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FRESHWATER BIVALVES

# Conservation of freshwater bivalves at the global scale: diversity, threats and research needs

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**Abstract** Bivalves are ubiquitous members of freshwater ecosystems and responsible for important functions and services. The present paper revises freshwater bivalve diversity, conservation status and threats at the global scale and discusses future research needs and management actions. The diversity patterns are uneven across the globe with hotspots in the interior basin in the United States of America (USA), Central America, Indian subcontinent and Southeast Asia. Freshwater bivalves are affected by multiple threats that vary across the globe; however, pollution and natural system (habitat) modifications being consistently found as the most impacting. Freshwater bivalves are among the most threatened groups in the world with 40% of the species being near threatened, threatened or extinct, and among them the order Unionida is the most endangered. We suggest that global cooperation between scientists, managers, politicians and general public, and application of new technologies (new generation sequencing and remote sensing, among others) will strengthen the quality of studies on the natural history and conservation of freshwater bivalves. Finally, we introduce

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the articles published in this special issue of *Hydrobiologia* under the scope of the Second International Meeting on Biology and Conservation of Freshwater Bivalves held in 2015 in Buffalo, New York, USA.

**Keywords** Bivalvia · Unionida · Venerida · IUCN Red List · Freshwater mussels · Conservation

## Introduction

Freshwater ecosystems are among the most threatened on the planet facing unprecedented pressures related to the increase of human population and socioeconomic development (Dudgeon et al., 2006; Vörösmarty et al., 2010). Increasing anthropogenic pressure worldwide results in habitat loss, habitat modification and fragmentation, overexploitation of natural resources (including water), pollution, introduction of invasive alien species (IAS) and climate change (Malmqvist & Rundle, 2002; Strayer & Dudgeon, 2010). Biodiversity crisis is one of the major consequences of steeply rising human demands, and among the animals with high extinction rates are freshwater bivalves (FB) (Strayer et al., 2004; Lydeard et al., 2004; Régnier et al., 2009; Lopes-Lima et al., 2014, 2017a). The future survival of FB is highly impaired and considering the large suite of ecosystem services they provide (Vaughn, 2017) scientists, managers, politicians and the general public need to strengthen their cooperation in order to conserve these species.

Whereas over the last years multiple studies have been published concerning the biology, ecology and conservation of FB, the majority of them were carried out in North America and Europe (Lopes-Lima et al., 2014). Consequently, a great ignorance about basic aspects (e.g. distribution, diversity, abundance, population structure and life cycle) concerning species inhabiting South America, Africa and Asia still persists and much more information is needed for these continents.

In the present paper, we compile data on FB diversity patterns, conservation status and threats from the International Union for Conservation of Nature (IUCN) database using a species list adapted from Graf & Cummings (2017) and mapped them in ecoregions adapted from Graf & Cummings (2007) and Haag (2010). We also briefly discuss research needs and urgent management actions that may help conserve these animals, and introduce the articles published in this special issue resulting from the Second International Meeting on Biology and Conservation of Freshwater Bivalves held in 2015 in Buffalo, United States of America (USA).

## Diversity patterns at the global scale

FB are a polyphyletic group of animals restricted to fresh waters with a little over 1,200 described species (Bogan, 2008; Bogan & Roe, 2008; Graf, 2013). The main core of the group (99%) is composed of freshwater mussels of the order Unionida (strictly freshwater) (72%) and species belonging to 7 families within the order Venerida (27%) (Fig. 1). The Venerida are composed mainly of families comprising 94% of the species the pea- or fingernail-clams Sphaeriidae (67%) and the Cyrenidae (27%), which include, for example, the invasive Asian clam *Corbicula fluminea* (Müller, 1774). The family Dreissenidae family (3%), well-known to contain important invasive alien species (IAS) such as the quagga mussel *Dreissena bugensis* Andrusov, 1897 and the zebra mussel *Dreissena polymorpha* (Pallas, 1771), is also included in the order Venerida. The remaining handful of FB species are scattered among other essentially marine orders or families within the order Venerida (Fig. 1).

FB are present in all continents except in glaciated (with the exception of few sphaeriid species) and desert areas, but the diversity patterns are not evenly distributed (Fig. 2). The diversity is higher in the Nearctic (NA), Neotropics (NT) and Indotropics (IN) with ≈ 25% species being found in each ecoregion. The Palaearctic (PA) and Afrotropics (AF) have a lower diversity (≈ 10%) with Australasia (AU) being the poorest ecoregion (≈ 5%) (Fig. 2A). There are also distinct distribution patterns across the main taxonomic groups. The Unionida is similar to the general pattern for all FB, with 33% of the species inhabiting the NA and 6% inhabiting the PA (Fig. 2B). The distribution of pea clams is completely distinct with the hotspots of diversity being the NT (31%) and the PA (22%), while the remaining diversity is scattered among the other continents (Fig. 2C). Sphaeriids are also the only FB species that are capable of living at the higher latitudes of the Arctic, such as the islands of Iceland, Greenland, Baffin,

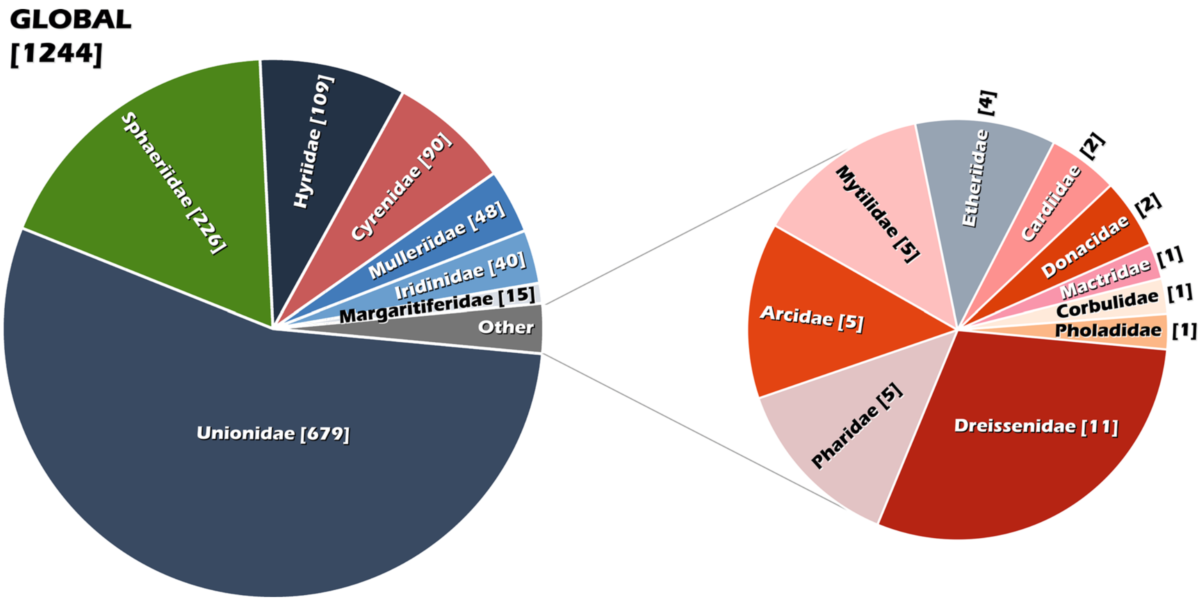


**Fig. 1** Global diversity of freshwater bivalves divided by families. Total number of species in brackets

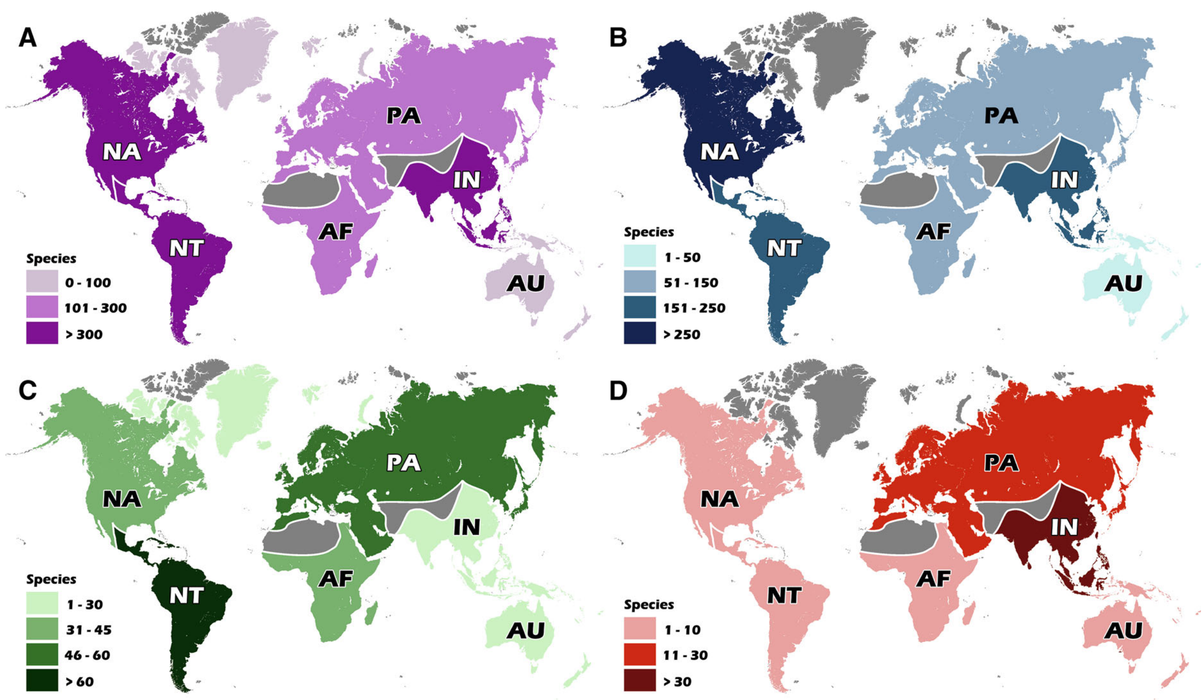


**Fig. 2** Diversity by ecoregions. **A** All freshwater bivalves; **B** Unionida; **C** Sphaeriidae; **D** Cyrenidae + remaining freshwater bivalve groups. Ecoregions adapted from Graf & Cummings (2007) and Haag (2010): *NA* Nearctic, *NT* Neotropical, *PA* Palaearctic, *AF* Afrotropical, *IN* Indotropical, *AU* Australasian. Glaciated and desert areas void of mussels in grey

Svalbard and Novaya Zemlya (Schiøtte & Warén, 1992; Bespalaya et al., 2017). Finally, for Cyrenidae and for a few other remaining species, the major diversity hotspot is in the IN that contains almost 70% of such species, followed by the PA (18%), while other ecoregions have a much lower diversity (Fig. 2D).

Diversity at an ecoregion scale is also not distributed evenly (Fig. 3). Within NA, the species diversity is generally higher in the interior basins, while in the NT the diversity is higher in Central America and in the Orinoco, Amazon and Paraguay River basins (Fig. 3A). In the AF, the Congo River basin is richer in Unionida species (Fig. 3B), and the Nile and Eastern African River basins have a higher sphaeriid diversity (Fig. 3C). While the Western Palaearctic is quite diverse in sphaeriids and dreissenids, Laurasia has a higher diversity in the IN, from the Hindu to the Amur River basin (Figs. 3A, C and D). Within IN, the diversity of sphaeriids is higher in the Indian subcontinent, while in the Unionida and the remaining groups the diversity is higher in Indochina and Sundaland (Fig. 3). In AU, a higher number of species is found in the East (Fig. 3).

Although specific diversity of FB is similar in NA, NT and IN, there is a higher taxonomic diversity in the IN than in NA and NT. In the IN there are representative species of 5 orders and 10 families compared to the 2 orders and 4 families in the NA and 3 orders and 8 families in the NT (Fig. 4). Even within the most species-rich FB family, the Unionidae, the IN exhibits a much higher taxonomic diversity than all of the other ecoregions, with representatives of all subfamilies of Unionidae occurring there, except for the NA Ambleminae.

We would like to stress that diversity patterns described above may be underestimated and may change substantially as a result of ongoing and future surveys in the less studied regions of Southeast Asia, Africa, NT and AU. For example, Bolotov et al. (2017) studying the FB of a poorly known and remote basin (Sittaung) in Myanmar described two new genera and seven new species. Also, even in Europe and NA, which are the most well-studied continents, the knowledge of the diversity of Unionida is still undergoing considerable changes (e.g. Froufe et al., 2016a, b, 2017; Araujo et al., 2017; Lopes-Lima et al., 2017a; Williams et al., 2017; Smith et al., 2018).

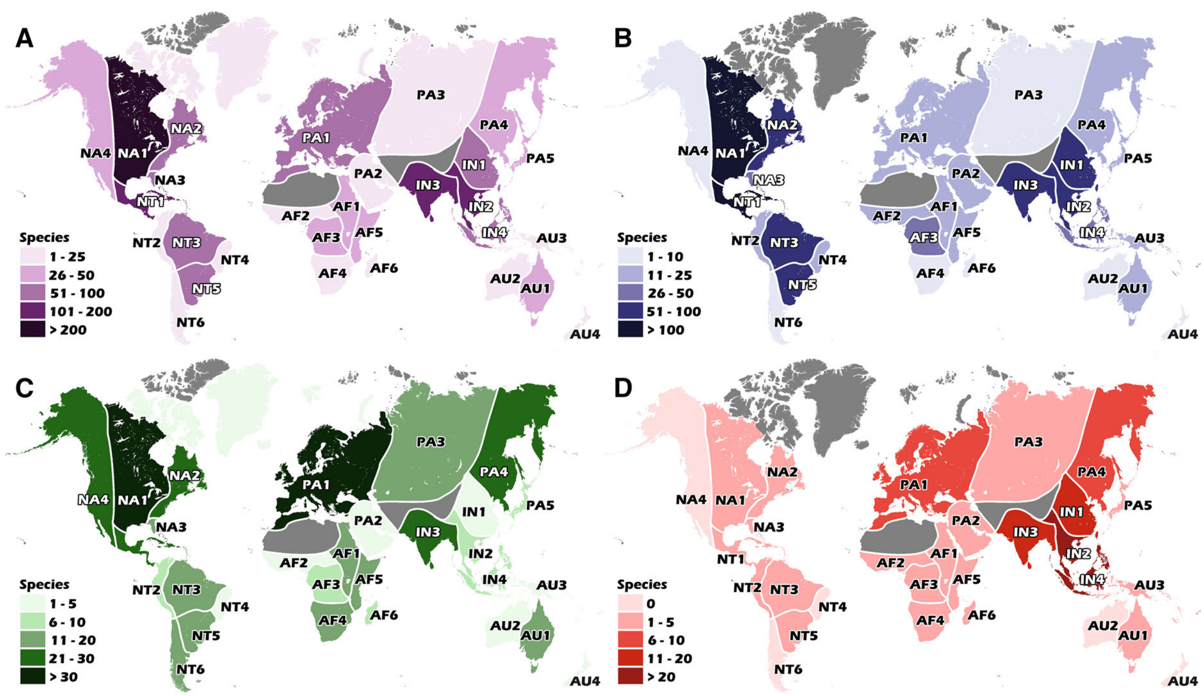


**Fig. 3** Diversity by ecoregions. **A** All freshwater bivalves; **B** Unionida; **C** Sphaeriidae; **D** Cyrenidae + remaining freshwater bivalve groups. Ecoregion subdivisions adapted from Graf & Cummings (2007) and Haag (2010): *NA* Nearctic, *NT* Neotropical, *PA* Palaearctic, *AF* Afrotropical, *IN* Indotropical, *AU* Australasian. Glaciated and desert areas lacking FB are in grey

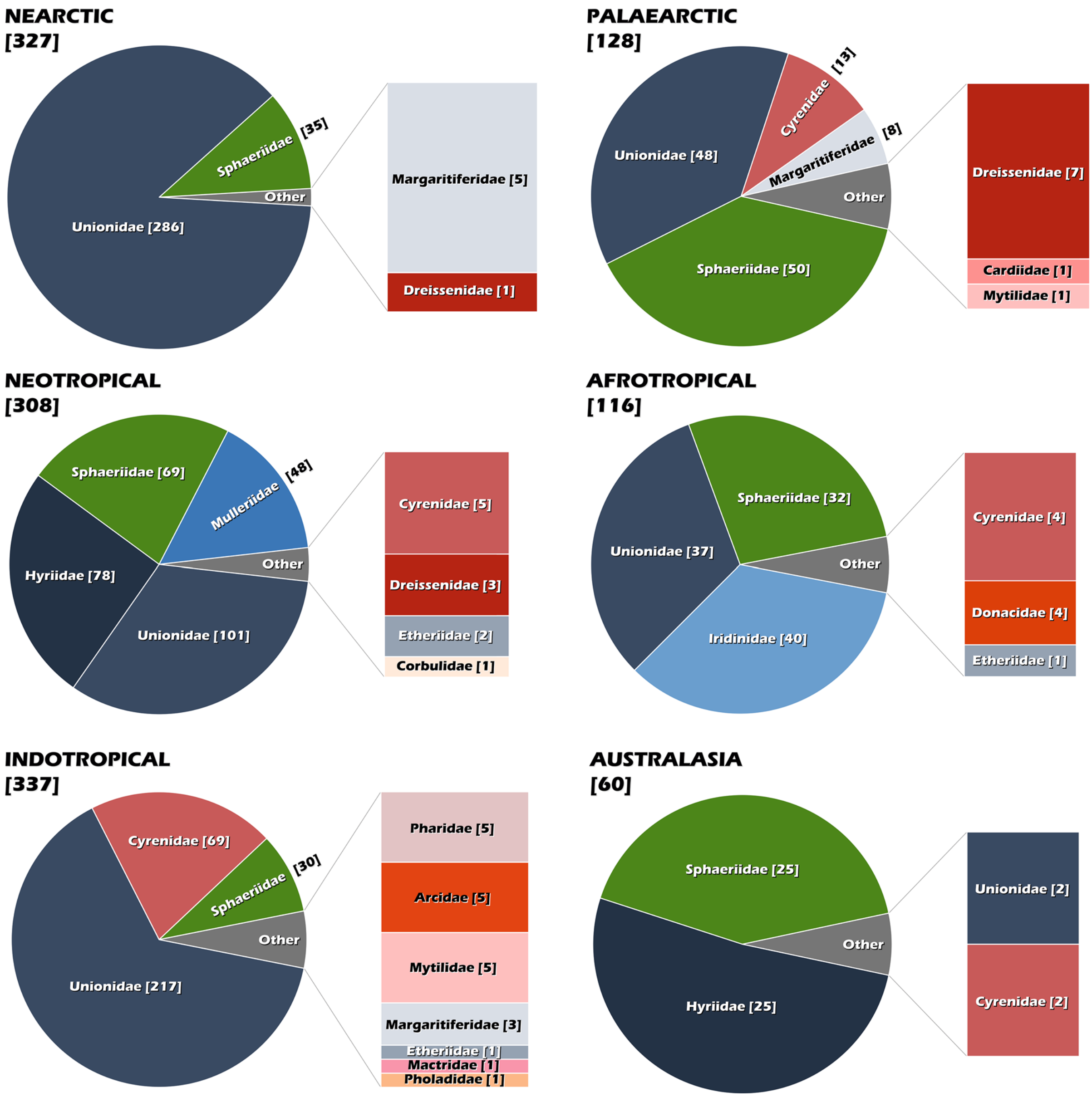


**Fig. 4** Taxonomic composition and diversity of freshwater bivalves in each ecoregion. Total number of species in brackets

## Conservation status and major threats

FB are among the most threatened taxonomic groups in the world, with almost 40% of the species being near threatened, threatened or extinct (Fig. 5). However, this high imperilment is mainly due to the contribution of Unionida since not all groups are evenly threatened or assessed for conservation status (Fig. 5, top). Based on the number of assessed species, the highest percentage (45%) of near-threatened, threatened and extinct species (including 25 [2.8%] extinct or probably extinct species) is in Unionida, while only 14.5% of Sphaeriidae and 8.8% of Cyrenidae (plus all the other remaining species) have a near-threatened or threatened status (Fig. 5, top part). However, IUCN assessments are not evenly distributed across taxa and countries and FB are a good example of this situation (Fig. 5). Thus, a higher percentage of large and more conspicuous unionids has been assessed compared to other FB groups

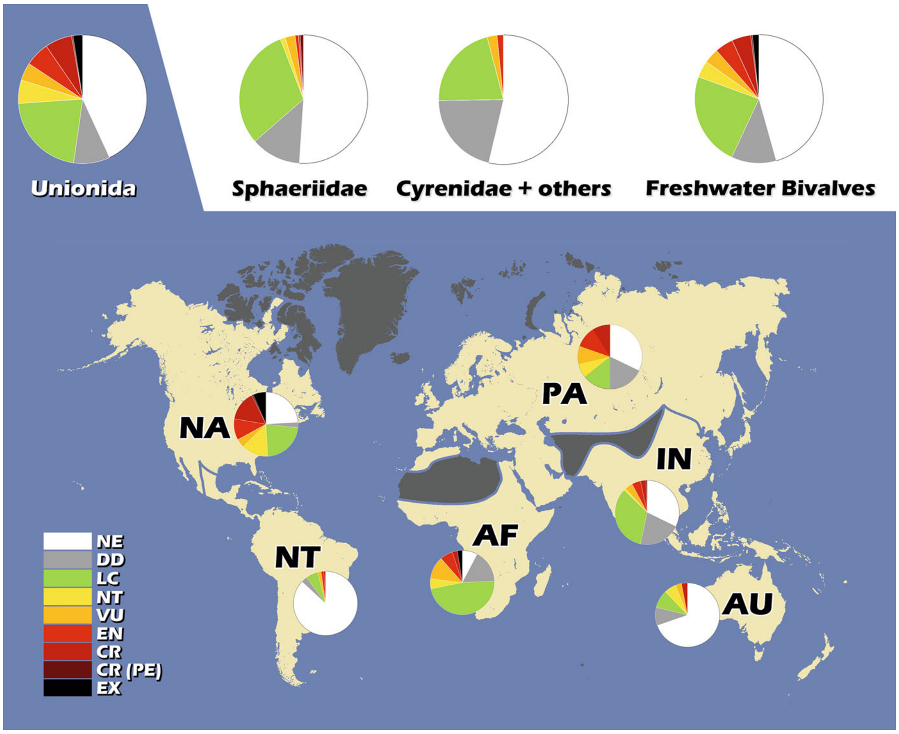


**Fig. 5** Map of IUCN Red List conservation status for Unionida freshwater mussels by ecoregions (bottom of the figure) and global conservation status for freshwater bivalves and each major freshwater bivalve group (top of the figure). Ecoregion subdivisions adapted from Graf & Cummings (2007) and Haag (2010): *NA* Nearctic, *NT* Neotropical, *PA* Palaearctic, *AF* Afrotropical, *IN* Indotropical, *AU* Australasian. On the scale bar: *NE* Not evaluated by the IUCN Red List; and the IUCN Red List categories: *DD* data deficient, *LC* least concern, *NT* near threatened, *VU* vulnerable, *EN* endangered, *CR* critically endangered, *CR (PE)* critically endangered probably extinct, *EX* extinct

(Fig. 5, top). Some ecoregions (e.g. NA, AF, PA and IN) have a high percentage of species evaluated, while species from AU and especially NT have a very low Red List coverage (Fig. 5, bottom part). The percentage of threatened and near-threatened Unionida species is higher in NA (67%) and PA (52%) than in other ecoregions, with the lowest percentage (19%) in the IN (Fig. 5, bottom). This does not necessarily mean that less species are threatened in the IN, since this ecoregion has a much higher percentage of data-deficient species, reflecting the lower level of knowledge and data on the threats available for IN species. On the other hand, almost half of the species have been assessed as of "least concern" in the AF, which might indicate a more favourable status of freshwater mussels in this ecoregion.

The IUCN Red List assessments are based on a set of five criteria: (A) population size reduction, (B) small geographic range, (C) small population size plus decline, (D) very small or restricted populations and (E) a quantitative analysis of extinction probability (IUCN, 2012). Most of the near-threatened and threatened FB species have been assessed using criteria A and B and to a much lesser extent using criteria C and D (Fig. 6). Since criterion E needs comprehensive data on a wide range of features (e.g. demography, life history, habitat requirements, threats and management options), no FB species was ever evaluated using this criterion (Fig. 6). Most FB species have been assessed based on their population size reduction and geographic range contraction compared to a few species with very small distribution ranges. In fact, it is difficult to assign a threatened status using criterion D for most FB species due to their generally large distribution ranges.

The global pattern is more or less similar in all ecoregions, with the exception of the NT and AF (Fig. 6). While the NT pattern may not be very representative of the ecoregion due to the few assessed species, in AF it reflects the poor knowledge about the

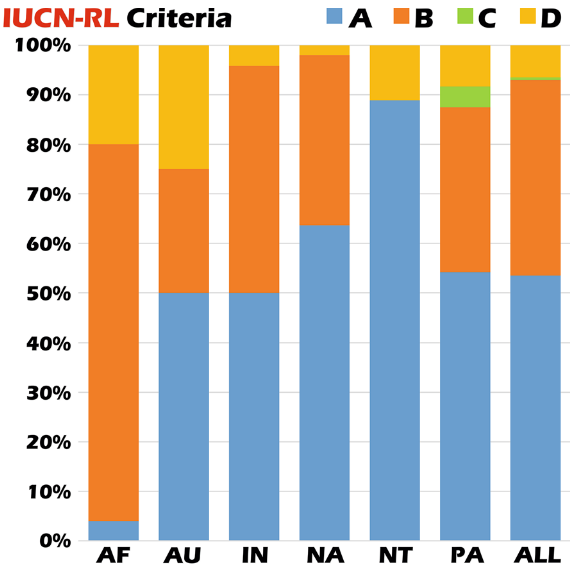


**Fig. 6** IUCN Red List criteria used for the assessment of freshwater bivalve species by ecoregions. Ecoregion subdivisions adapted from Graf & Cummings (2007) and Haag (2010): *AF* Afrotropical, *AU* Australasian, *IN* Indotropical, *NA* Nearctic, *NT* Neotropical, *PA* Palaearctic. IUCN Red List criteria: **A** population size reduction, **B** geographic range, **C** small population size and decline, **D** very small or restricted populations

population size and trends. This is due to the lack of research that is being done in the AF, where survey and monitoring studies are almost non-existent (Lopes-Lima et al., 2014; Sousa et al., 2016, 2017).

FB are affected by multiple threats that range from natural system modifications to degradation, pollution, introduction of IAS, exploitation and human disturbance. Within the assessed FB species for the IUCN Red List, pollution is still the most recorded global threat comprising 42% of all threats (Fig. 7). Natural system (habitat) modifications such as the construction of dams and channels are the second most cited threat (20%), followed by urban development, exploitation, agriculture, climate change, mining and IAS, together representing less than 10%. Other disturbances such as transport, recreational activities and geological events only play a minor role.

The relative percentage of recorded threats is generally similar across the main ecoregions with a few notable exceptions. For instance, in the NA and PA species seem to be less threatened by climate change than the tropical and southern hemisphere ecoregions. Conversely, in the more developed areas of the NA and the PA, habitat modifications seem to negatively affect more species in these ecoregions than in the AF and IN. Exploitation is a much more detrimental threat in the IN than elsewhere (Fig. 7). In fact, harvesting of mussels for human consumption in East and Southeast Asia is a major economic activity; for example, in Vietnam it may reach up to 50,000 tons per year in each major basin (Köhler et al., 2012). Furthermore, the ratio of agriculture related threats is higher in AU and PA, mainly due to water diversion and extraction.

## Research and conservation actions needs

Many species of FB are still poorly understood, especially in Central America, Southeast Asia and Sundaland (Lopes-Lima et al., 2014, 2017b). This lack of knowledge hampers their status assessment.

The IUCN database indicates that research needs are generally lower for the NA and PA compared to the other ecoregions, especially for the three top research needs, i.e. population size and distribution, identification of threats and life history (Fig. 8A). This may be explained by the stronger research effort and higher financial support available for North American and European studies. However, even in these ecoregions, basic data on distribution, population size, accurate identification of threats and basic life history traits are still lacking for many species. Taxonomical data and knowledge on life history traits are particularly needed for AF species. The same general trends in research needs can be seen for all species assessed by IUCN as well as for data-deficient species (Fig. 8B).

Due to the high risk of extinction, many species urgently need worldwide conservation actions. Land and water protection was found to be the top conservation measure globally and throughout all ecoregions, but especially for IN species (Fig. 9). Land and water management is also shown to be one of the top priorities for FB conservation, particularly in the PA and AF ecoregions (Fig. 9). Other types of conservation actions showed quite distinct patterns among ecoregions. For example, a stronger legislation is likely required for the AF, PA, NA and AU, but law enforcement needs to be enhanced only in the AF and PA ecoregions. Moreover, increasing awareness of the general public about the importance of conserving FB is quite essential for the PA and particularly in the IN.

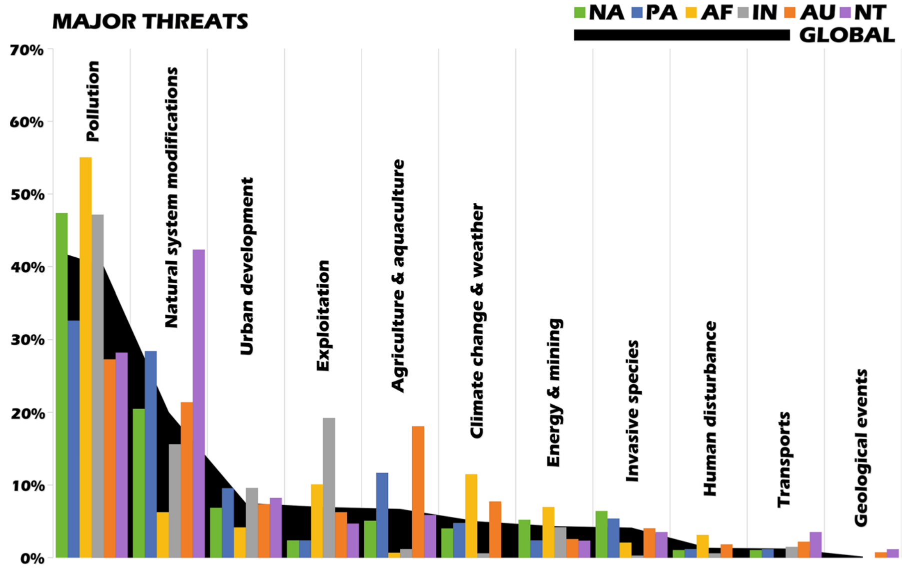


**Fig. 7** Main threats for freshwater bivalves recorded from the IUCN Red List database by ecoregions. Ecoregion subdivisions adapted from Graf & Cummings (2007) and Haag (2010): *NA* Nearctic, *NT* Neotropical, *PA* Palaearctic, *AF* Afrotropical, *IN* Indotropical, *AU* Australasian

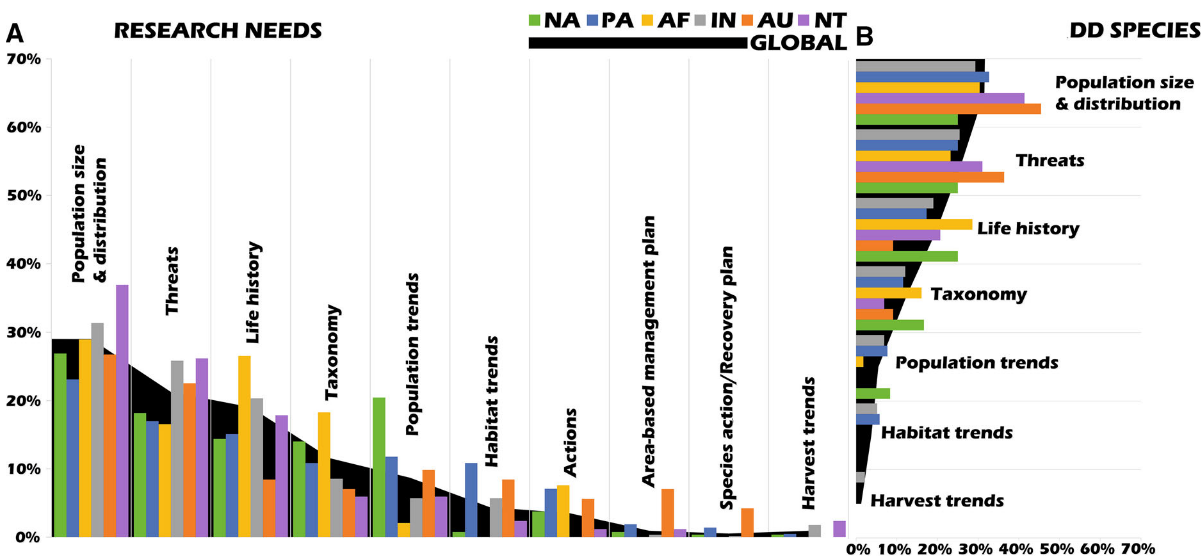


**Fig. 8** Research needs for freshwater bivalves recorded from the IUCN Red List database by ecoregions. **A** All assessed species in the IUCN Red List; **B** data-deficient species in the IUCN Red List. Ecoregion subdivisions adapted from Graf & Cummings (2007) and Haag (2010): *NA* Nearctic, *NT* Neotropical, *PA* Palaearctic, *AF* Afrotropical, *IN* Indotropical, *AU* Australasian. *DD* data-deficient species in the IUCN Red List

A special interest in species ex situ propagation and reintroduction programs is exhibited for the NA, emphasising the vast knowledge already accumulated for many species in the ecoregion (Fig. 9).

Although many research gaps and conservation needs have been identified in the last years, many recent technological advances can provide us with new insights that are needed for FB research. For example, new remote sensing techniques like underwater video and side-scan sonars may help survey FB populations, and identify more favourable habitats (Powers et al., 2014; Mehler et al., 2016). Use of drones in semi-arid regions can aid in tracking and identifying the remaining pools after droughts where mussels take refuge. These technologies and also the use of environmental DNA analyses may help

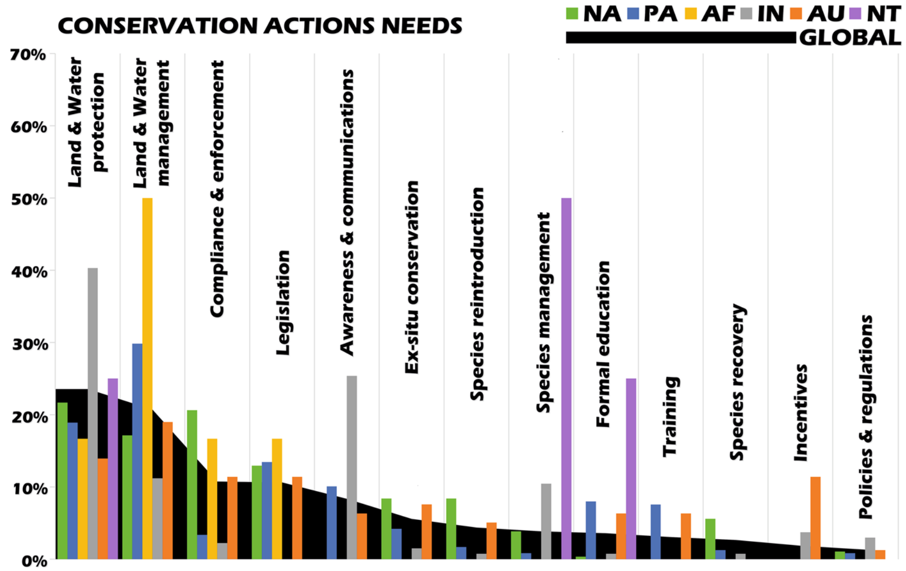


**Fig. 9** Conservation needs for freshwater bivalves extracted from the IUCN Red List database by ecoregions. Ecoregion subdivisions adapted from Graf & Cummings (2007) and Haag (2010): *NA* Nearctic, *NT* Neotropical, *PA* Palaearctic, *AF* Afrotropical, *IN* Indotropical, *AU* Australasian

gathering basic biological and ecological data on distribution and abundance, which are still missing for many species (Stoeckle et al., 2016). More powerful genetics and morphometric tools are also increasingly available, for instance, new statistical tools for species delimitation using molecular and/or other types of data such as morphometry and anatomical traits (e.g. Froufe et al., 2016b; Pfeiffer et al., 2016). These tools are particularly important owing to the fact that many species present hidden cryptic diversity (Froufe et al., 2016b; Pfeiffer et al., 2016). Additionally, next-generation sequencing is now allowing for quicker and less expensive robust phylogenies using methods like whole-transcriptome and whole-mitogenome analyses with a wide range of markers (Guerra et al., 2017; Lopes-Lima et al., 2017c). Furthermore, using reduced genome representations or snip analyses, it is now possible to get more information on the phylogeographic patterns of species and on the definition of conservation units (Catchen et al., 2017; Desalle & Amato, 2017).

While most of the global protected areas network is aimed at protecting essentially terrestrial vertebrates, the identification of sites to conserve freshwater vertebrates and invertebrates such as FB is also of crucial importance (Darwall et al., 2011; Maceda-Veiga et al., 2017). Using the IUCN Key Biodiversity Areas (KBAs) network (IUCN, 2016) or new systematic conservation planning approaches (e.g. Hermoso et al., 2015) may help to promote a better FB representation within protected area networks.

## The proceedings of the Second International Meeting on Biology and Conservation of Freshwater Bivalves

All the research and conservation needs summarised above make the facilitation of cooperation among scientists from different countries and continents particularly important. For example, recent reviews published by multinational teams of scientists provided vital baseline information about FB on different continents (e.g. Pereira et al., 2014 for South America, Walker et al., 2014 for Australia; Lopes-Lima et al., 2017a for Europe; Williams et al., 2017 for North America, and Zieritz et al., 2017 for East and Southeast Asia). Additionally, intercontinental cooperative research is also becoming increasingly common (see for example Zieritz et al., 2016; Lopes-Lima et al., 2017b). In order to discuss the current and future research challenges and needs, the Second International Meeting on Biology and Conservation of Freshwater Bivalves was hosted by the Great Lakes Centre at SUNY Buffalo State College in Buffalo, New York, USA, from 4 to 8 October 2015, bringing together over 80 scientists from 19 countries and four continents (Europe, North America, South America and Australia) (Burlakova et al., 2017).

The present special issue in *Hydrobiologia* comprises a total of 34 papers (including this introductory note) summarising some of the information presented in this meeting. These papers cover a wide variety of topics, from a review of ecosystem services provided by freshwater mussels (Vaughn, 2017) to papers describing the diversity patterns and conservation of Unionida in East and Southeast Asia (Zieritz et al., 2017) as a result of international collaboration. Seven papers focus on different biological aspects of invasive bivalve species, including diversity changes by species substitution (Karatayev et al., 2017), physiological aspects (Labecka & Domagala, 2016), dispersion (Collas et al., 2016), ecological effects on native bivalve species (Ferreira-Rodríguez et al., 2016), low palatability to distinct predators (Castro et al., 2017), metabolite emission suppression in zebra mussels exposed to predation stress (Antoł et al., 2017) and the use of a new sonar technology and underwater imagery analysis for the survey of FB in rivers (Mehler et al., 2016). Propagation as a conservation tool was the subject of three studies: one about an improved method of in vitro culture of glochidia (Ma et al., 2016), one introducing short-term breeding of the Endangered freshwater pearl mussel *Margaritifera margaritifera* (Linnaeus, 1758) as a new technique for the augmentation of declining populations (Moorkens, 2017) and one revising the challenges in the conservation progress of *Margaritifera auricularia* (Spengler, 1793) (Prié et al., 2017). Six papers used molecular tools to describe genetic structure or phylogeographic patterns of European (Feind et al., 2017), North American (Hewitt et al., 2016; Mathias et al., 2016) and South American species (da Cruz Santos-Neto et al., 2017); to reveal the uncommon doubly uniparental inheritance of mitochondria in a European species (Soroka and Burzynski, 2017) and the sequencing of transcriptomic resources for an invasive species (Soroka et al., 2017). The interaction between mussels and their host fishes was addressed in three papers that evaluate the effects of stress (Douda et al., 2016), cross-immunity (Chowdhury et al., 2017) and temperature (Schneider et al., 2017) on the reproduction of freshwater mussels. Three papers describe distribution patterns with distinct spatial and temporal scales: the population trends of Unionidae in Romania (Sîrbu and Benedek, 2017), the distribution of freshwater mussels and their host fishes in Texas (Dascher et al., 2017) and a study that reconstructs the historical range and population size of the threatened species *Popenaias popeii* (Karatayev et al., 2015). On a smaller scale, a study on the longitudinal variation in freshwater mussel assemblages within two rivers is presented by Chambers & Woolnough (2016), while Dittman et al. (2017) evaluate the microhabitat and biology of the poorly studied pea clam *Sphaerium striatinum*. Two papers assess the growth of *M. auricularia* (Nakamura et al., 2017) and of juvenile freshwater pearl mussels *M. margaritifera* at the river scale (Černá et al., 2017). One paper assesses the shell phenotypic plasticity of *Unio crassus* (Zając et al., 2017). The influence of the flood pulses and of near-bed hydrodynamics on freshwater mussels is evaluated by Callil et al. (2017) and Sansom et al. (2017), respectively. Finally, toxicology and archaeology are represented by a study of the effects of polycyclic aromatic hydrocarbons on unionid mussels (Archambault et al., 2017) and the conservation implications of freshwater mussel remains in a Texan river (Popejoy et al., 2016).

Conservation of FB requires urgent collaboration between scientists, managers, politicians and the general public, in order to share knowledge and efforts. An example of this collaboration is the International Meeting on Biology and Conservation of Freshwater Bivalves, but more efforts are necessary for the transfer of knowledge between scientists and the general public in order to raise awareness about the importance of FB conservation. These efforts can include, but not be limited to the increase in visibility of FB conservation issues in the media, better engagement with local communities and stakeholders (e.g. providing training and lifelong learning opportunities like workshops for public, better information dissemination and accessibility of collaborative research even integrating participants from civil society into surveys and research projects), publications and additions to national collections.

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