Macroinvertebrate biomonitoring in Latin America: Progress and challenges

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Abstract: Macroinvertebrates are used as bioindicators worldwide, but the high diversity of macroinvertebrate species and endemism in Latin America (LA) requires greater knowledge of this group to increase the effectiveness of biomonitoring. We examined some of the primary taxonomic and ecological studies on macroinvertebrates in the region, quantified the number of papers that used foreign and local indices, examined alternative approaches to bioassessment that may be more relevant for the region, and explored freshwater ecosystem management in LA. Here, we highlight the need to increase taxonomic knowledge and the number of specialists in local fauna, establish and maintain taxonomic collections in public institutions, and make online databases on the biodiversity in each country available. However, we also demonstrate that taxonomy specialists of different nationalities do collaborate on the generation of fundamental information about biodiversity in LA. We found that 57% of the 215 reviewed scientific articles from LA used foreign but locally adapted indices for biomonitoring aquatic ecosystems. Only 21% of these articles presented local indices developed in LA. New technologies, such as environmental DNA, offer substantial potential for bioassessment but only in regions where sufficient taxonomic knowledge exists and where species-level stressor–response relationships are well described. In the absence of more complete taxonomic records, there could be some value in developing biological trait and multimetric indices, and occupancy models could be developed to analyze the relationship between taxa and stress factors. These tools could be adopted by researchers to generate more accurate biotic indices based on local taxa. Finally, in LA, bioindicators are used to support scientific research more often than as environmental monitoring tools. Environmental laws and regulations that support the biomonitoring of LA freshwaters and unified criteria for evaluating and monitoring aquatic ecosystems are essential to face regional and global challenges.
Key words: invertebrates, bioindicators, indices, local knowledge, freshwater ecosystems, eDNA, management

The 1st step in protecting aquatic ecosystems is to know and value the biodiversity surrounding us. Gathering data about biota and creating comprehensive databases of species and their ecological requirements are essential for the successful application of management programs using bioindicator indices. Biomonitoring is the use of biological variables to survey the environment (Gerhardt 2000), to understand the extent of damage in the ecosystems, and to plan cost-effective recovery actions (Feio et al. 2021). The presence/absence and relative abundance of particular

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taxa, known as bioindicators, and their associated key traits at a given site are often considered to reflect that site's environmental quality (Keck et al. 2017). These bioindicators are essential tools for tracking and quantifying environmental impacts in the fields of biomonitoring, management, and freshwater conservation worldwide (Friberg et al. 2011). Macroinvertebrates are one of the most widely used animal species groups in bioassessment studies, and their use has been validated worldwide (Bonada et al. 2006). However, taxonomic information on macroinvertebrate populations are not universally robust, making their use as bioindicators in less-studied regions challenging.

The need for robust monitoring of ecosystems is urgently needed in many Latin America (LA) countries. This need is particularly strong for those regions whose economies rely heavily on agricultural commodities (e.g., beef, soy, maize, sugarcane, coffee) and extraction of raw materials (e.g., gold, copper, lithium, oil, wood), which severely affect the environment and, in particular, freshwater ecosystems (Castello et al. 2013). In these countries, institutional weaknesses (absent or precarious human, technical, and financial resources) result in the absence or discontinuity of monitoring programs for aquatic ecosystems (de Freitas et al. 2007). According to Feio et al. (2021), biomonitoring programs are in different stages of development among countries in LA, and these programs are infrequently grounded in laws or formal regulations. Some countries have well-structured and consolidated monitoring programs (e.g., Brazil, Peru, and Uruguay), and others have well-defined legal guidelines but no national initiatives (e.g., Bolivia, Paraguay, and Colombia). In contrast, some countries have no near-future prospects for monitoring (e.g., Venezuela).

Environmental policy in LA has shifted over the last 40 y from reactive policies (e.g., the privatization of resources), which aimed to ensure that environmental concerns did not hamper economic growth, to more preventive instruments, such as environmental impact assessments of large projects and laws. In some regions, environmental policies guided by social concerns and regulation of the external market are also employed (ORyan and Ibarra 2016). Despite these crucial advances, challenges to effective water resource protection and restoration remain across social, political, and economic domains in many, if not all, countries in the region (Hawkins and Carlisle 2022). In many cases, there is deliberate political opposition toward rigorous bioassessment programs, apparently because these programs threaten entrenched political and economic interests (Zhang et al. 2021).

The purpose of this *BRIDGES* article is to discuss progress and challenges of macroinvertebrate biomonitoring in LA. In particular, we review how knowledge generated in the Global North (GN: mainly western Europe, the United States, and Canada) has been applied to LA systems. We also evaluate the scope and challenges faced by LA countries by addressing the following topics: 1) available taxonomic information and shared databases; 2) application of local and foreign indices to LA biomonitoring programs; 3) other methodologies for biomonitoring that may be useful in the region including multimetric indices (MMIs), environmental DNA (eDNA), and occupancy models; and 4) freshwater ecosystem management and its challenges in LA. We begin by examining the availability of taxonomic, sensitivity, tolerance, and trait data for macroinvertebrate taxa. We then quantify the number of studies in LA that used foreign (developed in the GN), foreign but locally adapted (developed in GN and adapted to local fauna), and local (developed in LA) indices. Next, we examine recent contributions of emerging approaches to support biomonitoring (e.g., eDNA and occupancy models). Finally, we identify and discuss challenges in LA in implementing freshwater biomonitoring and management programs.

METHODS FOR LITERATURE SEARCH

To conduct our literature search we searched for the terms "biotic index" or "multimetric index" and "macroinvertebrates" and "freshwater" in each LA country. We limited our search to literature published on work in LA in the last 15 y (2006–2021). We used this time period because it gives us a current vision of the state of knowledge in LA. We used Google Scholar (scholar.google.com) to conduct this search because it is open access and provides both peer-reviewed and gray literature. Furthermore, because of cost, we do not have access to the primary alternative search engine, Web of Science (https://clarivate.com/webofsciencegroup/solutions/web-of-science/). We only considered biomonitoring research published in scientific journals, nonscientific reports, and information posted on official webpages of each LA government.

MACROINVERTEBRATE BIOLOGICAL AND LIFE HISTORY KNOWLEDGE IN LA

Much of the biological knowledge of aquatic macroinvertebrates has been generated in streams outside of LA. Since 2000, European countries have recorded >10,000 aquatic macroinvertebrate taxa in 14 countries. This effort originated with the Assessment System for the Ecological Quality of Streams and Rivers throughout Europe using Benthic Macroinvertebrates project (Hering et al. 2004), a system for stream assessment based on benthic macroinvertebrates in 8 European countries. In addition, the implementation of the European Water Framework Directive (European Commission 2000) has also contributed to increasing knowledge of biodiversity (including of macroinvertebrates) and aquatic ecosystem biomonitoring. In the United States, the Environmental Protection Agency has monitored rivers and streams using macroinvertebrate community composition since the passing of the Clean

Water Act of 1972 (Barbour et al. 2000). Both water quality and macroinvertebrate information from the GN are available from online databases (e.g., www.freshwaterecology.info, Schmidt-Kloiber and Hering 2015; Integrated Taxonomic Information System, www.itis.gov).

In LA, biodiversity studies and taxa inventories are still a necessary 1st step for bioassessment because of the high diversity of species and endemism in this region (Ramirez and Gutierrez-Fonseca 2020). The taxonomy and ecology from some orders in LA, including Ephemeroptera, Plecoptera, and Trichoptera (EPT), are better studied than others, supporting their potential use as bioindicators of water quality (Righi-Cavallaro et al. 2010). However, developing indices for groups characterized by relatively limited taxonomic and ecological information (e.g., annelids, mollusks, mites, and dipterans) is also a priority (Alonso-EguíaLis et al. 2014). Although much remains to be done, LA researchers have made important contributions to this effort, e.g., the development of species-level taxonomic guides for aquatic macroinvertebrates from Colombia (Roldán Pérez 1988), Chile (Palma 2013), Ecuador (Pérez et al. 2016), and Costa Rica (Hanson et al. 2010). In addition, 2 taxonomic keys of aquatic macroinvertebrates have collated information to facilitate identification of all known taxa for South America (Domínguez and Fernández 2009) and Central America (Alonso-EguíaLis et al. 2014). These texts contain information about macroinvertebrates currently known in LA. Additionally, in recent years, scientific societies (e.g., Argentine Association of Limnology and Macrolatinos@) have been established, making important contributions to freshwater science in LA (Gutiérrez-Fonseca and Tagliaferro 2023). Continuing enhancement of taxonomic knowledge and increasing the number of specialists in regional fauna are both essential to preserve and manage freshwater systems in LA. Additionally, establishing and maintaining taxonomic collections in public institutions, as well as creating and making online databases on the biodiversity of each country available, would support the development of more robust biomonitoring efforts.

The compilation of reliable measures of species sensitivity is one of the most critical challenges in biomonitoring (Leonardsson et al. 2015). Water-quality assessment typically involves the use of tolerance values, which describe the resistance of organisms to pollution and are often integrated into biotic indices (Carter and Resh 2013). Originally, taxa tolerance was assumed to be the response of organisms to an oxygen deficit resulting from wastewater inputs (Chang et al. 2014). Later, monitoring programs adopted methods like combining literature with best professional judgment or empirical derivation based on the presence of species in relation to ecosystem attributes. These approaches often resulted in rudimentary categories (e.g., tolerant/intolerant) or fixed species-sensitivity scores, which radically reduced the diagnostic power of indicator species (Ferreira et al. 2007).

Basic information about the tolerance of macroinvertebrate taxa to changing environmental conditions typically comes from the GN (e.g., Metcalfe 1989, Lenat 1993, Mandaville 2002, Whittier and Van Sickle 2010), although there is a lack of macroinvertebrate tolerance scores for stressors other than low dissolved oxygen. As for taxonomy, similar tolerance values have not been estimated for LA fauna (e.g., Ríos-Touma et al. 2014). Therefore, the extrapolation of tolerance data to LA systems is limited because of limited species overlap between the GN and LA and because tolerance values for species from the GN do not reflect stress responses to multiple pollutants. These challenges may be overcome by employing additional laboratory tests to assign sensitivity scores to LA species. However, extensively sampling community-level sensitivity to multiple stressors is not feasible (Van den Berg et al. 2020).

Compared with using tolerance scores, the application of biological traits within macroinvertebrate communities may be a more useful and realistic approach to assess the effect of multiple stressors, as well as a more robust way to evaluate environmental effects. Biological traits describe the morphological features of organisms and reflect environmental characteristics (Menezes et al. 2010, Statzner and Bêche 2010, Yadamsuren et al. 2020), and they can be used to assess the effects of complex environmental conditions, including changes in land use (Paz et al. 2022). Furthermore, some functional traits may not be constrained by taxonomy and could be applicable at multiple spatial scales (Vieira et al. 2006). Despite these benefits, robust trait analyses depend on extensive taxonomic information. Thus, improving local and regional diversity expertise remains an essential component to effectively use trait-based approaches.

APPLICATION AND ADAPTATION OF LOCAL AND FOREIGN INDICES

Biotic indices are one of the most common tools for habitat and water-quality assessment in monitoring programs because community analysis integrates biological responses across a large range of environmental conditions (Ríos-Touma et al. 2014). Indices, such as the Biological Monitoring Working Party (BMWP; Hellawell 1978), the Belgian Biotic Index (Plafkin et al. 1989), and the Family Biotic Index (Hilsenhoff 1988), and metrics, included in indices such as total richness of EPT (EPT Index; Weber 1973), were developed in Europe and North America in the early 1970s. The indices were built using species with wide ranges of tolerance to environmental conditions.

The results from our search suggest that the development and application of biotic indices are heterogeneous in LA. Of the 21 countries that constitute LA, we did not locate literature published between 2006 and 2021 on biotic indices for 6 of them (Haiti, Nicaragua, El Salvador, Guatemala, Dominican Republic, and Paraguay). Of the remaining 15 countries, we documented 215 articles that

Figure 1. Map of Latin America showing the distribution of studies published in scientific journals (2006–2021) focused on biotic and multimetric indices of macroinvertebrate assemblages. The total number of papers using biotic indices (upper number) and the number of multimetric indices (box) are shown for each country. a = Mexico, b = Honduras, c = Cuba, d = Puerto Rico, e = Costa Rica, f = Panama, g = Colombia, h = Venezuela, i = Ecuador, j = Peru, k = Bolivia, l = Brazil, m = Chile, n = Argentina, o = Uruguay.

included biotic indices. Studies from Brazil were most common (52 articles; Fig. 1). Of all the reviewed articles, 57% used foreign indices that were locally adapted and 16% directly applied foreign indices to biomonitoring programs (Table 1). Several of these articles reported combining different indices. Most studies used family as the lowest taxonomic level to support monitoring (67%), although a large proportion also used genus-level evaluation or combined genus and family-level metrics (15%).

The BMWP was the most broadly used index in LA biomonitoring studies. Of the total articles registered, 60% used BMWP, 92% of which adapted the index to the studied sites. Two of the common adaptations to the index included the addition of native families that were not present in the original tool and the exclusion of families that were not present in the region being evaluated. The EPT Index was also frequently used by authors (30% of studies), as was the Family Biotic Index (13% of studies). To characterize sites, authors included additional information including structural (47% of studies) and functional (9% of studies) metrics of the macroinvertebrate assemblage.

The development of new indices or the revision of existing indices for appropriate application to new sites typically requires both long-term studies and the investment of economic resources, which are not always available to LA researchers (Ruaro and Gubiani 2013, Ramirez and Gutiérrez-Fonseca 2020). Despite these constraints, local indices have been developed and reported in 21% of the reviewed articles. Uruguay and Argentina had the highest percentages of articles with local indices (66 and 54%, respectively), followed by Peru and Honduras (50% each).

ALTERNATIVE METHODS FOR BIOMONITORING

Biotic indices are extremely useful for bioassessment but only in regions where sufficient taxonomic knowledge exists and where species-level stressor–response relationships are well described. Despite their utility as tools for bioassessment, collecting data to support the use of biotic indices is time consuming and requires taxonomic expertise that may not be readily available in many regions of the world. Furthermore, the results from the application of indices may not reflect changes in the function of the ecosystem. However, alternative approaches, such as MMIs, eDNA, and occupancy models, offer potential for bioassessment and monitoring in regions that lack well-developed taxonomic databases and resources for extensive data collection. Each

Table 1. Information on biotic indices, taxonomic resolution level, and additional information (structural and functional metrics) of macroinvertebrate assemblages included in 215 scientific articles on macroinvertebrates in Latin American countries (see Table S1 for a list of the articles). Letters in parentheses correspond with countries in Figure 1.

	Biotic indices (%)				Level of taxonomic resolution (%)				Additional information (%)	
Country	Local	Foreign	Foreign but locally adapted	Multimetric	Genus	Family	Genus and Family	Not identified	Structural metrics	Functional metrics
Argentina (n)	58	4	71	4	0	46	38	17	92	25
Brazil (l)	8	35	59	28	9	61	21	8	37	8
Ecuador (i)	32	11	68	7	0	73	7	10	43	17
Bolivia (k)	0	80	40	38	0	88	13	0	25	0
Chile (m)	33	11	78	10	9	63	27	0	55	9
Colombia (g)	11	11	84	5	5	89	0	5	37	0
Peru (j)	46	23	69	7	0	75	6	19	69	6
Puerto Rico (d)	0	25	75	0	0	100	0	0	67	0
Mexico (a)	18	0	82	8	0	83	8	0	25	0
Uruguay (o)	50	0	50	0	67	33	0	0	67	33
Honduras (b)	100	0	100	0	75	25	0	0	75	0
Cuba (c)	0	0	100	0	0	100	0	0	0	0
Costa Rica (e)	20	40	60	0	0	50	0	0	0	0
Panama (h)	0	0	100	25	0	50	50	0	50	0
Venezuela (f)	17	17	67	0	0	100	0	0	60	0

of these approaches could improve different aspects of bioassessment, either by adding structural and functional variables to biotic indices (MMIs), contributing to taxonomic inventories (eDNA), or predicting the presence of species based on environmental variables (occupancy models).

MMIs

Development of MMIs facilitate the practical, accurate, and robust assessment of freshwater conditions within management frameworks—and they make these frameworks and their outcomes more accurate, complete, and protective of freshwater ecosystems. For example, Karr (1981) proposed an index of biological integrity based on multiple biological attributes (e.g., richness, abundance, habitat, trophic structure, tolerance, reproductive guilds) summarizing structural and functional variables of species assemblages. This index was the 1st application of the multimetric concept to assess water quality. Although this index was originally developed for fishes, it has influenced the development of analogous MMIs based on macroinvertebrates (Karr and Chu 1997, Moya et al. 2011, Chen et al. 2017).

Water management agencies in the United States and the European Union have widely adopted MMIs to support decisions on water quality (Barbour et al. 1999, Karr 1999, Ruaro and Gubiani 2013). However, the application of MMIs in LA were only reported in 13% of the total articles reviewed, with Brazil having the highest number of articles using these indices (Fig. 1). In Brazil, a consortium of scientists from 4 universities funded by a hydropower company developed MMIs after sampling 195 wadeable stream sites in 5 large hydrologic units in the Cerrado biome of Minas Gerais (Vadas et al. 2022). From this database, they developed both fish and macroinvertebrate MMIs (Macedo et al. 2016, de Carvalho et al. 2017, Silva et al. 2017) and conducted probability assessments of the major freshwater stressors in the biome (Silva et al. 2018, Martins et al. 2021). This example illustrates the usefulness of MMIs in bioassessments in LA but also highlights the resources and extensive data collection required to develop them.

eDNA

Genetic tools such as eDNA (Leese et al. 2016), developed in recent decades in the United States and European countries, may resolve some challenges to bioassessment in LA. eDNA is frequently used to detect populations with low densities because of the method's extremely high sensitivity (Darling 2019). In addition, DNA barcoding using a short sequence enables fast and reliable taxon identification to species level of whole or even parts of specimens across life stages, which holds promise in advancing freshwater bioassessment and monitoring routines (Stein et al. 2013). Despite the potential of eDNA for assessing the structural composition of aquatic communities, the current application of eDNA is still limited. eDNA may be useful in the long run (~10 y) in countries with lower-income economies (Hunting et al. 2017) once taxonomic databases are developed.

In LA, eDNA studies of freshwater invertebrates are scarce. Lack of funding, taxonomic resolution, and expertise, as well as incomplete DNA reference databases, hamper the development of eDNA techniques and their widespread application in LA. eDNA methods have most commonly been used in LA to support invasive species research, and some studies have used eDNA techniques to monitor endangered or rare vertebrate species (Brozio et al. 2017, Lopes et al. 2017). Our search yielded no studies that have used eDNA to support water-quality assessment programs in LA. We documented a single study in the Neotropical highland streams of Panama that used DNA barcodes to examine the genetic diversity of macroinvertebrate communities along an expansion gradient of chytrid fungus (Múrria et al. 2015).

Occupancy models

Another method used to analyze the relationship between taxa and environmental stressors is occupancy modeling (e.g., MacKenzie and Kendall 2002, Royle 2004). Occupancy modeling explicitly accounts for detectability of species and creates a framework that can be used to investigate ecological questions and processes, including species distribution modeling, habitat relationships, multispecies relationships, and community dynamics (Berkunsky et al. 2015). According to Bailey et al. (2014), >1000 papers have cited occupancy models since 2002, but none of the published studies evaluated water quality as predictors of macroinvertebrate distributions in LA. Our search results documented only 5 articles that used occupancy models to assess water quality. Three of these studies were from Argentina and described the sensitivity of Oligochaeta, Hirudinea, and Chironomidae species to environmental conditions (Cortelezzi et al. 2017, 2018, 2020). The other 2 studies were conducted in Costa Rica (Snyder et al. 2016) and Brazil (Callisto et al. 2021), and they used occupancy models to identify factors driving shrimp distribution in streams and to evaluate the effects of untreated wastewater on a macroinvertebrate assemblages, respectively.

The description of species sensitivity, in terms of occupancy and detection probability of taxa, allows scientists to evaluate how species distribution changes along an abiotic gradient. Studies using occupancy models to understand the sensitivity of local species to different types of stressors will allow researchers to generate more accurate biotic indices based on these taxa. Such studies will also allow scientists to create a priori predictions of the species that should be present or absent based on abiotic environmental conditions.

CHALLENGES IN FRESHWATER ECOSYSTEM MANAGEMENT

Biomonitoring originated in the GN approximately a century ago with the development of saprobic systems. These systems assessed rivers by measures of saprobity, i.e., the dependence of aquatic organisms on decomposing organic substances as a sole source of food (Persoone and De Pauw 1979). However, routine monitoring programs were not applied until 50 y later (Eriksen et al. 2021). Monitoring is essential because it is used to determine the success of management measures, evaluate the efficiency of management policy, and make decisions accordingly. Higher-income economies have implemented large-scale monitoring programs of continental European (European Union Water Framework Directive) and United States watersheds (Environmental Protection Agency's environmental monitoring). These programs are based on strict legislation to counteract degradation, initiate restoration, and manage aquatic ecosystems.

National biomonitoring programs are not as advanced in LA (Morse et al. 2007). In LA, the use of macroinvertebrates as bioindicators has almost exclusively been in research, although there are a few examples of their application to environmental monitoring (e.g., Monitoring Program of the Matanza-Riachuelo, Argentina; National Program for Monitoring Water Quality, Costa Rica; National Council for the Environment, Brazil). Thus, there is a need to shift biomonitoring applications from paper (research) to action (management). The tools generated by researchers should be applied to monitoring programs to inform management. Implementing this shift across countries in LA presents challenges involving, among other things, increasing citizen interest in freshwater ecosystem integrity leading to the exertion of pressure on decision-makers to propose and manage biomonitoring projects, increasing the political will to implement these programs, and increasing financial support for management efforts to improve the ecological quality of freshwater ecosystems.

Despite challenging relationships among governments, some countries in LA have managed to establish cross-border agreements and protocols. For example, 19 countries in LA and the Caribbean have codified the relationship between human rights and the environment by constitutionally recognizing the right to a healthy environment (UNECLAC 2018). Another example of multi-country efforts in environmental protection is the Ibero-American Network for the Formulation and Application of Protocols for the Evaluation of the Ecological Status, Management, and Restoration of Rivers (Rodríguez Olarte et al. 2020). This network promotes multilateral cooperation between people, institutions, and countries (Argentina, Brazil, Colombia, Chile, Ecuador, Spain, Portugal, Uruguay, and Venezuela) by providing tools for evaluating the ecological state of rivers, according to different regional conditions. One of their goals is to intercalibrate the protocols for assessing the ecological status of South American rivers, which will lay the technical scientific basis for the integrated management of rivers, especially in the face of an increasing climate emergency. Underscoring the importance of this kind of cooperation among countries is the fact that LA has 38 shared basins, which are home to at least 30% of its human population, and which supply 75% of the total surface water in the region (data taken from Transboundary Freshwater Dispute Database; https://transboundarywaters.science.oregonstate.edu/content/transboundary-freshwater-dispute-database). The integral management of these hydrographic basins represents a challenge to international cooperation. Integrating biomonitoring programs into efforts to manage shared basins could be a strategic way to enhance biodiversity information and to support the development of taxonomic expertise while enhancing regionally relevant management tools.

Despite great legal and environmental advances made in recent times, much remains to be done in LA in terms of availability of financial resources, training of qualified personnel in the environmental sectors of governments, introduction of transparency and accountability initiatives, and implementation of environmental impact assessments (Vizeu Pinheiro et al. 2020). In addition, ministries tasked with implementing environmental measures are often underfunded and politically weak compared with ministries responsible for economic or natural resource development (UNEP 2019). In view of this reality, the Escazú Agreement ratification (https://www.cepal.org/en/escazuagreement) before the United Nations is an opportunity to fill the gap between the laws and their application faced by LA. This agreement is the 1st environmental treaty at the regional level that seeks to promote access to information, participation, and justice in environmental matters. Although the Escazú Agreement will not provide funds for environmental research and restoration, it will ensure that the information on environmental impact assessment processes and environmental licenses or permits granted by public authorities can be consulted by any citizen of the participating countries. The problems related to the management of aquatic ecosystems in LA are complex, but the generation of networks and collaboration between countries are important ways to manage resources.

Conclusions and future perspectives

We call for countries in LA to make efforts to improve their biomonitoring standards by advancing the knowledge of their aquatic biodiversity. It is essential to have enough information about macroinvertebrate taxa to establish ecological status of LA ecosystems and evaluate the most effective management measures. This taxonomic knowledge is required to identify bioindicators capable of providing quantifiable links between changes in water quality and the condition of aquatic ecosystems. These advances will also support the development of more reliable and effective local indices for regional biomonitoring. Additionally, understanding the links between land use and freshwater biodiversity at the regional scale is urgent to plan biodiversity conservation. In addition, the use of trait-based approaches could potentially supplement traditional taxonomic monitoring tools. Above all, the biodiversity information gap in LA represents an opportunity to apply standardized methodologies that are comparable among studies and countries to monitor the effects of environmental challenges, including climate change and eutrophication of freshwater systems. Promoting collaborative projects between the GN and countries in LA is fundamental to the biodiversity conservation of the world. The participation of management institutions, universities, local and international specialists, and civil society is needed for the success of these international challenges. However, implementing monitoring and control programs is impossible without political will. A paradigm change is essential to strengthening the ecological and societal aspects of sustainability versus the primacy of the economic dimension. In addition to supporting sound scientific research, LA countries should introduce specific legislation and provide mandated agencies with proper training and funding to implement freshwater biomonitoring and bioassessment programs.

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LITERATURE CITED

Alonso-EguíaLis, P., J. M. Mora, B. Campbell, and M. Springer (editors). 2014. Diversidad, conservación y uso de los macroinvertebrados dulceacuícolas de México, Centroamérica, Colombia, Cuba y Puerto Rico. Instituto Mexicano de Tecnología del Agua, Jiutepec, México.

Bailey, L. L., D. I. MacKenzie, and J. D. Nichols. 2014. Advances and applications of occupancy models. Methods in Ecology and Evolution 5:1269–1279.

Barbour, M.T., J. Gerritsen, B. D. Snyder, and J. B. Stribling. 1999. Rapid bioassessment protocols for use in streams and wadeable rivers: Periphyton, benthic macroinvertebrates and fish. 2nd edition. EPA 841-B-99-002. United States Environmental Protection Agency, Office of Water, Washington, DC.

Barbour, M. T., W. F. Swietlik, and S. K. Jackson. 2000. Measuring the attainment of biological integrity in the USA: A critical element of ecological integrity. Hydrobiologia 422:453–464.

Berkunsky, I., M. V. Simoy, R. E. Cepeda, C. B. Marinelli, F. P. Kacoliris, G. Daniele, J. A. Díaz Luque, A. Cortelezzi, and R. M. Aramburu. 2015. Assessing the use of forest islands by parrot species in a neotropical savanna. Avian Conservation and Ecology 10:11.

Bonada, N., M. Rieradevall, N. Prat, and V. H. Resh. 2006. Benthic macroinvertebrate assemblages and macrohabitat connectivity

in Mediterranean-climate streams of northern California. Journal of the North American Benthological Society 25:32–43.
Brozio, S., C. Manson, E. Gourevitch, T. J. Burns, M. S. Greener, J. R. Downie, and P. A. Hoskisson. 2017. Development and application of an eDNA method to detect the critically endangered Trinidad golden tree frog (*Phytotriades auratus*) in bromeliad phytotelmata. PLoS ONE 12:e0170619.
Callisto, M., R. L. Massara, M. S. Linares, and R. M. Hughes. 2021. Benthic macroinvertebrate assemblages detect the consequences of a sewage spill: A case study of a South American environmental challenge. Limnology 23:181–194.
Carter, J. L., and V. H. Resh. 2013. Analytical approaches used in stream benthic macroinvertebrate biomonitoring programs of state agencies in the USA. Open-file Report 2013–1129. United States Geological Survey, Reston, Virginia.
Castello, L., D. G. McGrath, L. L. Hess, M. T. Coe, P. A. Lefebvre, P. Petry, M. N. Macedo, V. F. Renó, and C. C. Arantes. 2013. The vulnerability of Amazon freshwater ecosystems. Conservation Letters 6:217–229.
Chang, F. H., J. E. Lawrence, B. Rios-Touma, and V. H. Resh. 2014. Tolerance values of benthic macroinvertebrates for stream biomonitoring: Assessment of assumptions underlying scoring systems worldwide. Environmental Monitoring and Assessment 186:2135–2149.
Chen, K., R. M. Hughes, J. G. Brito, C. G. Leal, R. P. Leitão, J. M. de Oliveira-Júnior, and J. Zuanon. 2017. A multi-assemblage, multi-metric biological condition index for eastern Amazonia streams. Ecological Indicators 78:48–61.
Cortelezzi, A., L. Armendáriz, M. V. Simoy, C. B. Marinelli, R. E. Cepeda, A. Rodrigues Capítulo, and I. Berkunsky. 2017. Site-occupancy modelling: A new approach to assess sensitivity of indicator species. Ecological Indicators 79:191–195.
Cortelezzi, A., B. Gullo, M. V. Simoy, R. E. Cepeda, C. B. Marinelli, A. Rodrigues Capítulo, and I. Berkunsky. 2018. Assessing the sensitivity of leeches as indicators of water quality. Science of the Total Environmental 624:1244–1249.
Cortelezzi, A., M. V. Simoy, A. Siri, M. Donato, R. E. Cepeda, C. B. Marinelli, and I. Berkunsky. 2020. New insights on bioindicator value of Chironomids by using occupancy modelling. Ecological Indicators 117:106619.
Darling, J. A. 2019. How to learn to stop worrying and love environmental DNA monitoring, Aquatic Ecosystem Health & Management 22:440–451.
de Carvalho, D. R., C. G. Leal, N. T. Junqueira, M. A. de Castro, D. C. Fagundes, C. B. M. Alves, R. Hughes, and P. S. Pompeu. 2017. A fish-based multimetric index for Brazilian savanna streams. Ecological Indicators 77:386–396.
de Freitas, C. M., S. G. de Oliveira, G. E. Schütz, M. B. Freitas, and M. P. Gómez Camponovo. 2007. Ecosystem approaches and health in Latin America. Cadernos Saúde Pública 23:283–296.
Domínguez, E., and H. Fernández. 2009. Macroinvertebrados bentónicos sudamericanos: Sistemática y biología. 1st edición. Fundación Miguel Lillo. San Miguel de Tucumán, Argentina.
Eriksen, T. E., J. E. Brittain, G. Søli, D. Jacobsen, P. Goethals, and N. Friberg. 2021. A global perspective on the application of riverine macroinvertebrates as biological indicators in Africa, South-Central America, Mexico and Southern Asia. Ecological Indicators 126:107609.
European Commission. 2000. European Water Framework Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy. OJ L 327. European Environment Agency, Copenhagen, Denmark. (Available from: https://www.eea.europa.eu/policy-documents/directive-2000-60-ec-of)
Feio, M. J., R. M. Hughes, M. Callisto, S. J. Nichols, O. N. Odume, B. R. Quintella, M. Kuemmerlen, F. C. Aguiar, S. F. P. Almeida, P. Alonso-EguíaLis, F. O. Arimoro, F. J. Dyer, J. S. Harding, J. Sukhwan, P. R. Kaufmann, S. Lee, J. Li, D. R. Macedo, A. Mendes, N. Mercado-Silva, W. Monk, K. Nakamura, G. G. Ndiritu, R. Ogden, M. Peat, T. B. Reynoldson, B. Rios-Touma, P. Segurado, and A. G. Yates. 2021. The biological assessment and rehabilitation of the world's rivers: An overview. Water 13:371.
Ferreira, T., N. Caiola, F. Casals, J. M. Oliveira, and A. De Sostoa. 2007. Assessing perturbation of river fish communities in the Iberian Ecoregion. Fisheries Management and Ecology 14:519–530.
Friberg, N., N. Bonada, D. C. Bradley, M. J. Dunbar, F. K. Edwards, J. Grey, R. B. Hayes, A. G. Hildrew, N. Lamouroux, M. Trimmer, and G. Woodward. 2011. Biomonitoring of human impacts in freshwater ecosystems: The good, the bad and the ugly. Advances in Ecological Research 44:1–68.
Gerhardt, A. 2000. Biomonitoring of polluted water. Trans Tech Publications, Zurich-Uetikon, Switzerland.
Gutiérrez-Fonseca, P. E., and M. Tagliaferro. 2023. Context matters: An insider's view on freshwater ecosystem research in Latin America Freshwater Science 42:190–194.
Hanson, P., M. Springer, and A. Ramirez. 2010. Introducción a los grupos de macroinvertebrados acuáticos. Revista de Biología Tropical 58:3–37.
Hawkins, C. P., and D. M. Carlisle. 2022. Biological assessments of aquatic ecosystems. Encyclopedia of Inland Waters 2:525–536.
Hellawell, J. M. 1978. Biological surveillance of rivers: A biological monitoring handbook. Water Research Center, Stevenage Laboratory, United Kingdom.
Hering, D., O. Moog, L. Sandin, and P. F. M. Verdonschot. 2004. Overview and application of the AQEM assessment system. Hydrobiologia 516:1–20.
Hilsenhoff, W. L. 1988. Rapid field assessment of organic pollution with a family-level biotic index. Journal of the North American Benthological Society 7:65–68.
Hunting, E. R., S. de Jong, and M. G. Vijver. 2017. Assessment of monitoring tools and strategies safeguarding aquatic ecosystems within the European water framework directive. Lieden University, Institute of Environmental Sciences, Conservation Biology, Lieden, The Netherlands.
Karr, J. R. 1981. Assessment of biotic integrity using fish communities. Fisheries 6:21–27.
Karr, J. R. 1999. Defining and measuring river health. Freshwater Biology 41:221–234.
Karr, J. R., and E. W. Chu. 1997. Biological monitoring and assessment: Using multimetric indices effectively. EPA 235-R97-001. University of Washington, Seattle, Washinton.
Keck, F., V. Vasselon, K. Tapolczai, F. Rimet, and A. Bouchez. 2017. Freshwater biomonitoring in the Information Age. Frontiers in Ecology and Environment 15:266–274.
Leese, F., F. Altermatt, A. Bouchez, T. Ekrem, D. Hering, K. Meissner, P. Mergen, J. Pawlowski, J. Piggott, F. Rimet, D. Steinke, P. Taberlet, A. Weigand, K. Abarenkov, P. Beja, L. Bervoets, S. Björnsdóttir, P. Boets, A. Boggero, A. Bones,

Á. Borja, K. Bruce, V. Bursić, J. Carlsson, F. Čiampor, Z. Čiamporová-Zatovičová, E. Coissac, F. Costa, M. Costache, S. Creer, Z. Csabai, K. Deiner, Á. DelValls, S. Drakare, S. Duarte, T. Eleršek, S. Fazi, C. Fišer, J.-F. Flot, V. Fonseca, D. Fontaneto, M. Grabowski, W. Graf, J. Guðbrandsson, M. Hellström, Y. Hershkovitz, P. Hollingsworth, B. Japoshvili, J. Jones, M. Kahlert, B. K. Stroil, P. Kasapidis, M. Kelly, M. Kelly-Quinn, E. Keskin, U. Kõljalg, Z. Ljubešić, I. Maček, E. Mächler, A. Mahon, M. Marečková, M. Mejdandzic, G. Mircheva, M. Montagna, C. Moritz, V, Mulk, A. Naumoski, I. Navodaru, J. Padisák, S. Pálsson, K. Panksep, L. Penev, A. Petrusek, M. Pfannkuchen, C. Primmer, B. Rinkevich, A. Rotter, A. Schmidt-Kloiber, P. Segurado, A. Speksnijder, P. Stoev, M. Strand, S. Šulčius, P. Sundberg, M. Traugott, C. Tsigenopoulos, X. Turon, A. Valentini, B. van der Hoorn, G. Várbíró, M. V. Hadjilyra, J. Viguri, I. Vitonytė, A. Vogler, T. Vrålstad, W. Wägele, R. Wenne, A. Winding, G. Woodward, B. Zegura, and J. Zimmermann. 2016. DNAqua-Net: Developing new genetic tools for bioassessment and monitoring of aquatic ecosystems in Europe. Research Ideas and Outcomes 2:e11321.

Lenat, D. R. 1993. A biotic index for the southeastern United States: Derivation and list of tolerance values, with criteria for assigning water-quality ratings. Journal of the North American Benthological Society 12:279–290.

Leonardsson, K., M. Blomqvist, M. Magnusson, A. Wikström, and R. Rosenberg. 2015. Calculation of species sensitivity values and their precision in marine benthic faunal quality indices. Marine Pollution Bulletin 93:94–102.

Lopes, C. M., T. Sasso, A. Valentini, T. Dejean, M. Martins, K. R. Zamudio, and C. F. B. Haddad. 2017. eDNA metabarcoding: A promising method for anuran surveys in highly diverse tropical forests. Molecular Ecology Resources 17:904–914.

Macedo, D. R., R. M. Hughes, W. R. Ferreira, K. R. Firmiano, D. R. O. Silva, R. Ligeiro, P. R. Kaufmann, and M. Callisto. 2016. Development of a benthic macroinvertebrate multimetric index (MMI) for neotropical savanna headwater streams. Ecological Indicators 54:132–141.

MacKenzie, D. I., and W. L. Kendall. 2002. How should detection probabilities be incorporated into estimates of relative abundance? Ecology 83:2387–2393.

Mandaville, S. M. 2002. Benthic macroinvertebrates in freshwaters–Taxa tolerance, values, metrics, and protocols. Project H-1, Soil & Water Conservation Society of Metro Halifax, Halifax, Canada. (Available from: http://lakes.chebucto.org/H-1/tolerance.pdf)

Martins, I., D. R. Macedo, R. M. Hughes, and M. Callisto. 2021. Major risks to aquatic biotic condition in a neotropical savanna river basin. River Research and Application 37:858–868.

Menezes, S., D. J. Baird, and A. M. Soares. 2010. Beyond taxonomy: A review of macroinvertebrate trait-based community descriptors as tools for freshwater biomonitoring. Journal of Applied Ecology 47:711–719.

Metcalfe, J. L. 1989. Biological water quality assessment of running waters based on macroinvertebrate communities: History and present status in Europe. Environmental Pollution 60:101–139.

Morse, J. C., Y. J. Bae, G. Munkhjargal, N. Sangpradub, K. Tanida, T. S. Vshivkova, B. Wang, L. Yang, and C. M. Yule. 2007. Freshwater biomonitoring with macroinvertebrates in East Asia. Frontiers in Ecology and the Environment 5:33–42.

Moya, N., R. M. Hughes, E. Domínguez, F. M. Gibon, E. Goitia, and T. Oberdorff. 2011. Macroinvertebrate-based multimetric predictive models for evaluating the human impact on biotic condition of Bolivian streams. Ecological Indicators 11:840–847.

Múrria, C., A. T. Rugenski, M. R. Whiles, and A. P. Vogler. 2015. Long-term isolation and endemicity of Neotropical aquatic insects limit the community responses to recent amphibian decline. Diversity and Distributions 21:938–949.

ORyan, R., and C. Ibarra. 2016. Environmental policy in Latin America. Pages 1722–1730 *in* A. Farazmand (editor). Global encyclopedia of public administration, public policy, and governance. Springer, Cham, Switzerland.

Palma, A. 2013. Guía para la identificación de invertebrados acuáticos. 1era edición. Instituto de Filosofía y Ciencias de la Complejidad, Región Metropolitana, Chile. (Available from: shorturl.at/sKVW5)

Paz, L. E., M. Rodriguez, B. Gullo, and A. Rodrigues Capítulo. 2022. Impacts of urban and industrial pollution on functional traits of benthic macroinvertebrates: Are some traits advantageous for survival? Science of the Total Environmental 807: 150650.

Pérez, A., N. Salazar, F. Aguirre, M. Font, E. Zamora, A. Córdova, K. and K. Acosta. 2016. Guía de macroinvertebrados bentónicos de la provincia de Orellana. Associació Catalana d'Enginyeria Sense Fronteres, El Coca, Orellana, Ecuador. (Available from: shorturl.at/hxA23)

Persoone, G., and N. De Pauw. 1979. Systems of biological indicators for water quality assessment. Pages 39–75 *in* O. Ravera (editor). Biological Aspects of Freshwater Pollution. Proceedings of the Course Held at the Joint Research Centre of the Commission of the European Communities, Ispra, Italy, 5–9 June 1978.

Plafkin, J. L., M. T. Barbour, K. D. Porter, S. K. Gross, and R. M. Hughes. 1989. Rapid bioassessment protocols for use in streams and rivers: Benthic macroinvertebrates and fish. EPA/444/4-89-001. United States Environmental Protection Agency, Office of Water, Washington, DC.

Ramirez, A., and P. E. Gutiérrez-Fonseca. 2020. Freshwater research in Latin America: Current research topics, challenges, and opportunities. Revista de Biología Tropical 68:1–12.

Righi-Cavallaro, K. O., M. R. Spies, and A. E. Siegloch. 2010. Composição da fauna de Ephemeroptera, Plecoptera e Trichoptera na bacia do Rio Miranda, Estado do Mato Grosso do Sul, Brasil. Biota Neotropical 10:22010.

Ríos-Touma, B., R. Acosta, and N. Prat. 2014. The Andean Biotic Index (ABI): Revised tolerance to pollution values for macroinvertebrate families and index performance evaluation. Revista de Biología Tropical 62:249–273.

Rodríguez Olarte, D., M. Barrios, L. Caputo, P. Fierro, P. Jiménez-Prado, E. Navarro, P. Macchi, J. I. Mojica. J. Molinero, J. V. Montoya, A. Pantoja, M. Pompêo, B. Ríos-Touma, F. Teixeira de Mello, F. Tobón, A. Torremorell, A. Villalba, and C. Villamarín. 2020. Criterios para la evaluación de estresores y parámetros en la estimación del estado ecológico de ríos en Suramérica. Serie Publicaciones Especiales. Museo de Ciencias Naturales. Universidad Centroccidental Lisandro Alvarado, Barquisimeto, Lara, Venezuela. (Available from: https://www.academia.edu/43531945/Criterios_evaluacion_rios_Suramerica_baja)

Roldán Pérez, G. 1988. Guía para el estudio de los macroinvertebrados acuáticos del Departamento de Antioquia. Universidad de Antioquia, Medellín, Antioquia, Colombia. (Available from: https://ianas.org/wp-content/uploads/2020/07/wbp13.pdf)

Royle, J.A. 2004. N-Mixture models for estimating population size from spatially replicated counts. Biometrics 60: 108–115.

Ruaro, R., and E. A Gubiani. 2013. A scientometric assessment of 30 years of the Index of Biotic Integrity in aquatic ecosystems: Applications and main flaws. Ecological Indicators 29: 105–110.

Schmidt-Kloiber, A., and D. Hering. 2015. www.freshwaterecology.info—An online tool that unifies, standardises and codifies more than 20,000 European freshwater organisms and their ecological preferences. Ecological Indicators 53:271–282.

Silva, D. R. O., A. T. Herlihy, R. M. Hughes, and M. Callisto. 2017. An improved macroinvertebrate multimetric index for the assessment of wadeable streams in the neotropical savanna, Brazil. Ecological Indicators 81:514–525.

Silva, D. R. O., A. T. Herlihy, R. M. Hughes, D. R. Macedo, and M. Callisto. 2018. Assessing the extent and relative risk of aquatic stressors on stream macroinvertebrate assemblages in the neotropical savanna. Science of the Total Environmental 633:179–188.

Snyder, M. N., M. C. Freeman, S. T. Purucker, and C. M. Pringle. 2016. Using occupancy modeling and logistic regression to assess the distribution of shrimp species in lowland streams, Costa Rica: Does regional groundwater create favorable habitat? Freshwater Science 35:80–90.

Statzner, B., and L. A. Bêche. 2010. Can biological invertebrate traits resolve effects of multiple stressors on running water ecosystems? Freshwater Biology 55:80–119.

Stein, E. D., B. P. White, R. D. Mazor, J. K. Jackson, J. M. Battle, P. E. Miller, E. M. Pilgrim, and B. W. Sweeney. 2013. Does DNA barcoding improve performance of traditional stream bioassessment metrics? Freshwater Science 33:302–311.

UNECLAC (United Nations Economic Commission for Latin America and the Caribbean). 2018. Access to information, participation and justice in environmental matters in Latin America and the Caribbean: Towards achievement of the 2030 Agenda for Sustainable Development. LC/TS.2017/83. United Nations Economic Commission for Latin America and the Caribbean, Santiago, Chile.

UNEP (United Nations Environment Programme). 2019. Environmental Rule of Law: First Global Report. United Nations Environment Programme, Nairobi, Kenya.

Vadas, R. L., R. M. Hughes, Y. J. Bae, M. J. Baek, O. C. Bello Gonzáles, M. Callisto, D. Reis de Carvalho, K. Chen, M. T. Ferreira, P. Fierro, J. S. Harding, D. M. Infante, C. J. Kleynhans, D. R. Macedo, I. Martins, N. Mercado Silva, N. Moya, S. J. Nichols, P. S. Pompeu, R. Ruaro, D. R. O. Silva, R. J. Stevenson, B. de Freitas Terra, C. Thirion, D. Ticiani, L. Wang, and C. O. Yoder. 2022. Assemblage-based biomonitoring of freshwater ecosystem health via multimetric indices: A critical review and suggestions for improving their applicability. Water Biology and Security 1:100054.

Van den Berg, S. J., L. Maltby, T. Sinclair, R. Liang, and P. J. van den Brink. 2020. Cross-species extrapolation of chemical sensitivity. Science of Total Environmental 753:141800.

Vieira, N. K. M., N. L. Poff, D. M. Carlisle, S. R. Moulton II, M. L. Koski, and B. C. Kondratieff. 2006. A database of lotic invertebrate traits for North America. Data Series 187. United States Geological Survey, Reston, Virginia.

Vizeu Pinheiro, M., L. Rojas Sánchez, S. C. Long, and A. Ponce. 2020. Environmental governance indicators for Latin America & the Caribbean: A cross-country assessment of environmental governance in practice in Argentina, Bolivia, Brazil, Colombia, Costa Rica, the Dominican Republic, El Salvador, Jamaica, Peru & Uruguay. Inter-American Development Bank, Washington, DC. (Available from: https://publications.iadb.org/publications/english/viewer/Environmental-Governance-Indicators-for-Latin-America–the-Caribbean.pdf)

Weber, C. I. 1973. Biological field and laboratory methods for measuring the quality of surface waters and effluents: Cincinnati, Ohio. EPA-670/4-73-001. United States Environmental Protection Agency, Cincinnati, Ohio.

Whittier, T. R., and J. Van Sickle. 2010. Macroinvertebrate tolerance values and an assemblage tolerance index (ATI) for western USA streams and rivers. Journal of the North American Benthological Society 29:852–866.

Yadamsuren, O., J. C. Morse, B. Hayford, J. K. Gelhaus, and P.H. Adler. 2020. Macroinvertebrate community responses to land use: A trait-based approach for freshwater biomonitoring in Mongolia. Hydrobiologia 847:1887–1902.

Zhang, B., R. M. Hughes, W. S. Davis, and C. Cao. 2021. Big data challenges in overcoming China's water and air pollution: Relevant data and indicators. SN Applied Sciences 3:469.