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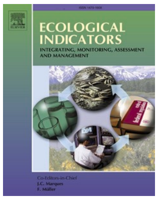

Review

Freshwater riparian zones in a changing climate: A comprehensive review

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ABSTRACT

Riparian zones, the transitional areas between aquatic and terrestrial environments, are vital for supporting biodiversity and maintaining ecosystem health. However, their functionality is being increasingly threatened by climate change. This study systematically reviews recent research published between 2000 and 2023 to evaluate the response of riparian zones to future climate change, following the PRISMA guidelines. The review comprehensively investigates how various aspects of freshwater riparian zones, including hydrology, water and soil quality, morphology, and ecology are impacted by future climate change. The results highlight the variability of climate change impacts on these aspects, with the direction and magnitude of changes differing based on study sites, climate scenarios, and management actions. Moreover, the findings underscore the need to incorporate climate change projections into riparian management, conservation, and restoration to ensure the long-term sustainability of these critical ecosystems. Adaptive management, which integrates future climate projections, enables more resilient restoration efforts, ensuring that riparian zones continue to deliver essential ecosystem services despite increasing climate variability and instability. Finally, the outcomes indicate that integrating riparian maintenance and restoration with supplementary management measures across watersheds may optimize the long-term benefits of riparian zones.

1. Introduction

Riparian zones, which are transitional areas between terrestrial lands and water bodies such as rivers, lakes, and estuaries (Oakley et al., 1985), play a key role in providing and enhancing a broad array of ecosystem services, thereby improving human well-being (Cole et al., 2020; Graziano et al., 2022; Hanna et al., 2020; Stutter et al., 2021). Such benefits encompass biodiversity conservation and habitat connectivity (Maestas et al., 2023; Singh et al., 2021; Zhang et al., 2023), the enhancement of water quality through the interception of nutrients, sediments, and contaminants, as well as erosion control via riverbank stabilization (Cole et al., 2020; Huang et al., 2019; Zaimes et al., 2011a; Zaimes & Schultz, 2012), and the provision of recreational opportunities (Burdon et al., 2020; Hanna et al., 2020). Furthermore, riparian buffers help to build resilience to climate change, a growing global concern, by providing shade, improving water retention, mitigating floods, sequestering carbon, and regulating water temperature (Cole et al., 2020; Huang et al., 2019; Knouft et al., 2021).

Nonetheless, studies highlight that changes in temperature, precipitation, hydrological patterns, and extreme weather events driven by climate change can affect riparian zones. These changes may influence their hydrology, biodiversity, and essential functions and services (Gentilin-Avanci et al., 2022; Latella et al., 2020; Rincón et al., 2022). Increasing air temperatures, for example, can raise stream water temperature and lower dissolved oxygen levels, thereby threatening aquatic communities (Fullerton et al., 2022; Spanjer et al., 2022; Zhai et al., 2023). Fluctuations in flow rates, intense flooding, and prolonged droughts can disrupt natural processes such as water flow, nutrient filtering, and sediment transport. These disruptions can result in severe riverbank erosion, increased pollution, degradation of riparian habitat, and loss of biodiversity within riparian zones (Mullan et al., 2016; Van Looy & Piffady, 2017; Wu et al., 2021). Moreover, climate change may exacerbate the susceptibility of riparian zones to the spread of invasive species, while native species decline. This further diminishes biodiversity and reduces the capacity of riparian zones to provide essential ecosystem services such as pollutant filtration and habitat provision (Gillard et al., 2017; Mtengwana et al., 2021).

Several excellent literature reviews have addressed different aspects of riparian zones, including the functions and benefits of riparian buffers, the threats and challenges impacting their effectiveness, and the

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synergies and trade-offs between ecosystem services and riparian management and conservation (Cole et al., 2020; Graziano et al., 2022; Singh et al., 2021; Vidon et al., 2019; Zaimes et al., 2011b). In addition to highlighting the ecological and socio-ecological functions of riparian zones, examining major human impacts, and reviewing key management policies and regulations, Majumdar & Avishek (2023) provided a comprehensive review of studies employing field-based, geospatial, and other monitoring techniques. They reported that the limitations of field-based monitoring methods can be overcome by using geospatial technologies. Stutter et al. (2021) examined the use of spatial datasets to represent riparian functions, delineate them across rivers, and evaluate their application in enhancing or restoring riparian functions for more effective management. Zaimes (2020) reviewed the vulnerability of Mediterranean riparian areas to climate change and anthropogenic activities, emphasizing the need for ecosystem-based strategies for their sustainable management. Through a *meta*-analysis of scientific studies on buffer zones, Lind et al. (2019) introduced the "step-by-step Ecologically Functional Riparian Zones (ERZ) framework" to optimize riparian buffer widths for supporting diverse ecosystem functions and biodiversity goals in agricultural landscapes. Vesipa et al. (2017) reviewed research examining the impact of river flow fluctuations on riparian vegetation dynamics. Another thorough review by Perry et al. (2015) discussed the importance of incorporating potential future climate conditions into riparian restoration planning and design. Garssen et al. (2014) conducted a literature survey and *meta*-analysis on riparian zones along lowland streams outside of the tropics and subtropics, aiming to quantify the response of riparian vegetation to summer drought. Other valuable reviews, including those by Capon et al. (2013), Nilsson et al. (2013), and Perry et al. (2012), underscore the vulnerability of riparian ecosystems to climate change across various regions (e.g., dryland western North America and boreal areas), emphasizing the need for adaptive management to sustain their ecological functions and biodiversity.

Even though previous reviews have provided important insights into the impacts of climate change on riparian habitats, a new review is needed to analyze more recent studies and systematically investigate the quantitative responses of riparian zones and their hydrological (e.g., streamflow, water level), biochemical (e.g., temperature, nutrients), and biotic (e.g., habitat abundance and distribution) components to climate change. In particular, it is important to understand the future trajectories of these variables (i.e., whether they are likely to increase or decrease) under climate change. Therefore, the aim of this study is to comprehensively review the expected future response to climate change of different components of riparian zones (including hydrological, water and soil quality, morphological, and ecological). Particular attention is given to studies that assess the potential effectiveness of riparian management practices in delivering ecosystem services under future conditions. Due to the extensive volume of existing literature, it became evident that certain restrictions were required for this review. This review is therefore limited to English-language peer-reviewed research articles that investigate the relationship between freshwater riparian areas and future climate change.

2. Methods

This review is conducted based on the protocol developed by the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) (Page et al., 2021).

2.1. Eligibility criteria

As previously mentioned, the present review is restricted to English-language peer-reviewed research articles published between 2000 and 2023 that explore the interactions between freshwater riparian areas and future climate change. Therefore, non-English studies, review papers, technical reports, academic theses, and conference papers, as well as studies whose primary focus is not relevant to the aim of the present review, such as those that assess non-freshwater riparian areas or those that do not evaluate future climate change are not eligible for this work.

2.2. Information sources, search strategy and duplicates removal

SCOPUS and Web of Science were searched on 22 January 2024 using specified search strings (see Supplement A). A total of 1052 records were identified from these two databases. The corresponding details of these records (e.g., names of authors, the publication year, and the title) were exported into a Microsoft Excel spreadsheet. These records were then screened by the first author of this review (Hamed Vagheei) to identify and remove duplicates. After eliminating duplicates, 692 records remained for further screening to assess their relevance and eligibility (Fig. 1).

2.3. Selection process and data collection

In the selection process, double screening was performed by two authors (Hamed Vagheei and Fulvio Boano) in two stages: title and abstract screening (stage one), followed by full-text screening (stage two), to identify relevant studies based on predefined eligibility criteria.

In stage one, Hamed Vagheei screened the titles and abstracts of all 692 records, while Fulvio Boano reviewed the titles and abstracts of a random sample of records (20 %) to ensure consistency with the predefined eligibility criteria and investigated topics. Records for which the title and abstract did not provide sufficient information were carried over to the next stage (i.e., full-text screening). As a result, 532 records were excluded in the first stage, and 160 records proceeded to full-text screening (i.e., stage two).

In stage two, Hamed Vagheei conducted full-text screening for all 160 records, while Fulvio Boano reviewed full-texts of a random sample of 40 % (64 records). As a result, 61 records were excluded, and 99 relevant studies were included in the review (Baker & Bonar, 2019; Balderacchi et al., 2016; Bertolet et al., 2018; Bestgen et al., 2020; Borgwardt et al., 2020; Botero-Acosta et al., 2018; Buffin-Bélanger et al., 2015; Cao et al., 2016; Carstensen et al., 2023; Cooper et al., 2006; Cristea & Burges, 2010; Crossman et al., 2013; Cubley et al., 2023; Daigneault et al., 2016; de Freitas et al., 2022; Dhyani et al., 2018; Ellis & Eaton, 2021; Fan & Shibata, 2015; Fernandes et al., 2016; Fink & Scheidegger, 2018, 2021; Flanagan et al., 2015; Fossey & Rousseau, 2016b, 2016a; Fuller et al., 2022; Fullerton et al., 2022; Garssen et al., 2017; Gay et al., 2023; Gentilin-Avanci et al., 2022; Ghimire et al., 2021; Gillard et al., 2017; Gold et al., 2011; Ha & Wu, 2017; Holsinger et al., 2014; House et al., 2016; Hoyer & Chang, 2014; Huang et al., 2019; Jansson et al., 2019; Jayakody et al., 2014; Justice et al., 2017; Kasprak et al., 2018; Knouft et al., 2021; Köhler et al., 2009; Kujawa et al., 2022; Latella et al., 2020; Lawrence et al., 2014; Ledesma et al., 2021; Liew et al., 2013; Lupon et al., 2018; Lytle et al., 2017; Lyu et al., 2019; Martínez-Fernández et al., 2018; McKernan et al., 2018; Miyamoto & Kimura, 2016; Moradkhani et al., 2010; Mosner et al., 2015; Mtengwana et al., 2021; Mullan et al., 2016; Murray et al., 2012; Nusslé et al., 2015; Olson & Burton, 2019; Oni et al., 2017; Pastor et al., 2019; Pignalosa et al., 2022; Piniewski et al., 2014; Poblador et al., 2019; Politti et al., 2014; Primack, 2000; Rincón et al., 2022; Rivaes et al., 2013; Rivaes et al., 2014; Rocha et al., 2015; Schönhart et al., 2018; Serrat-Capdevila et al., 2007, 2011; Siqueira et al., 2021; Spanjer et al., 2022; Stark & Fridley, 2022; Stephens et al., 2022; Ström et al., 2011, 2012; Stromberg et al., 2010; Szporak-Wasilewska et al., 2015; Tainio et al., 2016; Thodsen et al., 2016; Thompson et al., 2023; Trimmel et al., 2018; Turschwell et al., 2018; Van Looy & Piffady, 2017; van Oorschot et al., 2018; Wagena & Easton, 2018; Woltemade & Hawkins, 2016; Wondzell et al., 2019; Wooster et al., 2019; Wu et al., 2021; Yi et al., 2016, 2018; Zhai et al., 2023; Zhang et al., 2023).

Once the relevant studies were finalized, the data collection process was initiated. Information such as study area, methodology, and

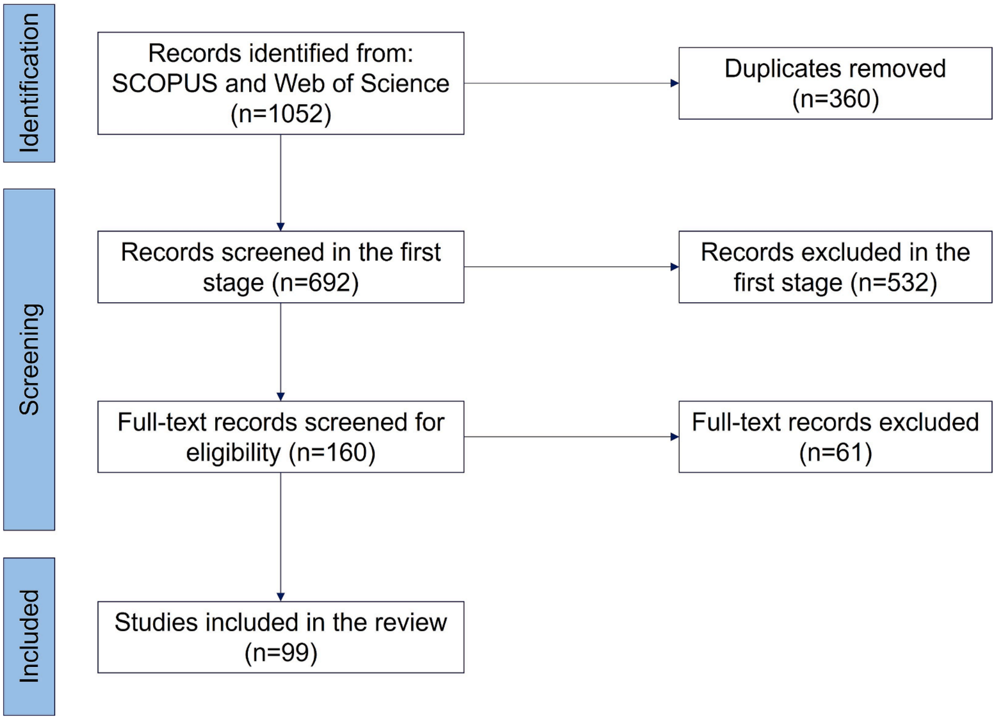

Fig. 1. Flowchart of the systematic review process adopted in this work for identifying studies on freshwater riparian zones and future climate change.

outcomes was extracted from the 99 studies by Hamed Vagheei, with regular monitoring of the collected data by Fulvio Boano.

3. Results and discussion

The data extracted from the 99 relevant studies are presented in a spreadsheet (Supplement B) and will be discussed in the subsequent sections.

3.1. General information

General information on the relevant studies (e.g., titles, publishing journal, year of publication, and keywords) has been summarized and presented in Supplement B (sheet “Study Gen. Inf.”).

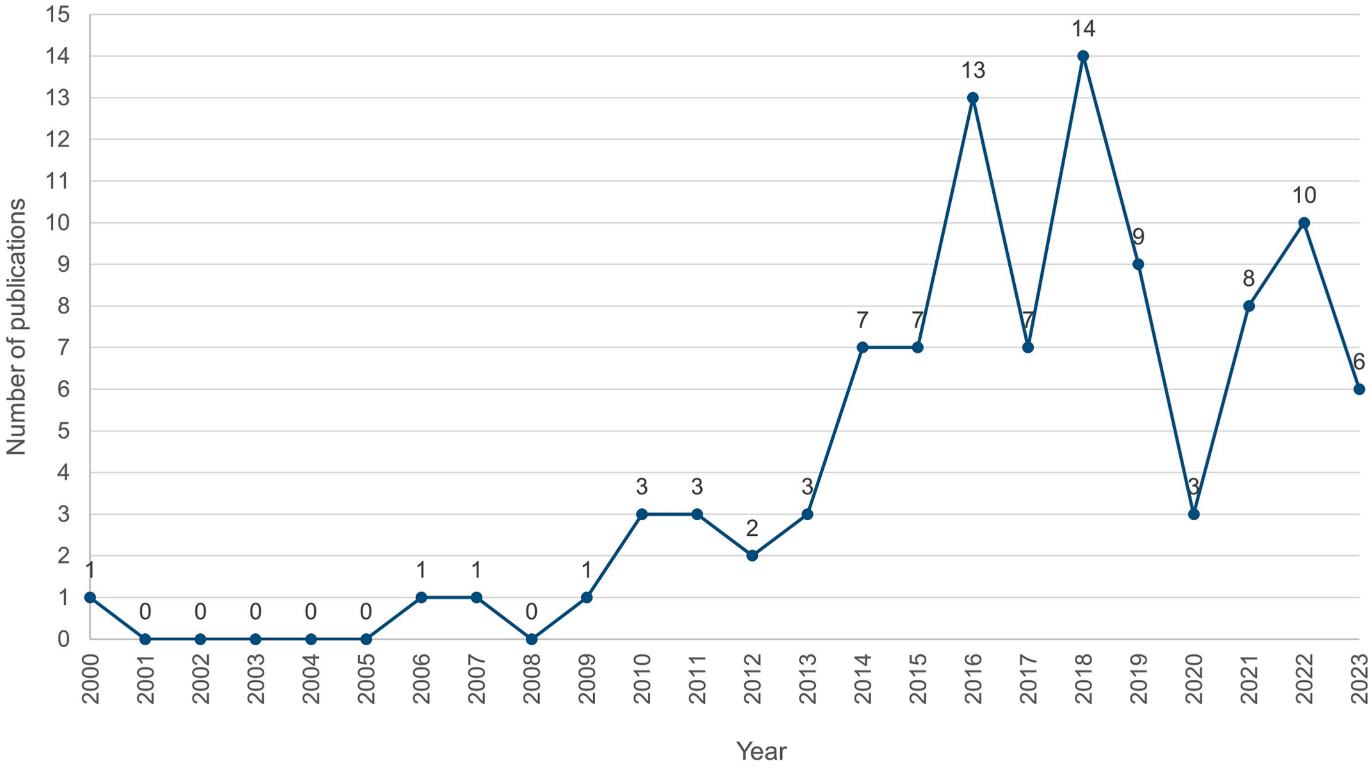

Fig. 2. Temporal distribution of studies included in the review.

The 99 relevant studies were published across 56 journals, with Journal of Hydrology, Science of the Total Environment, and Ecological Applications leading the list, publishing seven, six, and five studies, respectively. As shown in Fig. 2, the majority of these studies were published after 2014, with 2018 seeing the highest number of publications. Subsequently, the rate of publication appears to have stabilized.

The five most frequently used keywords in the relevant literature are climate change (54 occurrences), SWAT (10 occurrences), hydrology (eight occurrences), land use/cover change (eight occurrences), and riparian (six occurrences). Furthermore, the terms modelling, riparian vegetation, and species distribution models each appeared five times. A graphical representation of authors' keywords is provided in Fig. 3.

3.2. Study area

In terms of geographical distribution as depicted in Fig. 4, the majority of studies were conducted in North America and Europe with a share of 46 % and 38 %, respectively. Among the countries, The USA led with 42 studies, followed by Spain with seven, and Austria, Portugal, and Sweden each with five. This distribution reveals a clear geographic imbalance, emphasizing the need for future research to focus on the less investigated regions. Detailed information regarding the study sites for the 99 relevant studies can be found in Supplement B (sheet "Study area").

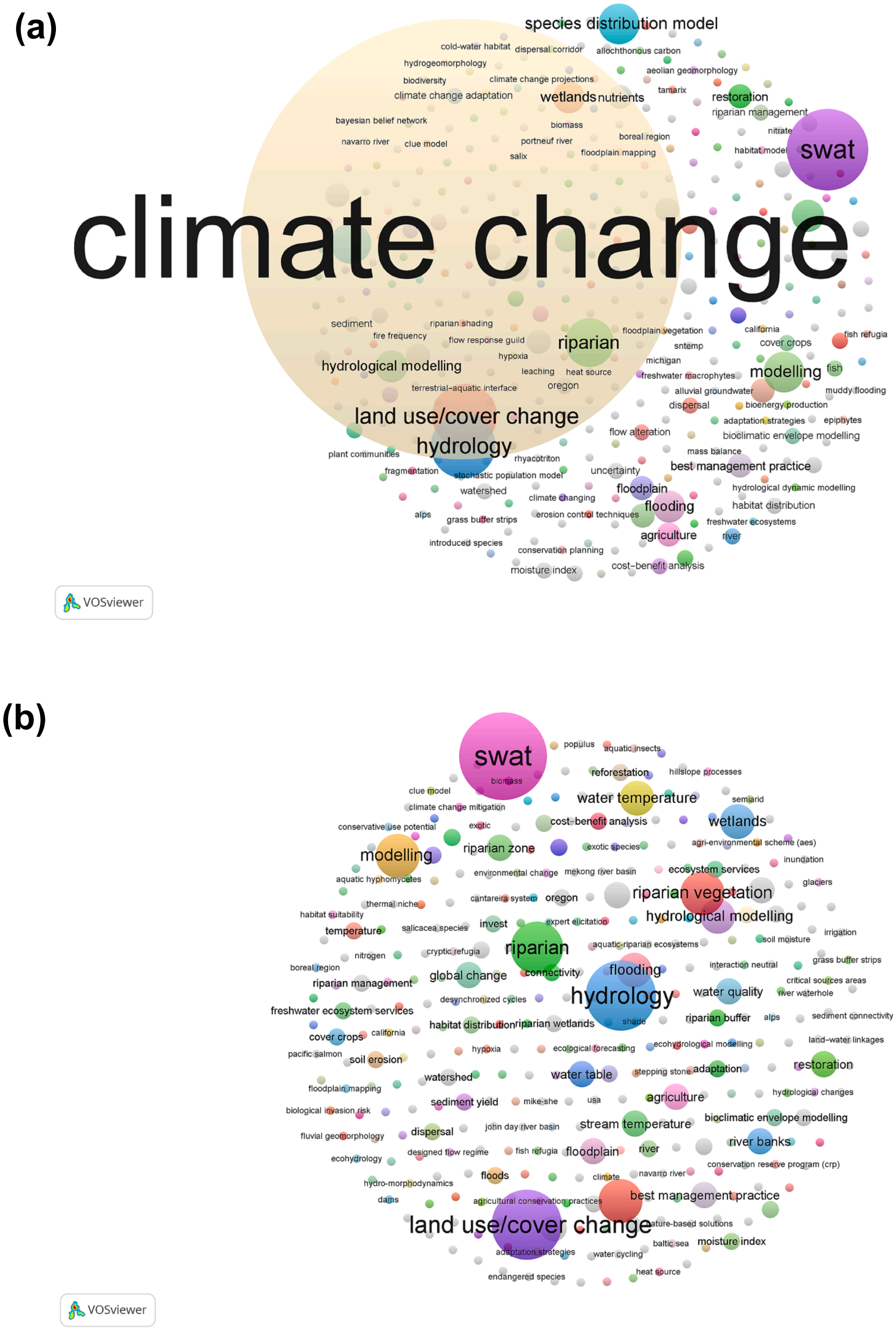

Fig. 3. Graphical analysis of authors' keywords including (a) and excluding "climate change" (b).

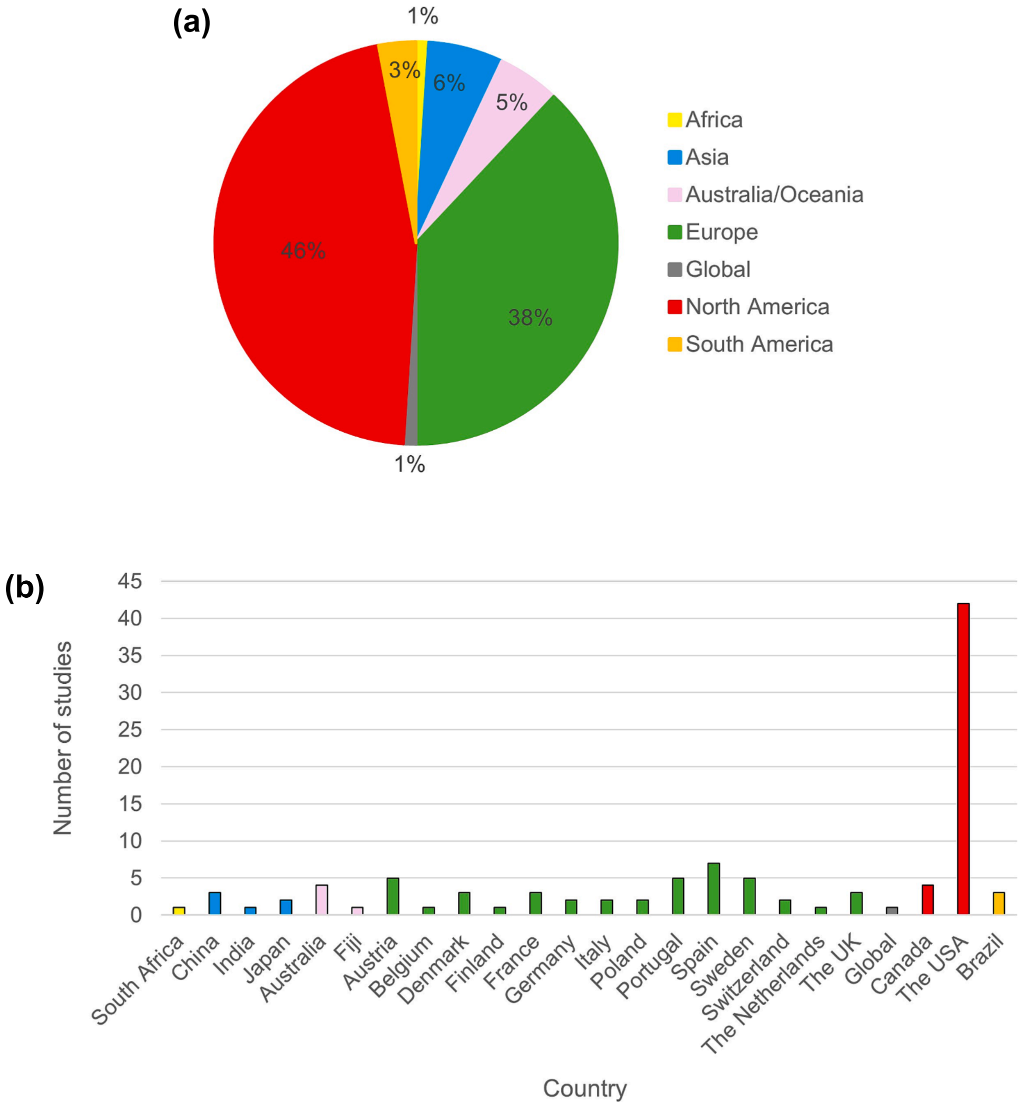

Fig. 4. Geographical distribution of the areas investigated by the selected studies by continent (a) and country (b).

3.3. *Methodological overview of selected studies*

3.3.1. *Study approaches*

The study approach of the relevant studies was assessed: revealing that 66.7 % of the studies relied solely on modeling, while the remaining studies employed a combination of field work and modeling. In the field-based studies (e.g., Baker & Bonar, 2019; Cubley et al., 2023; Ledesma et al., 2021), a range of hydrological, water and soil quality, morphological, and ecological variables were monitored and incorporated into the analysis. Further details on the approach adopted by each study are available in Supplement B (sheet "Study approach").

3.3.2. *Modeling types*

The modeling types employed in the relevant studies were also classified, with numerical emerging as the most prevalent (Fig. 5). Specifically, 44 studies utilized numerical modeling, 29 studies employed statistical modeling, and 4 studies applied analytical modeling. Additionally, 22 out of the 99 studies were based on a combination of different modeling types (see Fig. 5). Detailed information on the types of modeling, including specific tools used in each study, is provided in Supplement B (sheet "Modeling type").

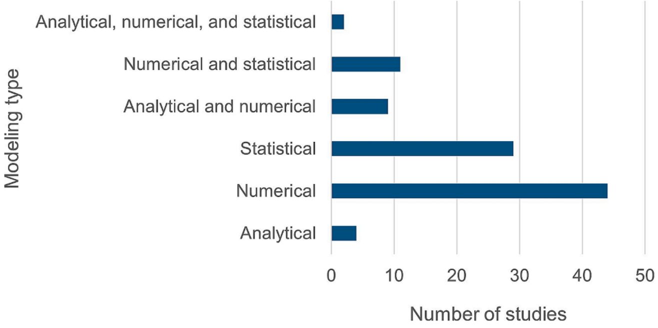

Fig. 5. Types of modeling employed in the studies included in the review.

3.3.3. *Study applications*

The application of the relevant studies was categorized according to the variables examined under future climate conditions (Fig. 6). Each study was assigned to a specific category depending on the main variables that were explicitly analyzed. However, it is important to note that most studies incorporated a hydrological sub-model as part of their methodology. As depicted in Fig. 6, relatively few studies have addressed future morphological changes, underscoring the need for

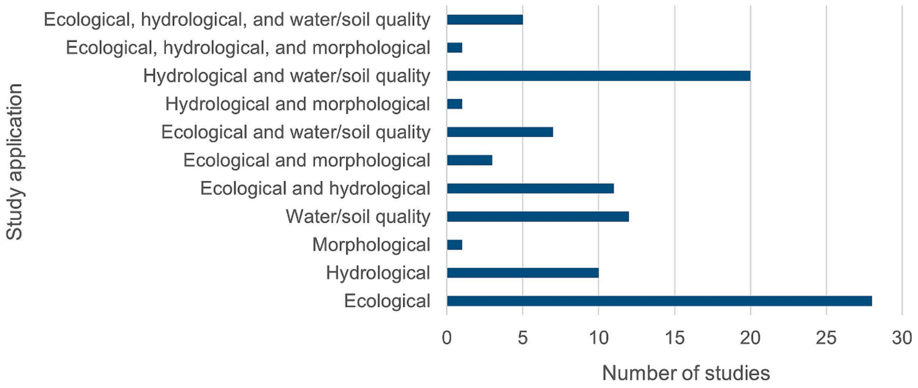

Fig. 6. Distribution of application fields in the studies included in the review.

further investigation in this area. Detailed information on each study's application, including the variables and elements examined under future climate change, is available in Supplement B (sheet "Study application").

3.3.4. *Climate scenario representation*

Regarding the approach for describing future climate, two main groups were identified. As reported in Supplement B (sheet "Future scenarios"), the majority of studies (e.g., Serrat-Capdevila et al., 2007; Siqueira et al., 2021; Yi et al., 2016; Zhai et al., 2023) used the projections of climate models (e.g., air temperature, precipitation, and solar radiation) as input data to predict the responses of their study sites to future climate conditions. In contrast, other studies (e.g., Cubley et al., 2023; Gentilin-Avanci et al., 2022; Latella et al., 2020; Schönhart et al., 2018) assessed their study sites under simplified future scenarios (e.g., scenarios of changes in flow, groundwater level, water temperature, and precipitation) based on predictions from previous works. In addition to these groups, McKernan et al. (2018) and Flanagan et al. (2015) focused on possible future climate change impacts by studying different sites that represent likely future climate conditions. Moreover, Garssen et al. (2017) experimentally manipulated the hydrology of five streams to simulate future climate change effects. In a comparable manner, Lytle et al. (2017) iteratively adjusted the timing of flood peaks to occur earlier or later in the year, representing climate change-driven alterations in flow. More detailed information on how each relevant study assessed the future climate change effects is available in Supplement B (sheet "Future scenarios", column "D").

3.3.5. *Other driving forces*

While climate change was the primary future driving force considered in the current review, other factors such as land use and the implementation of management practices have also been examined in certain studies (e.g., Fan & Shibata, 2015; Gay et al., 2023; Pastor et al., 2019) alongside climate change. Further details on the future elements and driving forces examined by each study are available in Supplement B (sheet "Future scenarios").

3.4. *Outputs overview of selected studies*

3.4.1. *Climate change effects on riparian features*

Supplement B (sheet 'Outcome A') offers an overview of climate change impacts on various riparian zone characteristics. The following subsections briefly discuss these effects for each specific examined variable.

3.4.1.1. Hydrology. Climate change is expected to influence various hydrological variables, including streamflow (Fossey & Rousseau, 2016b; Gay et al., 2023; Rincón et al., 2022), baseflow (Siqueira et al., 2021), surface runoff (Fan & Shibata, 2015; Olson & Burton, 2019; Siqueira et al., 2021), water yield (Gay et al., 2023; Ha & Wu, 2017; Huang et al., 2019), flooding/inundation (Jansson et al., 2019; Thodsen et al., 2016; Thompson et al., 2023), groundwater and sub-surface flow (Balderacchi et al., 2016; Fan & Shibata, 2015; Ledesma et al., 2021), water table levels (Botero-Acosta et al., 2018; Fernandes et al., 2016; Thompson et al., 2023), wetland water levels (Fossey & Rousseau, 2016a; House et al., 2016; Szporak-Wasilewska et al., 2015), evapotranspiration (Siqueira et al., 2021; Stephens et al., 2022; Thompson et al., 2023), and soil moisture(Cooper et al., 2006; Fernandes et al., 2016).

As summarized in Supplement B (sheet "Outcome A"), most hydrological variables such as streamflow, groundwater levels, and flooding show no consistent increasing or decreasing trend in response to future climate change. While changes are anticipated, predictions vary, with both increases and decreases projected depending on study sites, climate scenarios, and the specific modeling assumptions employed in each study. An exception is evapotranspiration, which is generally projected to increase (Gay et al., 2023; Kujawa et al., 2022). Furthermore, future changes in the timing and frequency of flow events have been also projected (Daigneault et al., 2016; Fernandes et al., 2016; Thompson et al., 2023).

3.4.1.2. Water and soil quality. As provided in Supplement B (sheet "Outcome A"), future climate change is projected to affect various water and soil quality indicators. These include water temperature (Spanjer et al., 2022; Wondzell et al., 2019; Zhai et al., 2023), pH and electrical conductivity (Gentilin-Avanci et al., 2022), dissolved oxygen (Ghimire et al., 2021; Zhai et al., 2023), soil temperature (Oni et al., 2017), soil aeration stress (Thompson et al., 2023), nitrogen in water (Balderacchi et al., 2016; Carstensen et al., 2023; Schönhart et al., 2018), phosphorus in water (Crossman et al., 2013; Fan & Shibata, 2015; Kujawa et al., 2022), water organic carbon and BOD (Ghimire et al., 2021; Köhler et al., 2009; Ledesma et al., 2021), nitrogen in soil (Garssen et al., 2017; Ledesma et al., 2021; Poblador et al., 2019), phosphorus in soil (Bertolet et al., 2018; Garssen et al., 2017), soil organic matter and carbon (Bertolet et al., 2018; Ledesma et al., 2021), pesticide leaching (Balderacchi et al., 2016), and sediment transport (Mullan et al., 2016; Pignalosa et al., 2022; Wu et al., 2021). For most of these variables, the direction and magnitude of change depend on site-specific conditions, climate scenarios, and the implementation of management practices. Nevertheless, there is a general agreement that water temperature will increase, likely leading to reduced dissolved oxygen levels (Zhai et al., 2023). Moreover, increased suspended sediment transport from riparian areas to streams is projected, particularly in the absence of effective management interventions (Ghimire et al., 2021; Ha & Wu, 2017; Wu et al., 2021).

3.4.1.3. Morphology. A summary of climate change impacts on morphological features is provided in Supplement B (sheet "Outcome

A"). Studies suggest that morphological characteristics, such as channel structure and freedom space, will be influenced by future climate conditions, depending on flow scenarios (Bestgen et al., 2020; Buffin-Bélanger et al., 2015; Martínez-Fernández et al., 2018; van Oorschot et al., 2018). It is important to note that relatively few studies have examined future morphological changes, despite the critical need to understand and anticipate climate-driven shifts in river morphology for effective riparian management. These changes are crucial for maintaining riparian habitat connectivity, which relies on dynamic interactions with river processes to sustain structural integrity and ecological functions (Camporeale et al., 2013; Henriques et al., 2022; López-Sánchez et al., 2024). Therefore, there is a clear need for further research to integrate morphological responses into riparian management frameworks, ensuring ecosystem resilience and the long-term sustainability of riparian systems in a changing climate.

3.4.1.4. Ecology and ecosystem services. Climate change is expected to affect the abundance, distribution, and habitat suitability of several riparian flora and fauna (Bestgen et al., 2020; Cubley et al., 2023; Ellis & Eaton, 2021; Spanjer et al., 2022; van Oorschot et al., 2018). Fish (Fullerton et al., 2022; Spanjer et al., 2022), fungal communities (Gentilin-Avanci et al., 2022), and amphibian species (Olson & Burton, 2019) are projected to be negatively impacted, unless management strategies are implemented (Justice et al., 2017). While some studies predict adverse effects on vegetation (e.g., Dhyani et al., 2018; Van Looy & Piffady, 2017), others highlight considerable variability in impacts depending on the species and climate scenarios considered (e.g., Martínez-Fernández et al., 2018; Stark & Fridley, 2022). Additionally, invasive species may benefit under future climate change conditions, while native species are likely to experience negative consequences (Gillard et al., 2017; Gold et al., 2011; Lawrence et al., 2014; Mtengwana et al., 2021). Furthermore, changes in crop yields and food production are also predicted (Lyu et al., 2019; Schönhart et al., 2018). One study (Lyu et al., 2019) also forecasted reductions in carbon sequestration and nitrogen retention, while highlighting potential increases in sand fixation and recreational opportunities. Ecological responses to future climate change across the studies are summarized in Supplement B (sheet "Outcome A").

3.4.2. *Effectiveness of riparian management practices*

The implementation of adaptive management practices, such as vegetation restoration and the establishment of buffer strips, has been proposed to mitigate or offset the adverse impacts of climate change on riparian areas. Supplement B (sheet "Outcome B") summarizes findings from studies assessing the effectiveness of such riparian management strategies under future climate scenarios. The majority of these studies highlight the evident role of vegetated riparian zones in regulating the physical, chemical, and biological conditions of riparian ecosystems.

The future effectiveness of riparian buffers for water management was evaluated by 14 studies (see Supplement B, sheet "Outcome B"). Several studies reported no significant impact of riparian buffer on streamflow and water availability (Hoyer & Chang, 2014; Knouft et al., 2021; Olson & Burton, 2019; Siqueira et al., 2021; Wagena & Easton, 2018). Gay et al. (2023) similarly found minimal impact of buffer treatments on streamflow at the watershed scale but noted that buffer treatment could help regulate low and high flows in the most developed areas. Other studies affirmed the effectiveness of riparian buffers for water management, but discussed that combining buffers with additional management practices yields greater benefits (de Freitas et al., 2022; Huang et al., 2019; Pignalosa et al., 2022). For instance, Daigneault et al. (2016) compared the future flood mitigation capability of different ecosystem-based measures and hard infrastructures. They identified riparian buffer planting as the most cost-effective measure, though it offered limited protection, and recommended upland afforestation as the most beneficial option. Several studies also concluded that while existing buffers and riparian restoration efforts may support flow regulation, water supply resilience, and flood mitigation under future climate conditions, they are unlikely to fully offset the impacts of climate change. Moreover, their effectiveness is expected to decline over time (Botero-Acosta et al., 2018; Fossey & Rousseau, 2016b; Huang et al., 2019; Jayakody et al., 2014; Mullan et al., 2016).

All 14 studies that assessed the future water temperature regulation potential of riparian buffers (see Supplement B, sheet "Outcome B") emphasized the critical role of shading and riparian vegetation in mitigating the thermal impacts of climate change. However, several studies noted that riparian vegetation restoration alone may not be sufficient to fully counteract future warming trends (Fullerton et al., 2022; Trimmel et al., 2018). Consequently, complementary strategies are recommended to enhance the thermal benefits of riparian vegetation (Fuller et al., 2022; Justice et al., 2017). Research indicates that stream temperatures are considerably more responsive to changes in riparian vegetation than to variations in air temperature, streamflow, or land cover within the basin (Cao et al., 2016; Woltemade & Hawkins, 2016; Wondzell et al., 2019). In the absence of riparian vegetation, stream temperatures tend to increase significantly (Cristea & Burges, 2010; Fullerton et al., 2022; Spanjer et al., 2022; Trimmel et al., 2018; Woltemade & Hawkins, 2016). Conversely, restoring riparian vegetation can substantially reduce stream temperatures, potentially lowering them below current levels despite a warming climate (Wondzell et al., 2019). Several studies have also demonstrated that riparian vegetation restoration may have a stronger cooling influence on smaller streams, leading to greater reductions in water temperature (Borgwardt et al., 2020; Cristea & Burges, 2010; Lawrence et al., 2014).

12 Studies (see Supplement B, sheet "Outcome B") examined the future effectiveness of riparian buffers in controlling nitrogen loads. Most of these studies found that riparian buffers, either alone or in combination with other management practices, can effectively reduce nitrogen levels (Carstensen et al., 2023; Fan & Shibata, 2015; Ghimire et al., 2021; Hoyer & Chang, 2014; Huang et al., 2019; Kujawa et al., 2022; Schönhart et al., 2018; Wagena & Easton, 2018). However, Piniewski et al. (2014) reported no significant reduction in nitrate nitrogen ($N\text{-}NO_3\text{-}$) loads from riparian buffers, even when implemented alongside other measures such as vegetation cover, reduced fertilization, and constructed wetlands. They concluded that these strategies would not be sufficient to offset the anticipated increases in nitrogen loading driven by climate change and intensified agriculture. Additionally, some studies suggested that alternative management practices such as land conversion to pasture or switchgrass and the implementation of cover crops may be more effective than riparian buffers in reducing nitrogen load (Ha & Wu, 2017; Liew et al., 2013)

All 12 studies (see Supplement B, sheet "Outcome B") confirmed the positive effects of riparian buffers on future phosphorus reduction. Nonetheless, some studies identified other management practices, such as vegetative cover, land conversion to pasture and switchgrass, and the use of cover crops, as more effective options for managing phosphorus loads (Ha & Wu, 2017; Liew et al., 2013; Piniewski et al., 2014).

13 Studies (see Supplement B, sheet "Outcome B") investigated the sediment control capability of riparian buffers under future conditions, with several addressing erosion, where "sediment" was used as a proxy for erosion (e.g., Pignalosa et al., 2022; Wu et al., 2021; Pastor et al., 2019). All of these studies concluded that riparian buffers can effectively reduce sediment loads. Some studies (e.g., Wu et al., 2021) explicitly proposed implementing riparian management practices, such as riparian reforestation, as a measure for streambank stabilization. Nonetheless, Jayakody et al. (2014) and Wu et al. (2021) reported that while riparian buffers can reduce sediment outputs, this reduction is unlikely to fully compensate the impacts of climate change. In addition, some studies suggested that the maximum effectiveness of buffers can be achieved when combined with other management practices (de Freitas et al., 2022; Ha & Wu, 2017; Pignalosa et al., 2022)

12 Studies (see Supplement B, sheet "Outcome B") assessed the

effectiveness of riparian buffers in mitigating the impacts of climate change on biodiversity across different species. Zhang et al. (2023) highlighted that riparian buffers are a key strategy for conserving plant biodiversity in riparian zones. Riparian shading can also help protect fish biodiversity by providing suitable thermal habitats, thereby mitigating the effects of climate change (Borgwardt et al., 2020; Knouft et al., 2021; Lawrence et al., 2014; Spanjer et al., 2022). A study conducted in the interior Columbia river basin revealed that the loss of riparian vegetation negatively impacts steelhead performance, particularly under the extreme scenario of completely removing riparian buffers (Wooster et al., 2019). Turschwell et al. (2018) found that the negative impacts of climate change on fish populations could be nearly entirely mitigated, or even reversed, through riparian zone restoration at the catchment scale. However, other studies suggest that riparian restoration alone may not fully counteract future warming (Fuller et al., 2022; Fullerton et al., 2022). As a result, additional strategies such as enhancing floodplain connectivity, restoring streamflow, and protecting cold-water refuges should be considered to preserve threatened fish populations (Justice et al., 2017). Likewise, Ellis & Eaton (2021) explored habitat suitability for cyanolichens and proposed that expanding riparian woodlands and improving habitat quality by shifting toward preferred tree species could help maintain microhabitat conditions for rainforest cyanolichens despite future climate change. A study on butterfly habitat suitability (Tainio et al., 2016) also found that while buffer zones and traditional biotopes offered comparable cost-effectiveness as adaptation strategies, the management of traditional biotopes, typically through grazing, emerged as the most effective agri-environmental scheme (AES) for maintaining suitable habitats for grassland butterflies. Other AES measures were relatively less beneficial for supporting these species.

Regarding other ecosystem services, Ghimire et al., (2021) evaluated the responses of various riparian buffer designs (grass, urban, two-zone forest, three-zone forest, wildlife, and naturalized) to climate change across three watersheds in the Albemarle-Pamlico River Basins (USA). Their findings identified urban riparian buffers as the most sensitive and effective design, contributing to reduced BOD and increased dissolved oxygen. Using a case study of the City Belt along the Yellow River in Ningxia, China, Lyu et al. (2019) demonstrated that compact urban growth, riparian vegetation buffers, and ecological protection strategies can help mitigate the impacts of future global warming on critical ecosystem services. These strategies were found to reduce trade-offs and minimize simultaneous losses in ecosystem services, including food production, sand fixation, carbon sequestration, recreational opportunities, and nutrient retention. Buffin-Bélanger et al. (2015) also evaluated the economic value of ecosystem services provided by freedom space, which includes expanded riparian wetland zones and broader riparian buffers. Their findings indicated that river management strategies focused on freedom space are cost-effective and provide substantial benefits over a 50-year period.

4. Limitations

While this study provides valuable insights, several limitations should be acknowledged. The first limitation stems from the search criteria: only English-language research articles published between 2000 and 2023 were included. As a result, studies published in other languages, outside the specified period, or as gray literature (such as technical reports and academic theses) were excluded, despite their potential contribution to future riparian management. Another limitation concerns the selection process, where studies were initially screened based on titles and abstracts, followed by a more thorough review of the full content. This approach may have biased the review toward studies with clear, relevant, and well-structured abstracts. Additionally, the review was carried out by two researchers, who were responsible for selecting, interpreting, and analyzing the studies. This approach may have introduced human error or bias into the findings, although such issues were mitigated through cross-checking and verification. Lastly, while the review focused specifically on quantifying the effects of future climate change on riparian zones, other stressors that may impact riparian areas over time should also be considered in management strategies (Olokeogun & Kumar, 2020, 2022; Xia et al., 2025).

5. Conclusions

Riparian zones provide essential ecosystem services, including biodiversity support, water quality improvement, and water management, playing a crucial role in sustaining both aquatic and terrestrial ecosystems. However, climate change can significantly impact these areas by altering hydrological patterns, increasing water temperatures, and shifting sediment and nutrient dynamics, leading to water quality degradation and habitat loss. This review finds that the direction and magnitude of such impacts are context – and scenario –dependent. The review also highlights the need for adaptive riparian management that incorporates climate projections to ensure the long-term sustainability of these ecosystems. Enhancing the resilience of riparian zones to climate change will require not only the restoration and maintenance of riparian buffers but also the integration of broader watershed-scale management practices. Such strategies are vital to maintaining the capacity of riparian zones to deliver essential ecosystem services under future climate conditions. This review also points to key methodological limitations that offer valuable guidance for future research. Broadening the scope to include diverse sources and accounting for multiple interacting stressors will help build a more comprehensive and globally relevant understanding of riparian vulnerability and adaptation.

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CRediT authorship contribution statement

Hamed Vagheei: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fulvio Boano:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: the authors report financial support was provided by European Commission. The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113600.

Data availability

No data was used for the research described in the article.

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