RESI), Stammel et al. 2020). In addition, since certain types of ecosystem services have been less covered, their valuation may need to be revisited in a post-pandemic society as we still need to understand potential changes in social perception of natural systems.

5.2 Challenge 8: Improve numerical modeling and simulation tools

Despite great progress in modeling and simulation tools in general, reliable modeling of riparian processes is still needed. We need to realistically consider the complexity of riparian vegetation processes interacting with for example hydrogeomorphological components (Camporeale et al. 2013; Politti et al. 2017), notably over long-time scales. General modeling challenges involve: 1) illuminating long-term processes, with enough detailed resolution to properly model riparian ecosystem trajectories; 2) anticipating critical thresholds and tipping points leading to irreversible and undesirable ecosystem functioning; and 3) incorporating the interactive effects of multiple stressors. Specific limitations of riparian vegetation modeling include data input requirements, (linked with the need of large and high-quality empirical datasets). This involves fostering the collection (which requires funding) and sharing of data to determine the biological parameters of models. Other specific limitations include the transfer to practice of the theoretical understanding of dynamic processes. Building models to quantify socio-ecological interactions that accommodate differences in spatio-temporal scales in the expression of each driver and response is important for integrating our understanding of riparian systems trajectories. For example, floods may operate over minutes or hours, vegetation may change over months or decades, changes to river morphology, while event-driven, can be observed over periods of several years to decades, and management actions have their own timeframes for planning and implementation.

5.3 Challenge 9. Calibrate and standardize methods and manage data availability for better indicators and monitoring practices

The high context dependence of riparian processes highlights two key objectives to application of theoretical knowledge in management and conservation. First, to develop replicable indicators and standardized methods, and second, to make the data and methods available for researchers and practitioners elsewhere. To address this, we should develop multi-scale protocols to assess riparian vegetation at various scales with taxonomical, functional, and landscape attributes, as well as tools and models to predict riparian vegetation responses (Rohde et al. 2021). It would also be necessary to promote the integration of riparian vegetation in mandatory river status assessments (González del Tánago et al. 2021). Standardization methods should include the definition of riparian vegetation reference conditions according to biophysical and social driver typologies. This challenge also implies better international coordination in common definitions and data collection techniques, so that information can be integrated and studies compared (e.g. in meta-analyses). This is particularly relevant for the development of large datasets coming from remote sensing tools, low-cost sensor networks, and citizen science (eg Huylenbroeck et al. 2020). After standard practices are identified, developing the proper channels to share data, making databases interoperable, and establishing assessment and monitoring protocols are crucial in order to complete the knowledge production cycle. Even for existing knowledge, public databases are often scattered across states, regional and subregional organizations, and they are thus hard to find, are incompatible and valuable knowledge may be lost with frequent staff turnover.

5.4 Challenge 10. Validate best management practices

Finally, evidence-based decision making needs to be promoted to avoid the persistence of “business as usual” in riparian management. Quantitative and reliable methods are required to validate best practices and assess their effects. This is crucial in facing global changes in a context of adaptation to future uncertain conditions. This issue includes a dynamic vision of how riparian vegetation is currently providing ecosystem services, and how this will change under various management and climatic scenarios. Moreover, many mainstream practices need to be reconsidered in light of recent scientific progress. For example, the common approach of planting trees in river margins to restore riparian systems needs to be framed in the context of the relevance for that kind of strategy (González et al. 2018). It should be preceded by a reliable assessment of pressures, and informed by reliable genetic considerations, ecological and hydromorphological criteria, and coordination with measures to prevent the spread of infections or invasive species, e.g. through nurseries (Jung et al. 2016). More effective ways to reinforce knowledge transfer from the scientific community to managers and stakeholders can be developed, such as demonstration projects or early-stage collaboration in practical applications. Promoting such a transdisciplinary approach implies society involvement and, for the academic community, a reflective approach for conducting science embedded within society (Rigolot 2020).

CONCLUSION: REALLY RECOGNIZE RIPARIAN ZONES AS CO-CONSTRUCTED SOCIO-ECOLOGICAL SYSTEMS

Enhancing riparian vegetation science, and thus its management, requires further scientific research, but also reducing the wide geographical dispersion and heterogeneity of current knowledge, policies, and management practices across countries with different environmental and socio-ecological contexts. In many regions, riparian vegetation remains marginal in environmental policies, and management tends to focus on the control of riparian vegetation rather than creating appropriate levels of functioning, in contrast to other contexts (e.g. rainforests, marine protected areas) where assessment tools and stakeholder mobilization appears to be more advanced. Thus, the communication and sharing of knowledge among stakeholders (including academics, managers and practitioners) and with society need to be substantially improved. This win-win approach will benefit the integrated conservation and restoration of riparian ecosystems and the sustainability of the many ecosystem services provided to people into the future.

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