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Conservation of freshwater macroinvertebrate biodiversity in tropical regions

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Abstract

1. Motivated by recent global initiatives for biodiversity conservation and restoration, this article reviews the gaps in our understanding of, and the challenges facing, freshwater macroinvertebrate biodiversity and conservation in tropical regions.
2. This study revealed a lack of adequate taxonomic, phylogenetic, and ecological information for most macroinvertebrate groups, and consequently there are large-scale knowledge gaps regarding the response of macroinvertebrate diversity to potential climate change and other human impacts in tropical regions.
3. We propose ideas to reduce the impact of key drivers of declines in macroinvertebrate biodiversity, including habitat degradation and loss, hydrological alteration, overexploitation, invasive species, pollution, and the multiple impacts of climate change.
4. The review also provides recommendations to enhance conservation planning in these systems (as well as providing clear management plans at local, regional, and national levels), integrated catchment management, the formulation of regulatory measures, the understanding of the determinants of macroinvertebrate diversity across multiple scales and taxonomic groups, and the collaboration between researchers and conservation professionals.
5. It is suggested that the integrated use of macroinvertebrate biodiversity information in biomonitoring can improve ecosystem management. This goal can be facilitated in part by conservation psychology, marketing, and the use of the media and the Internet.

KEYWORDS

Anthropocene, biodiversity, extinction, freshwater ecosystems, invertebrates

1 | INTRODUCTION

Owing to increasing human impacts worldwide, current species extinction rates may be 1000 times faster than background extinction rates, and are as high as those of past mass extinction events (Barnosky et al., 2011; Ceballos, Ehrlich, & Dirzo, 2017; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2019). Such pressures are increasingly threatening freshwater ecosystems with the potential extinctions of tens of thousands of aquatic species (Dudgeon, 2014; IUCN, 2010, 2016, 2017;

Strayer, 2006; Strayer & Dudgeon, 2010; Vörösmarty et al., 2010). The World Wide Fund for Nature (WWF) (2018)) reported that since 1970, approximately 83% of global freshwater species have declined, and the maximum biodiversity loss has been observed in the Neotropics, Indo-Pacific, and Afrotropics. In particular, aquatic insects are likely to be experiencing similar declines to those of freshwater species in general, and the International Union for Conservation of Nature (IUCN) Red List assessment found that 15% of dragonflies and damselflies (Odonata) were under threat of extinction (Collen, Böhm, Kemp, & Baillie, 2012; IUCN, 2012). Despite this trend, freshwater biodiversity continues to receive less attention than its terrestrial and marine counterparts, particularly in tropical regions (Boyero, Ramirez, Dudgeon, & Pearson, 2009; Godet & Devictor, 2018). This lack of attention is surprising given the urgency to protect freshwater ecosystems and the services that they provide in the face of numerous stressors threatening biodiversity (Dudgeon et al., 2006; Heino, Virkkala, & Toivonen, 2009; Poff, Olden, & Strayer, 2012; Woodward, Perkins, & Brown, 2010).

Research biases considerably affect decisions on biodiversity conservation. The initiatives of biodiversity conservation require adequate knowledge of different taxonomic groups and ecological systems to achieve global goals (e.g. the 2030 Agenda for Sustainable Development and the Convention on Biological Diversity 'Aichi Targets' in 2020). In tropical regions, in particular, previous studies have highlighted the limited scope of conservation research and implementation of policies on invertebrate species and freshwater ecosystems (Darwall et al., 2011; Di Marco, Watson, Venter, & Possingham, 2016). Acknowledging that a large body of knowledge has been gathered on macroinvertebrates and freshwater conservation after the groundbreaking papers of Dudgeon et al. (2006) and Strayer (2006), this article provides a thorough and critical review of the scientific literature and examples of macroinvertebrate conservation in tropical regions. It first provides an overview of the overall importance of macroinvertebrate diversity in tropical regions. Second, it covers the threats and causes of macroinvertebrate biodiversity decline in tropical regions, emphasizing the potential impacts of climate change. Third, it sheds light on the main research topics, gaps, and regions studied in recent years involving macroinvertebrate conservation through a bibliometric analysis of the literature. Finally, building on these results, the review identifies key research gaps and proposed improvements for the use and integration of freshwater macroinvertebrate information in regional and global initiatives for biodiversity conservation in tropical regions.

2 | BIOLOGICAL DIVERSITY AND MULTIPLE VALUES OF FRESHWATER MACROINVERTEBRATES

Freshwater ecosystems harbour considerable numbers and types of macroinvertebrates, despite their small spatial coverage of the planet. Despite possibly representing around 80% of the Earth's freshwater macroinvertebrate fauna (Dudgeon, 2003, 2006), tropical macroinvertebrates are poorly documented. The number of freshwater invertebrate species has been estimated to be approximately 107,295, with insects representing the dominant group (60.4%), followed by crustaceans (10%), molluscs (4%), and annelids (1.4%) (Balian, Segers, Lévèque, & Martens, 2008). Dudgeon (2008) reported that for six tropical regions the average percentage of individual insect order diversity was dominated by caddisflies (Trichoptera, 25.1%), followed by true flies (Diptera, 21.2%), beetles (Coleoptera, 16.3%), mayflies (Ephemeroptera, 13.4%), dragonflies and damselflies (Odonata, 11.5%), true bugs (Heteroptera, 5.2%), stoneflies (Plecoptera, 2.8%), moths (Lepidoptera, 2.7%), and alderflies and dobsonflies (Megaloptera, 1.8%).

The conservation of aquatic macroinvertebrate diversity is an urgent task because of its material and non-material values, including intrinsic, ecological, genetic, social, economic, scientific, educational, cultural, recreational, and aesthetic values (Table 1). Macroinvertebrates perform a variety of functions in freshwater ecosystems, including the decomposition of organic matter and nutrient cycling (shredders) (Wallace & Webster, 1996), the processing of organic matter (collectors) (Hershey, 1987), the consumption of algal producer biomass (scrapers) (Feminella & Hawkins, 1995), the cellular fluid consumption of individual cells of algae (piercers) (Merritt & Cummins, 1978; Swanson, Hrinda, & Keiper, 2007), and energy transfer to higher trophic levels (predators) (Cooper, Walde, & Peckarsky, 1990; Drysdale, 1998) (Table 1). Aquatic macroinvertebrates that have an emergent adult stage are also a key food source for terrestrial consumers (e.g. spiders, birds, lizards, and turtles) (Recalde, Postali, & Romero, 2016). Their diverse functions and abiotic tolerances also make macroinvertebrates good bioindicators of human impacts (Rosenberg & Resh, 1993).

3 | THREATS AND CAUSES OF MACROINVERTEBRATE BIODIVERSITY DECLINE IN TROPICAL REGIONS, EMPHASIZING THE ROLE OF CLIMATE CHANGE

Tropical fresh waters are among the most threatened ecosystems, experiencing biodiversity loss at alarming rates (Allan & Castillo, 2007; Antunes et al., 2016; Boyero et al., 2009; Boyero & Bailey, 2001). Threats to these systems include deforestation, habitat fragmentation, habitat degradation, overexploitation, pollution, eutrophication, siltation, channel impoundment, flood control, exotic species invasions, fisheries, increasing salinity, and climate change (Figure 1; Dudgeon et al., 2006). Habitat loss and degradation, caused by an array of interacting factors, including the intensive mining of river sand, deforestation for intensive agriculture (e.g. sugarcane, soybean, and palm oil), alien plant invasion, and urbanization are more severe in tropical than in temperate areas (Al-Shami et al., 2017; Che Salmah, Al-Shami, Madrus, & Abu, 2013; Dudgeon, 2008; Miettinen, Shi, & Liew, 2011). Agricultural expansion for growing sugar cane, soybean, oil palm, and cattle raising is

TABLE 1 Examples of ecosystem goods and services provided by freshwater macroinvertebrates

Service type	Examples of goods or services provided by biodiversity in general	Examples of goods or services provided by macroinvertebrates in tropical regions
Provisioning	Production (food); therapeutic uses; resources (e.g. genetic, ornamental)	Freshwater crustaceans, molluscs, and insects are important sources of protein, vitamins, minerals, and income for humans and livestock (Chakravorty, Ghosh, & Meyer-Rochow, 2013; Shantibalaa, Lokeshwari, & Debaraj, 2014; Van Huis et al., 2013; Williams & Williams, 2017). Dragonflies are used in traditional medicine, have ornamental value (e.g. displayed in museums), and are eaten in some traditional societies (Simaika & Samways, 2008). Water striders (Gerridae: Hemiptera) are used for dog bites, and other hemipterans are used in the treatment of mental illness (Srivastava, Babu, & Pandey, 2009; Tango, 1981)
Regulation and maintenance	Disease control and suppression of pathogens; water purification and regulation; nutrient cycling regulation; decomposition regulation	Aquatic macroinvertebrates such as bugs, beetles, and dragonfly and damselfly larvae control the abundance of pests and disease-vector mosquitoes (Benbow et al., 2014; Mandal, Ghosh, Bhattacharjee, & Chandra, 2008; Ohba et al., 2011; Saha, Aditya, Banerjee, & Saha, 2012; Tupinambás, Cortes, Hughes, Varandas, & Callisto, 2016). Dragonflies are hosts to parasites and are vectors of disease to humans and livestock (Simaika & Samways, 2008). Aquatic macroinvertebrates play a key role in nutrient cycling (Granados-Martínez, Zúñiga-Céspedes, & Acuña-Vargas, 2016; Yuen & Dudgeon, 2016), with some species being widely dispersed top predators
Cultural	Aesthetics; cultural heritage and sense of place; educational; recreational; spiritual and religious	The high abundance and diversity of forms make macroinvertebrates suitable for use in science education programmes for children or citizen science programmes (Fore, Paulsen, & O'Laughlin, 2001; Silvertown, 2009; Suter & Cormier, 2015). Dragonflies are significant in numerous cultures, as evidenced by dragonfly parks and trails, games for children, and field guides. In Japan, dragonflies also have religious significance (Simaika & Samways, 2008)

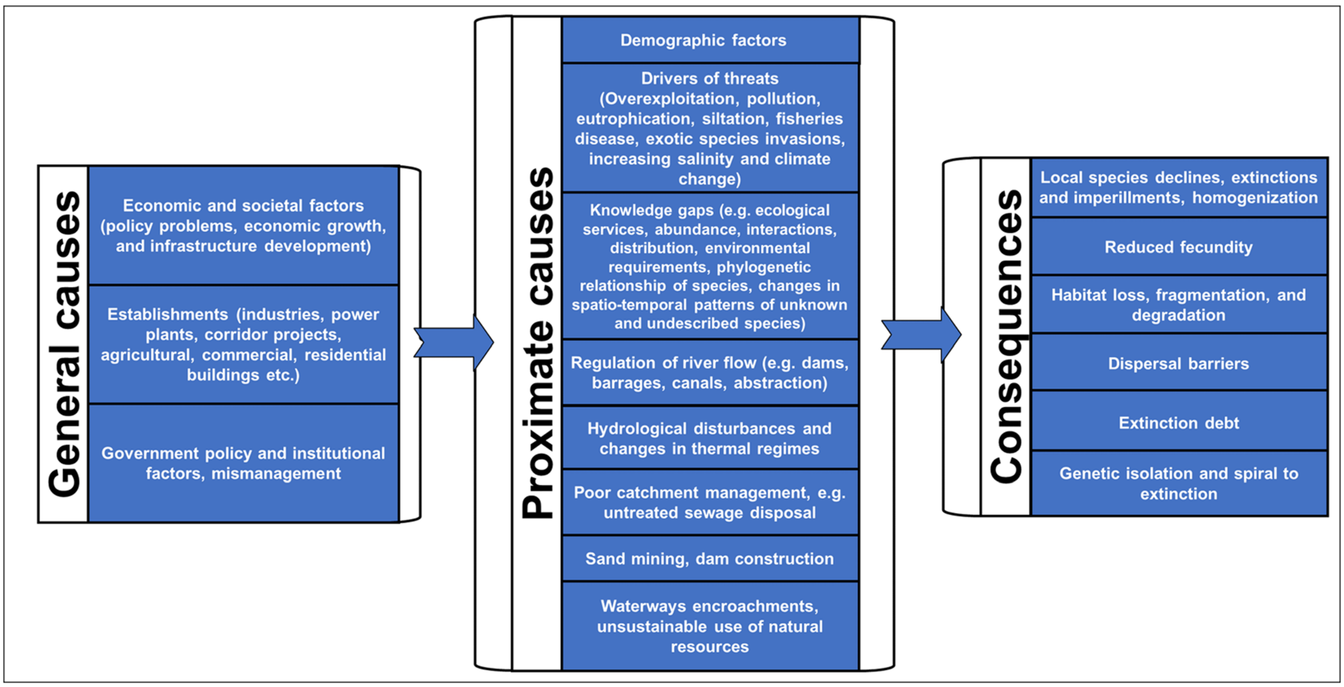

FIGURE 1 Factors driving declines of freshwater macroinvertebrate biodiversity in tropical regions

rapidly increasing in tropical regions (Curtis, Slay, Harris, Tyukavina, & Hansen, 2018; Foley et al., 2011; Gibbs et al., 2010), and is increasingly threatening macroinvertebrate biodiversity (Cuke & Srivastava, 2016; Kleine, Trivinho-Strixino, & Corbi, 2011; Luiza-Andrade et al., 2017; Svensson, Bellamy, Van den Brink, Tedengren, & Gunnarsson, 2018). The large-scale conversion of forests into agriculture and illegal gold mining also adversely affect macroinvertebrate biodiversity (Chula, Rutebuka, & Yáñez, 2013; van

Biervliet, Wiśniewski, Daniels, & Vonesh, 2009) in high-elevation rainforest streams by affecting the water quality and physical habitat of river ecosystems (Kasangaki, Chapman, & Balirwa, 2008).

Invasive species are among the main threats to freshwater biodiversity. They are likely to be the most important driver of biodiversity loss in aquatic ecosystems after land use and climate change by the year 2100 (Sala et al., 2000). For example, the long-term consumption of leaves of invasive *Eucalyptus* negatively affects the growth and existence of shredding insects in Brazilian Atlantic Forest streams (Kiffer, Mendes, Casotti, Costa, & Moretti, 2018).

Predicting the consequences of climate change on biodiversity and ecosystem functioning is an urgent challenge (Dudgeon, 2014). Modelling studies may provide useful conservation information, correlating known species occurrences and climatic variables for future scenarios, in order to evaluate the effects of climate change on the distribution of aquatic macroinvertebrates (Bálint et al., 2011; Bellard, Bertelsmeie, Leadley, Thuiller, & Courchamp, 2012; Domisch et al., 2013; Silva, Dias, Lecci, & Simião-Ferreira, 2018; Tierno de Figueroa et al., 2010), and thereby estimate their impacts on geographical distributions and support practical conservation actions (Guisan et al., 2013). Mechanistic models based on various processes, however, including the physiological processes of individual species, may be more precise in predicting population and community changes under a rapidly changing climate, where river flow regimes are moving beyond their historical envelopes (McMullen, Leenheer, Tonkin, & Lytle, 2017; Tonkin et al., 2019; Urban et al., 2016). Studies using microcosms or mesocosms to run temperature experiments with aquatic animals (Petchey, McPhearson, Casey, & Morin, 1999; Vasseur et al., 2014) and historical analyses of biological communities (e.g. Luoto & Nevalainen, 2013) may also help to understand the effects of climate change on aquatic macroinvertebrates.

Despite considerable increases in research over recent decades (Al-Shami et al., 2013; Al-Shami, Che Salmah, Abu Hassan, & Madrus, 2013; Al-Shami, Che Salmah, Abu Hassan, Madrus, & Al-Mutairi, 2014; Che Salmah et al., 2013; Che Salmah, Al-Shami, Madrus, & Abu, 2014), clear knowledge gaps remain on the effects of climate change on freshwater biodiversity in tropical regions. Climate change is likely to have damaging effects on tropical freshwater macroinvertebrate biodiversity through altering natural hydrological and physicochemical regimes (Clausnitzer et al., 2009; Dolný, Harabiš, Bárta, Lhota, & Drozd, 2012; Gutiérrez-Fonseca, Ramírez, & Pringle, 2018; Pearson, 2014; Taniwaki, Piggott, Ferraz, & Matthaei, 2017; Tonkin, Bogan, Bonada, Rios-Touma, & Lytle, 2017). Few studies have evaluated the effects of climate change on macroinvertebrate distribution and survival in tropical regions (Jourdan et al., 2018; Simaika et al., 2013; Simaika & Samways, 2015). Some studies have predicted increases in disease transmission with climate change, such as for snails hosting schistosomes and other trematodes (Manyangadze, Chimbari, Gebreslasie, Ceccato, & Mukaratirwa, 2016; Pederson et al., 2014). By altering the seasonality and predictability of flow regimes and physicochemical water parameters, climate change may directly alter the physiology, phenology, abundance, and distribution of species, thereby indirectly affecting species interactions within communities (Parmesan, 2006; Pecl et al., 2017; Ruhi, Dong, McDaniel, Batzer, & Sabo, 2018; Tonkin et al., 2017).

In the long term, species may adapt to such changes, but in situ adaptation to the changing climate and environmental characteristics is by no means guaranteed, potentially compromising species survival. Species will only persist in areas allowing their normal physiological performance; consequently, climate change may lead to shifts in species ranges towards higher latitudes or higher elevations (Haase et al., 2017; Simaika & Samways, 2015), resulting in extinctions via the 'summit-trap' effect (i.e. preventing the migration of species towards climatically suitable areas in higher mountains and restricting them to the summits of lower mountains) (Sauer, Domisch, Nowak, & Haase, 2011). Climate change is also expected to homogenize regional aquatic biodiversity, resulting in the persistence of generalist species only, given their broad physiological tolerances (Hughes, 2000; Pecl et al., 2017). The effects of climate change on freshwater faunas are alarming because water availability throughout the tropics is expected to change considerably (Rodell et al., 2018), as is already apparent in the Brazilian Atlantic Forest (Dobrovolski & Rattis, 2015). These areas are facing severe droughts, causing rivers to dry completely, thereby affecting the habitats available for aquatic species (Coutinho, Kraenkel, & Prado, 2015; Dobrovolski & Rattis, 2015; Escobar, 2015; Loyola & Bini, 2015).

Climate change affects the geographical location of the best climatic isotherms that regulate the physiological functions of species. Climatically suitable areas where species are expected to maintain viable populations under current conditions may become unsuitable, causing species to become extinct regionally. In the future, such changes in climatic suitability for species may decrease the effectiveness of established protected area networks significantly (Hannah et al., 2007). In a theoretical example, a species believed to have many of its populations connected to one another under current climatic conditions (Figure 2a) may become threatened in the future once a significant portion of its populations become disconnected from other climatically suitable areas within the species' range (Figure 2b). In this example, under the current climatic conditions the target species does not occur in half of region 1 and in region 2. In future climatic conditions, region 2 may become unsuitable for this species for many reasons (e.g. through agricultural intensification, road construction, habitat change, and fragmentation), interacting with climate change. Northern populations from region 3 will no longer disperse southwards, which may cause regional extinctions of the species. A systematic conservation planning solution that considers landscape connectivity in both scenarios is necessary in order to increase the effectiveness of protection from one scenario to the other. To assure the future protection of a species, dispersal among protected areas must be accounted for (Thompson & Gonzalez, 2017). In the current scenario, the species populations are connected throughout the landscape; however, in future scenarios, the populations from region 3 are no longer connected to those in regions 1 and 2. There was also a significant decrease in the area of suitable habitat available for the species in region 2. In order to avoid local extinctions in both regions 2

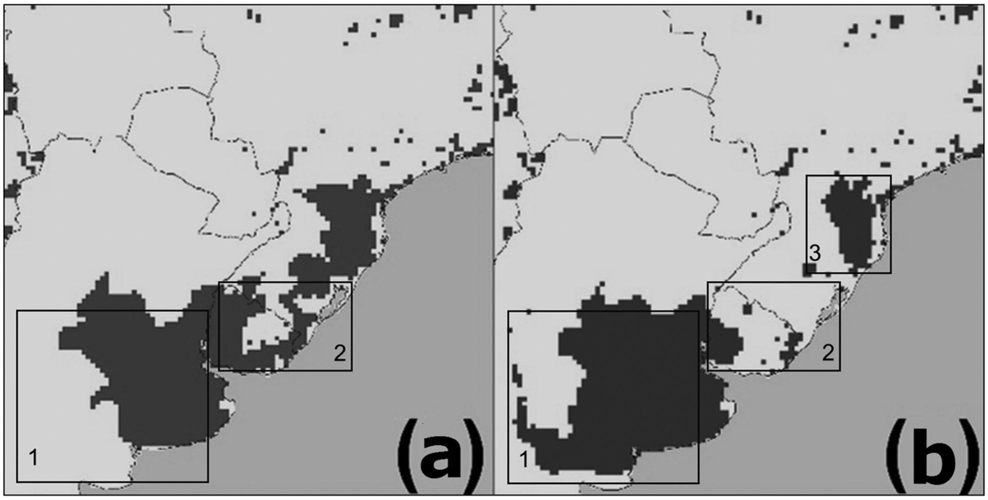

FIGURE 2 A theoretical example of how climate change may affect the geographical range of an aquatic macroinvertebrate species when comparing both (a) current and (b) future climate scenarios. The grey areas represent grid cells with suitable climatic conditions for a theoretical species in both scenarios

and 3 for the theoretical species considered, a systematic conservation planning approach that accounts for landscape connectivity in different climatic scenarios is necessary.

Recent research has demonstrated that it is possible to design protected area networks that are robust to divergent connectivity, for the conservation of multiple species under uncertain future climate change and land use (Albert, Rayfield, Dumitru, & Gonzalez, 2017); however, such an approach has yet to be applied in freshwater systems (Azevedo-Santos et al., 2019). If the various potential connectivity needs of multiple species are not considered concomitantly, populations of these species may face local or regional extinction (Sauer et al., 2011), particularly if dispersal is restricted along the river network (Bush & Hoskins, 2017; Tonkin et al., 2018).

4 | GAPS, CHALLENGES, AND STRATEGIES FOR CONSERVING MACROINVERTEBRATE BIODIVERSITY

The basic biological and ecological data available for macroinvertebrates are affected by both Linnean (lack of proper description of species by science) and Wallacean (lack of knowledge on the geographical distribution of species) shortfalls (Hortal et al., 2015; Oliveira et al., 2016), but other data shortfalls are also important. For instance, fundamental information on the phylogenetic relationships (e.g. no knowledge on evolutionary models connecting macroinvertebrate phylogenies to relevant ecological traits and life-history variation) of different aquatic insect groups (the so-called 'Darwinian shortfall'; Diniz-Filho, Loyola, Raia, Mooers, & Bini, 2013; Assis, 2018) is generally missing. There are also gaps in our knowledge of the ecological interactions that aquatic macroinvertebrates maintain with other species (the 'Eltonian shortfall'; Hortal et al., 2015), of their local abundances (the 'Prestonian shortfall'; Hortal et al., 2015), of their ecological and functional traits (the 'Raunkiaeran shortfall'; Hortal et al., 2015), and of their abiotic tolerances, limiting the understanding of their ecological roles in the environment.

To exemplify the literature trends and gaps, the Web of Science Core collection for literature on macroinvertebrate conservation was searched, using the following keyword combinations: tropical conservation AND (freshwater OR aquatic) AND (*invertebrate* OR insect*). The timeline for the appearance of the different terms and the keyword co-occurrence patterns (Figure 3) and the countries of affiliation of the authors (Figure 4) were both identified using VOSviewer (van Eck & Waltman, 2010).

The results indicated that the literature on macroinvertebrate conservation covers a variety of those topics. The results of the analyses show that the focus of the literature is moving from studies that address basic aspects of the ecology, seasonality, diet, and distribution of macroinvertebrates towards studies about the effects of human impacts on biodiversity, represented by keywords such as 'land use', 'indicator', and 'water quality'. It is important to note that topics such as climate change and habitat restoration have seen an increase in representation in recent publications, which suggests that macroinvertebrate literature has been aligning with global demands to influence decision making. Dragonflies (Odonata), mayflies (Ephemeroptera), stoneflies (Plecoptera), and caddisflies (Trichoptera) are the most cited groups in the literature and include the species most sensitive to human impacts, which are used as bioindicators of water condition. They also comprise the taxonomically and ecologically best-known aquatic insect groups.

Most papers were published by authors from developed nations, such as the USA, Canada, Australia, and European countries (e.g. the UK, France, Germany, and Spain); however, we also noted an increased number of studies being carried out in tropical countries that were historically under-represented, including Brazil, Colombia, Mexico, and Malaysia. South Africa, which includes a range of climatic zones from subtropical to temperate, stands out from the analysis because it has a long history in studies about insect conservation. Large geographical areas in tropical regions remain overlooked, particularly in highly speciose regions, such as Papua New Guinea, Indonesia, India, and Congo.

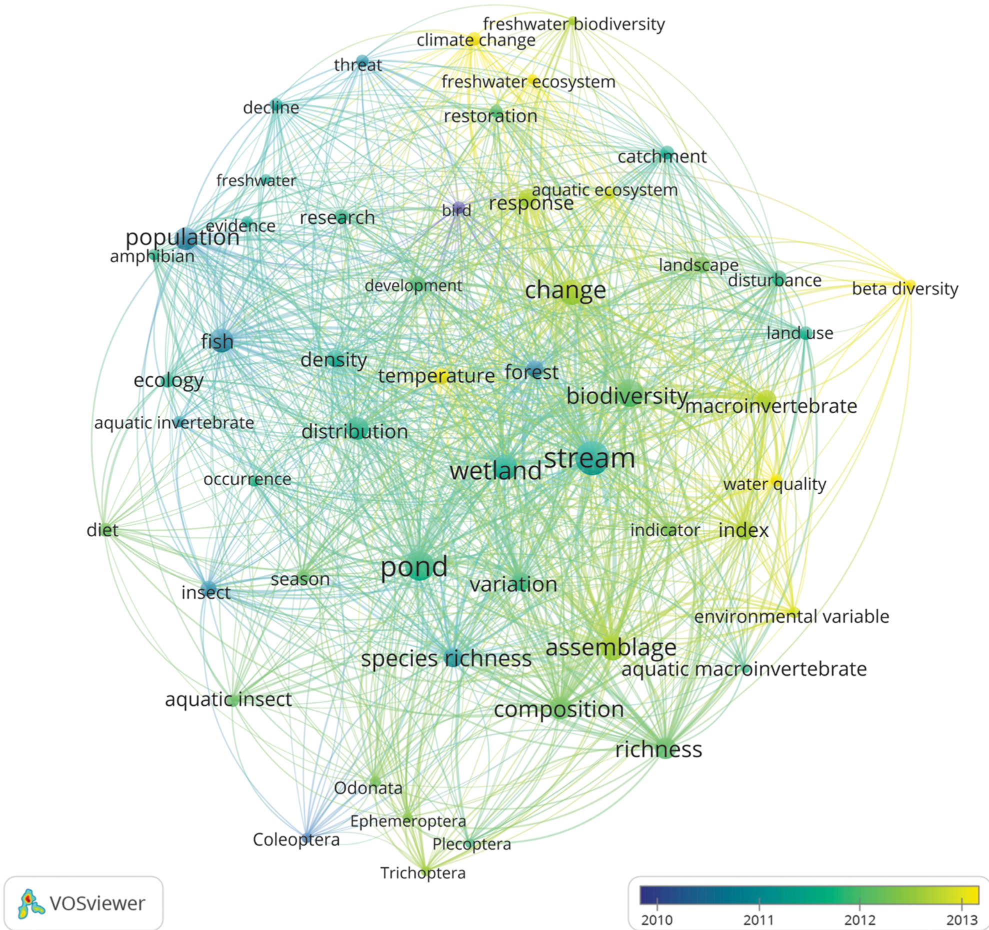

FIGURE 3 Graphical analysis representing the distance-based map of the most frequent terms used in 1880 papers across title, abstract, and keywords, searched for on the Web of Science by entering the following keyword combination: tropical conservation AND (freshwater OR aquatic) AND (*invertebrate* OR insect*). The analysis was carried out using VOSviewer (van Eck & Waltman, 2010). The figure highlights 53 terms appearing at least 100 times across the papers, separated in four clusters and with 1374 links between them. The most widely occurring term is 'stream', with 1361 occurrences and 52 links. Each circle represents one term, and its size corresponds to the relative frequency at which it occurs. The lines represent a link between two terms, and the thickness shows the relative frequency with which the two terms occur together (the 1000 strongest connections are shown). The colours represent the year in which the term was most recurrent according to the gradient given in the bottom-right corner

To overcome some of the knowledge gaps on very speciose groups (e.g. aquatic macroinvertebrates in tropical fresh waters) in the context of systematic conservation planning, Diniz-Filho, De Marco, and Hawkins (2010) proposed the use of macroecological tools, such as species distribution modelling. Other authors have suggested possible ecological modelling tools for assessing various macroinvertebrate taxa for conservation in tropical regions. These include, for example, the development of ecological models for pollution-sensitive macroinvertebrate taxa that can be more easily adapted to any river basins with similar environmental conditions (Forio et al., 2016; Nieto et al., 2017).

Advances in taxonomy, improvements in the understanding of nomenclature, and changes in classification will be important for conservation efforts and the mitigation of macroinvertebrate biodiversity loss (Thomson et al., 2018). The use of the flagship species concept (popular species that work as symbols or icons, and inspire people to provide money or support for their conservation) can assist in conserving macroinvertebrates (Jepson & Barua, 2015; Veríssimo, MacMillan, & Smith, 2011). Also, studies should focus on increasing landscape heterogeneity and spatial connectivity in order to maintain and conserve different hydrological regimes, water quality, and basic ecological patterns and processes at various spatial and temporal scales, and to conserve remnants of macroinvertebrate habitat (Brainwood & Burgin, 2009; Heino et al., 2015; Schindler & Hilborn, 2015; Sim et al., 2013; Tonkin, Heino, & Altermatt, 2018).

The prioritization of areas for conservation is a challenging task that involves serious resource constraints and trade-offs. There are few examples of tropical protected areas created primarily to conserve macacroinvertebrates, although the Refúgio Estadual de Vida Silvestre Libélulas da Serra de São José, a Brazilian protected area in the Atlantic Forest created to conserve dragonflies, is notable. Creating new protected areas and improving those that already exist should be the cornerstone of any strategy for conserving freshwater macroinvertebrates in tropical regions. Therefore, we recommend

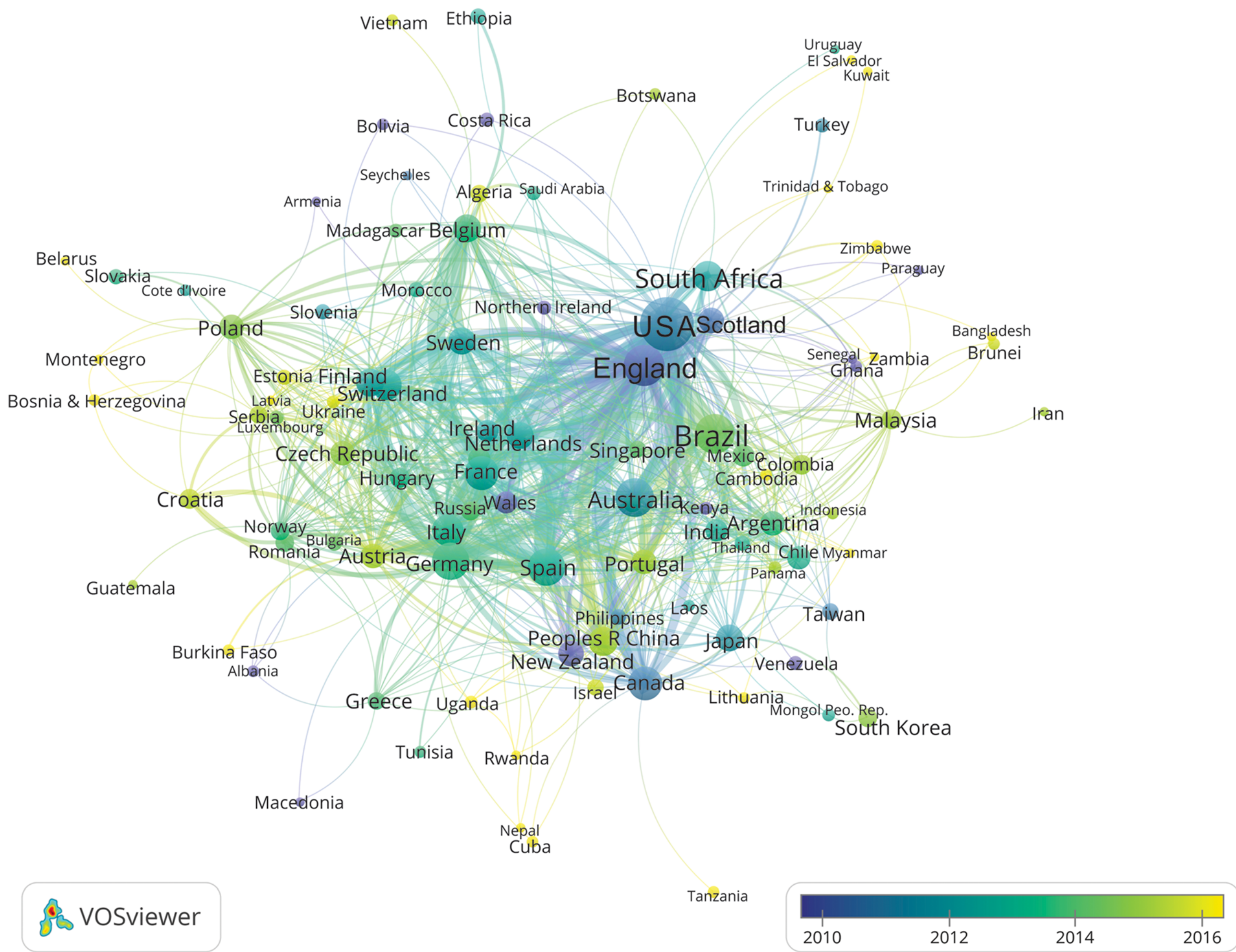

FIGURE 4 Analysis of the country affiliations of all the authors of the 1880 papers found on the Web of Science with the keyword combination: tropical conservation AND (freshwater OR aquatic) AND (*invertebrate* OR insect*). The analysis was carried out using VOSviewer (van Eck & Waltman, 2010). There are 107 countries with at least one author affiliation across the 1880 papers, all separated into 17 clusters and with 798 links between them. Each circle represents one country and its size indicates the relative frequency of papers affiliated to this country. The country with most participants in these publications is the USA, which is affiliated to 523 papers and has 66 links with other countries. The lines represent a link between two countries, and their thickness shows the relative frequency with which the two countries published together. The colours represent the year in which the country published the most according to the gradient given in the bottom-right corner. Some countries do not appear on the image as they did not have connections with any other countries: Malta, Hong Kong, Nigeria, Egypt, Iceland, and Pakistan

using modern and objective systematic conservation planning tools (Margules & Pressey, 2000) to account for cost-effective strategies to preserve subsets of the regional macroinvertebrate biodiversity under clear quantitative conservation targets. Such theoretical frameworks have been used to design networks of protected areas for protecting different values of biodiversity around the world, including priority conservation areas in tropical regions for aquatic macroinvertebrates (e.g. Nieto et al., 2017; Simaika et al., 2013).

We provide recommendations (Figure 5) that could enhance the conservation planning of tropical macroinvertebrate biodiversity, including: (i) clear management plans at local, regional, and national levels that must be used as rehabilitation and adaptation strategies (Mantyka-Pringle et al., 2016); (ii) increased protection of riparian vegetation in order to prevent soil erosion and siltation; (iii) integrated catchment management; (iv) formulation of regulatory measures, such as landscape and policy (Flitcroft, Cooperman, Harrison, Juffe-Bignoli, & Boon, 2019); (v) strict action against human encroachments of waterways; and (vi) increased awareness of the flood pulse concept, an ecologically significant phenomenon particularly relevant to tropical river systems, of lateral and longitudinal hydrological connectivity along river basins (Junk & Wantzen, 2006; Tockner, Malard, & Ward, 2000). In addition, other points should be considered, such as: (vii) understanding the determinants of macroinvertebrate diversity across multiple scales and taxonomic groups (Heino, Melo, & Bini, 2015; Heino, Muotka, & Paavola, 2003); (viii) collaboration among conservation professionals, including scientists, and non-governmental and government agencies at the local, regional, and global levels; and (ix) documentation of threatened and endangered aquatic macroinvertebrate species. The classification of macroinvertebrates on the basis of their extinction risk and IUCN Red

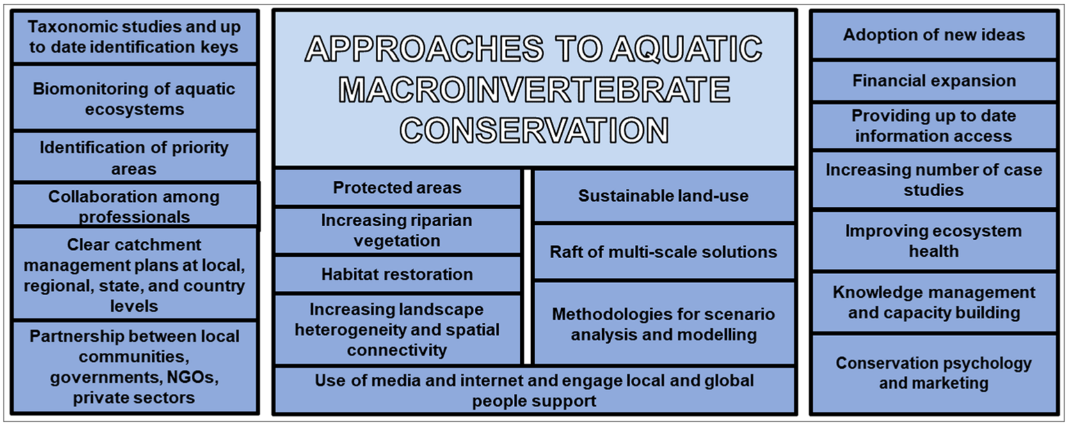

FIGURE 5 Possible conservation approaches to decrease the impact of the key causes of macroinvertebrate biodiversity declines

List assessments (Cardoso, Borges, Triantis, Ferrández, & Martín, 2011) are important for mapping areas of interest in macroinvertebrate conservation (Cardoso, Rigal, Fattorini, Terzopoulou, & Borges, 2013; Simaika & Samways, 2009, 2011).

A significant step towards conserving aquatic macroinvertebrate biodiversity is to create public awareness (Arlettaz et al., 2010; Knight et al., 2008; Laurance et al., 2012) to rekindle personal contact with nature (Samways, 2007) and raise a biophilic ethic: a societal change in attitude and behaviour through education and focused nature experience (Simaika & Samways, 2010). This can be achieved through conducting many specialized programmes, such as educational, incentive, and volunteer monitoring of freshwater ecosystems and macroinvertebrates, especially for children. For instance, bringing the field of ecosystem conservation into schools and imbuing children with the importance of conserving freshwater ecosystems is of great importance for the future fate of these ecosystems (Pinho, 2018). The new field of conservation psychology, established through the realization by conservationists that awareness and values alone are not enough to drive conservation-minded decisions in individuals, aims to close the intention–behaviour gap exhibited by people (Kollmuss & Agyeman, 2002; Simaika & Samways, 2010, 2018). Conservation psychology and marketing are essential tools, as conservationists cannot rely only on the good intention of people alone but need to effectively advertise for species conservation through positive reinforcement. Particularly in the tropics, where rates of urbanization are high, there is a great risk that personal connections to nature, and consequently larger societal values, do not include conservation-minded thinking.

Improvements in the conservation of aquatic macroinvertebrates can also be achieved through remediation approaches. Recent results have shown that degraded habitats may be restored to some extent, but that they rarely return to their original condition: for instance, sites that were restored recovered their capacity to store water and sequester carbon, and important ecosystem services of societal value, but remained poor in supporting biodiversity (Bakker, Pagès, Arthur, & Alcoverro, 2016; Moss, 2015). Typically, habitat degradation gets worse before it gets better, and restoration actions are needed to reverse the trend. Habitat restoration is possible on a local basis, but materials (reservoirs of local species) and expertise (knowledge on the biota) are critical (Stoll, Breyer, Tonkin, Früh, & Haase, 2016; Tonkin, Stoll, Sundermann, & Haase, 2014). Habitat restoration, however, provides an opportunity to put research findings into practice in partially degraded freshwater environments.

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