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Facultad de Ciencias

Fish conservation in the 21st century: Lessons learned and perspectives for a sustainable future

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Submitted by **Imanol Miqueleiz Legaz** in partial fulfillment of the requirements for the Doctoral Degree of the University of Navarra

This dissertation has been written under our supervision in the Doctoral Program in Natural and Applied Sciences, and we approve its submission to the Defense Committe.

Signed on October 2^{nd}, 2020

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No caben aquí todas las personas a las que querría dar gracias por haber sido amistad, compañía, apoyo y ánimo durante estos maravillosos años.

A la asociación de amigos de la Universidad de Navarra y a la Fundación La Caixa, por su apoyo económico para la realización de esta tesis.

A Rafa y Arturo, gracias por haberme acompañado desde el primer momento. Para lo académico y lo que no. Por ser ejemplo y modelo, como profesores, como investigadores y como personas. A Monni, por ser un ejemplo de investigación pasional y vivida. Ojalá que el futuro me permita seguir trabajando junto a vosotros y compartiendo proyectos. Y gracias a todas las personas que, desinteresadamente y muchas veces sin conocerme, me han ayudado en los distintos proyectos de la tesis.

A Tom y David, ladrones de datos y manzanas. Por las miradas cómplices y el apoyo cada vez que os he necesitado. Al resto de compañeros que ya acabasteis este camino, o que lo haréis pronto: Amaia, María, Rubén, Nora, Mónica, gracias por las comidas, el café y la ayuda desinteresada. A todo el departamento de Biología Ambiental, por haber hecho de estos años no un trabajo sino un disfrute constante.

A mis compañeros de la carrera, de bata y de bota, por escucharme las turras y apoyarme en todo momento. Por los años que hemos pasado juntos y por seguir apuntándoos a mis planes y estar ahí a pesar de los años y la distancia.

A mi grupo scout, especialmente a los chavales con los que he tenido la suerte de compartir esta etapa de mi vida, gracias por enseñarme a ver la realidad a través de los ojos de un niño, a creer que un mundo mejor siempre es posible. Y a mis compañeros del kraal, gracias por ser únicos. Gracias por tantos años de campamentos, travesías, findes, cenas y aventuras, en vosotros he descubierto a personas maravillosas que nunca voy a olvidar.

A Assen, Marcaida y Tibe, sois la clase de amigos que todo el mundo querría tener. Muchas gracias por haber sido un apoyo fundamental durante tantos años, por la amistad y los abrazos sinceros. Por estar disponibles en todo momento, siempre dispuestos a escuchar y compartir los momentos buenos y malos.

A mi familia, a mis padres y a mi hermana, muchas gracias por haberme acompañado desde que tengo memoria. Por haber soportado mis frustraciones, malas caras y agobios con grandes dosis de paciencia. Por enseñarme a ser como soy. Por el cariño. Porque por muy lejos que estéis, siempre os llevo cerca.

A todos vosotros, gracias por acompañarme en esta maravillosa aventura que es vivir.

"I wish it need not have happened in my time," said Frodo.
"So do I," said Gandalf, "and so do all who live to see such times. But that is not for them to decide. All we have to decide is what to do with the time that is given us."

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General Abstract

Resumen General

Aquatic biodiversity is severely jeopardized by human actions. Among all vertebrates that live in aquatic environments, fish species are the most diverse and essential for the role they play in aquatic ecosystems. Fish conservation status had been partially and increasingly assessed by the IUCN Red List, but they still remain much less assessed than any other vertebrate group. Thus, further studies are required to understand fish conservation and propose new solutions to improve their assessments and subsequently their conservation status and future viability.

In this work, we started by evaluating the completeness of the IUCN Red List fish assessment itself. Finding a 50% gap in the list of assessed species, we explored species traits underlying the assessment status of fish species, distinguishing freshwater and marine species, and identifying several geographical, life history and social drives underpinning the assessment selection. We also analysed the assessment gap on the top commercial fish species, which featured prominently in the results of the first analysis. We evaluated their conservation status concerning the data available about reported and reconstructed landing trends, and the implications on the sustainability of fisheries.

We expanded the evaluation of IUCN Red List assessments to include the trends in the last decades for fish. We analysed assessments and evaluated the role of each country in fish conservation linking it with its economic capacity and proposing guidelines for future IUCN assessment and reassessment efforts. Following the results of the trend analysis, we explored the situation of freshwater fish assessments in the Iberian Peninsula, as an example of a region with a high proportion of endangered species with out of date assessments. We proposed recommendations based on the use of molecular techniques to increase the information available and improve future reassessments of Iberian freshwater ichthyofauna.

As protected areas have been deemed as critical conservation tools, we further explored the coverage that such areas offer to freshwater fish diversity. To do so, we identified the most irreplaceable rivers through freshwater fish distribution and compared them to the current network of protected areas, which was found to grant little protection to irreplaceable rivers. Moreover, we compared irreplaceable protected areas for freshwater fish with those identified as irreplaceable for terrestrial vertebrates, finding a general discordance that suggested a need for reevaluating future design and management of protected areas.

We conclude with a discussion on the implications that our results suggest for the future of fish conservation, listing several recommendations and action lines which we find essential to guide fish conservation in the upcoming years.

Las acciones humanas amenazan gravemente la biodiversidad acuática. De entre todos los vertebrados que viven en los ambientes acuáticos, los peces son los más diversos y esenciales por el papel que juegan en los ecosistemas acuáticos. Anteriormente, el estado de conservación de los peces ha sido evaluado gradualmente por la Lista Roja de la IUCN, pero aún están peor evaluados que otros vertebrados. Por ello, se necesitan más estudios para entender la conservación de los peces y proponer nuevas soluciones que mejoren sus evaluaciones y su estado de conservación y viabilidad.

En este trabajo, comenzamos por evaluar la completitud de las evaluaciones de los peces en la Lista Roja de la IUCN. Al encontrar un 50% de especies sin evaluar, analizamos los rasgos de las especies de peces para explicar cuáles están influyendo en su evaluación, distinguiendo entre especies dulceacuícolas y marinas e identificando varias razones biogeográficas, biológicas y sociales. También analizamos el sesgo de evaluación en los peces de mayor importancia comercial, que resaltaron en el primer análisis. Evaluamos su estado de conservación con relación a los datos disponibles sobre capturas declaradas y reconstruidas, y sus implicaciones en la sostenibilidad de las pesquerías.

Expandimos el estudio de las evaluaciones de la Lista Roja de la IUCN para incluir las tendencias de evaluación de peces en las últimas décadas. Analizamos las evaluaciones y evaluamos el papel de cada país en la conservación de los peces relacionándolo con la capacidad económica de los países y proponiendo líneas de acción para futuras evaluaciones y reevaluaciones de la Lista Roja de la IUCN. Siguiendo los resultados obtenidos, exploramos la situación de las evaluaciones de peces dulceacuícolas en la península Ibérica, como ejemplo de región con una gran proporción de peces amenazados con evaluaciones desfasadas. Propusimos recomendaciones basadas en el uso de técnicas moleculares para aumentar la información disponible mejorar futuras reevaluaciones de la ictiofauna ibérica de agua dulce.

Como las áreas protegidas críticas son herramientas críticas de conservación, exploramos la cobertura que éstas ofrecen a las especies de peces. Para ello, identificamos los ríos más irremplazables utilizando mapas de distribución de peces dulceacuícolas, y los comparamos con la red actual de áreas protegidas, que resultó ofrecer una baja protección a los ríos irremplazables. Además, comparamos las áreas protegidas irremplazables para peces de agua dulce con aquellas que se han identificado como irremplazables para los vertebrados terrestres, encontrando discordancias que sugirieron la necesidad de reevaluar el diseño y gestión de áreas protegidas.

Finalizamos esta tesis discutiendo los resultados y concluyendo con varias recomendaciones y líneas de acción para guiar la conservación de peces en los próximos años.

Aims and structure

Objetivos y estructura

We chose our topic because aquatic species, and especially fishes, are under serious threats and its conservation perspectives are compromised unless we take urgent action to preserve species and prevent extinctions. The need for this action should, however, be informed by Science, and this thesis, therefore, aims to evaluate the progress in the knowledge of the conservation status of fishes, identify priority areas for their conservation and propose new conservation perspectives for the upcoming years. To do so, we have analysed global databases on conservation and biogeography of fish species and detected biases and trends in the conservation status of fishes. Furthermore, we have produced indices and statistical outcomes to support our findings. Data were current at the time of analysis, and may naturally evolve (e.g. proportion of fish assessed in IUCN Red List). Thus, the results obtained in this project are based on the data available and should be considered as provisional as new data will update the databases used. Nevertheless, our study reflects a generally improving trend in the coverage of biodiversity databases and that will be further discussed in the last chapter.

The thesis starts with a general introduction to the topic of fish assessments (Chapter 1), and proceeds to develop the five major research questions related to fish assessment that we aimed to answer:

- What gaps and biases could be identified in the world's authoritative IUCN Red List for fishes (Chapter 2);
- The consequences that such degree of completeness in assessments could have for the main commercial species and their conservation (Chapter 3);
- How those assessments changed over time and whether they were related to socioeconomic parameters and conservation commitments in the countries undertaking them (Chapter 4);
- What role those conservations commitments (e.g. protected areas) could have in the protection of threatened species and irreplaceable habitats (Chapter 5);
- How the above findings could be applied to one case study, the Iberian Peninsula (Chapter 6).

We end with a general discussion (Chapter 7) and the thesis' Conclusions.

As the five topics are well delimited and correspond to five compact subprojects within the overall research topic with varying methodologies, each chapter carries its own Introduction, Methods, Results, and References subsections.

The methodological approaches and main findings of the research will be summarized below.

The first objective of this thesis was to analyse the biases present in the IUCN Red List for fish species. We compared species present in FishBase (global database of fish) and IUCN Red List and analysed species traits to find the reasons underlying the assessment gap of fish species. Assessments were found to be biased towards developed regions, early description rates and specific IUCN specialist groups. Our results highlighted the low assessment rates of south American freshwater species. Moreover, fish species commercial importance did not influence assessment status.

Following the previous findings, we focused our analyses on the conservation status of top fished commercial fish species. We analysed data on reported catches from FAO and reconstructed catches from Sea Around Us project. No difference was found in the assessment rates of top-fished species and fish species of commercial interest in general. Furthermore, FishBase Vulnerability index was not related to IUCN Red List population trends or fishing threat. Finally, reconstructed catches showed an increase in landings of many species with declining population trends, even after IUCN Red List evaluations. We considered that urgent action between stakeholders to improve species knowledge related to conservation is essential to ensure future fisheries sustainability.

We then explored fish assessment trends by IUCN Red List in the last decades. In this study, we analysed species description rates and assessments between 1996-2019 and evaluated the role of countries in fish conservation according to their economic capacity. Our results showed an increase in the number and quality of assessments in the last years. Furthermore, we also found higher proportions of threat and data deficiency for recently described species. Higher-income countries should pay more attention to reassessing out of date species, whereas countries with lower levels of assessment were also the ones where more species have been described in the following years. We found essential to strengthening evaluations in the upcoming years to develop the role of National Red List and its integration in the global IUCN Red List.

Considering the need for protection for freshwater fish, we analysed the role played by protected areas in their conservation. To that end, we applied an irreplaceability index to identify those rivers in the world with higher irreplaceability value based on their freshwater fish fauna. Then, we examined whether these irreplaceable rivers fall within the current network of PAs and the concordance with identified irreplaceable PAs for terrestrial vertebrates. PAs offer low protection to irreplaceable rivers for freshwater fish, continuing a traditional trend of miss protection of freshwaters within PAs. Moreover, terrestrial and freshwater irreplaceable PAs do not generally agree, potentially under considering freshwater fish necessities in PAs management and design. A paradigm shift is needed to incorporate freshwaters in future conservation perspectives and ensure the protection of freshwater ecosystems and the biodiversity they host.

Finally, we applied the previous findings in a case study of a region which hosts high numbers of endemic and endangered freshwater fish species, high assessment rates and many outdated assessments, the Iberian Peninsula. Our study found that the rate of threatened species differed between National and global Red Lists. Considering the high number of out of date assessments, we identify priority areas inhabited by fish species in need of reassessments. To ease the reassessment process, we propose the use of eDNA, for which the coverage for Iberian freshwater fish is high. In the future, the regular update and maintenance of National Red Lists are essential to ensure effective protection of freshwater fish.

We conclude with a general discussion of the results and the main conclusions of this thesis.

CHAPTER 1:

Concerning fishes

Capítulo 1:

Acerca de los peces

Water is widely recognised as the most essential of human resources, on which our life-support system depends (Dudgeon et al. 2006; Vörösmarty et al. 2010, 2013). Aquatic ecosystems (rivers, lakes, groundwater, coastal waters or seas) support the delivery of crucial ecosystem services. Among them, we can mention services as food (fish production and water for drinking), industry, flood and erosion protection, carbon sequestration and recreation, most of which can be directly appreciated by people (Grizzetti et al. 2016). Moreover, aquatic ecosystems harbour outstanding biodiversity. Since the first living organisms millions of years ago, life has evolved in the aquatic environments and currently, 330,000 species live in the oceans (www.marinespecies.org) and at least 126,000 in the freshwater ecosystems, and many more may remain yet undiscovered (Mora et al. 2011).

In this chapter, we introduce the topic of the research. We analyse the threats of aquatic ecosystems and how they are considered within the global conservation objectives. We focus on fish as study taxa for this project, analysing their conservation challenges and addressing them in the different chapters of the thesis.

Aquatic biodiversity: threats

In a rapidly changing world, aquatic ecosystems and their biodiversity are threatened by a wide suite of anthropogenic stressors. Concerning the marine environment, main threats emerge from overfishing, pollutant, sediment and nutrient input (Halpern et al. 2007, 2008), habitat loss (Dulvy et al. 2003) and invasive alien species (Bax et al. 2003). These anthropogenic processes are causing a strong impact on critical ecosystem services such as fisheries or nutrient cycling (Selig et al. 2014). Furthermore, climate change is very likely to be a driver of marine fish species turnover, local extinction and invasion in the upcoming years (Cheung et al. 2009). Biodiversity loss in the oceans will increase resource collapses and decrease stability and recovery potential (Worm et al. 2006). In the freshwater environment, human activities have globally increased in the last century, overexploiting natural resources (Garcia-Moreno et al. 2014). Freshwater ecosystems are potentially the most endangered ecosystems in the world (Dudgeon et al. 2006). Nowadays, freshwaters receive impacts from habitat loss and fragmentation, water pollution, extensive wetland drainage, groundwater depletion, the establishment of introduced alien species, and overfishing of native ones (Dudgeon et al. 2006; Strayer & Dudgeon 2010; Vörösmarty et al. 2010). Climate change is also challenging freshwater ecosystems function (Woodward et al. 2010) and the physiology, distribution, and survival of freshwater species, such as fishes (Poesch et al. 2016). Immersed in the Anthropocene, we are undergoing the “sixth mass extinction” (Barnosky et al. 2011), not only causing direct extinctions but also populations extirpations and declines in species abundance (Dirzo et al. 2014; McCauley et al. 2015) (Figure 1.1).

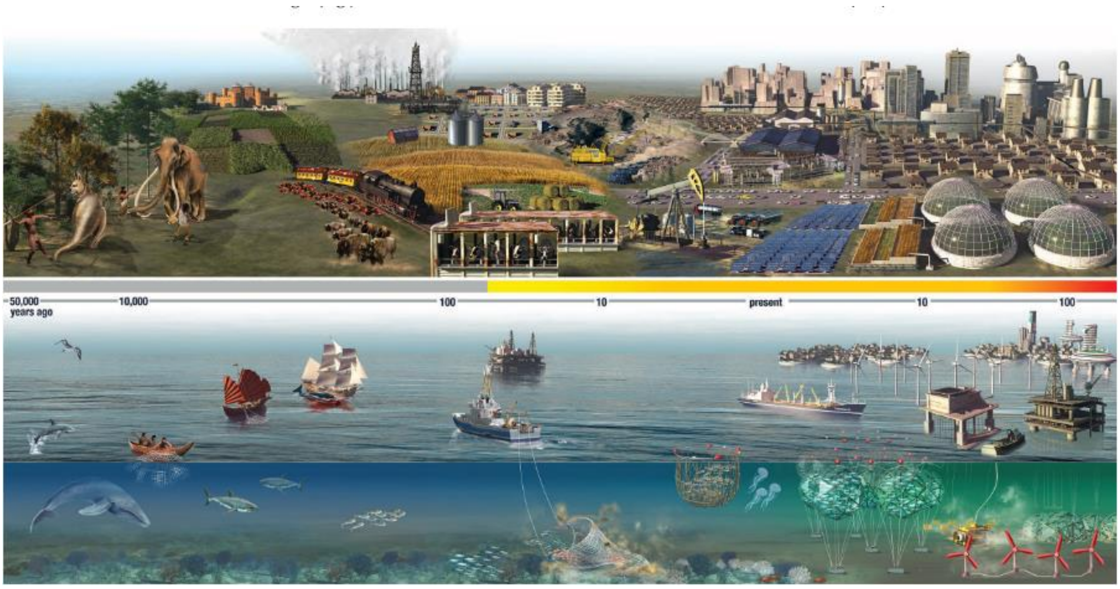

Figure 1.1: Terrestrial and marine anthropogenic stressors driving defaunation processes. From McCauley et al. (2015).

In the early 2000s, world countries committed through the Convention on Biological Diversity (CBD) "to achieve by 2010 a significant reduction of the current rate of biodiversity loss". Indicators developed to evaluate this target showed increased pressures towards biodiversity and the rate of biodiversity loss in the first decade of the millennia did not slow down (Butchart et al. 2010). To overcome this failure, the CBD created in 2010 the Aichi Biodiversity Targets for the 2011-2020 period "to take effective and urgent action to halt the loss of biodiversity to ensure that by 2020 ecosystems are resilient and continue to provide essential services, thereby securing the planet's variety of life, and contributing to human well-being, and poverty eradication (SCBD 2010). This plan relates directly to the UN's Sustainable Development Goals (SDGs), particularly, to the 2 goals focused on the protection of terrestrial and marine life (Green et al. 2019). Among these targets, two of them address biodiversity loss and their conservation: Targets number 11 and 12. Target number 11 states that "by 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes". Target 12 proposes that "by 2020 the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained".

Aiming at Target 11: Protected Areas and aquatic ecosystems

Over the last 20 years, the number and extent of protected areas established globally have increased dramatically, with more than 240,000 Protected Areas (PAs) covering over 46,000,000 km^2 in both land and sea (https://www.protectedplanet.net/). This progress represents the growing recognition of their value as a way to safeguard nature and cultural resources and mitigate human impacts on biodiversity (UNEP-WCMC and IUCN 2016), contributing to human wellbeing and sustainable development. According to the last Protected Planet report, PAs cover now 15.2 % of the earth land's surface and 7.4% of the world's oceans, and CBD target 11 was expected to be achieved by 2020 (UNEP-WCMC et al. 2018), though we consider this hypothesis optimistic (Figure 1.2).

Nevertheless, PAs designation does not necessarily imply direct protection to biodiversity and ecosystems. Traditionally, PAs designation has been biased towards remote areas (Venter et al. 2014) and still favours low-cost lands. This low-cost trend has intensified through time (Venter et al. 2018) and does not take into consideration species or ecosystems necessities. Given the current targets established for conservation and development, the key role of PAs in many social and environmental agendas, and the reduced political commitment in some countries (Watson et al. 2014), we need some changes in the way how PAs are established and managed.

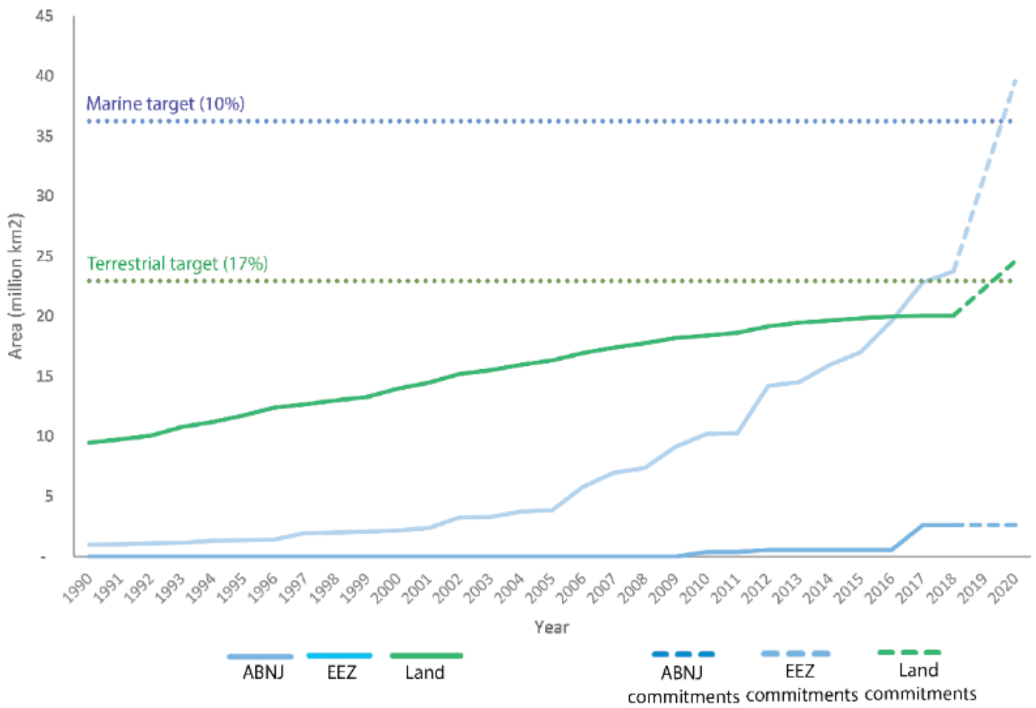

Figure 1.2: Evolution in protected area coverage on land and ocean EEZ (Exclusive Economic Zones) and ABNJ (Areas Beyond National Jurisdiction) between 1990 and 2018 and projected growth to 2020 according to commitments from countries and territories. From UNEP-WCMC et al. (2018)

Countries are underperforming in locating PAs such that they contribute to representing threatened species and reach the goal of stopping their decline (Venter et al. 2018). Furthermore, PAs tend to be allocated according to terrestrial necessities, lagging behind effective freshwater protection (Juffe-Bignoli et al. 2016). These under consideration of freshwater necessities in PAs design has been widely discussed in the past (Abell et al. 2007, 2011) and many suggestions have been done on how to effectively allocate PAs to protect freshwater biodiversity (Hermoso et al. 2016, 2017; Juffe-Bignoli et al. 2016). The objective of 17% of inland water protection must go together with realistic conservation objectives, owing to the extreme level of threat that freshwater biodiversity suffers (Collen et al. 2014).

In the marine realm, there are high differences in protection between PAs in countries' Exclusive Economic Zone (EEZ) and in Areas Beyond National Jurisdiction (ABNJ), where almost no protection is offered for biodiversity (UNEP-WCMC et al. 2018). With the exponential growth of Marine Protected Areas (MPAs) in the last years, there is a growing concern about how these areas can be managed or the industrial fishing that is sometimes developed within them (Sala et al. 2018).

Aiming at target 12: Species conservation status and extinction risk in aquatic ecosystems.

Human activities have driven hundreds of species to extinction (Barnosky et al. 2011). Aware of this problem, several initiatives and institutions have emerged to protect nature and achieve a sustainable future. Among them, we could cite the World Wildlife Fund (WWF), the above-mentioned Convention on Biological Diversity, or the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). Nevertheless, in this project, we will focus on one of the most important institutions for the direct implication that it has on the establishment of conservation priorities (Rodrigues et al. 2006), the International Union for the Conservation of Nature Red List (IUCN Red List).

In 1948, the International Union for the Conservation of Nature (IUCN) was founded, bringing together governments and civil society with a common goal, to protect nature. The IUCN aimed to encourage international cooperation and provide scientific knowledge and tools to guide conservation action. In 1964, IUCN created the IUCN Red List of Threatened Species, which made available to public access the first comprehensive list of threatened mammals and birds, compiling information from evaluations in previous years. More and more species have been added every year since its establishment, and full assessments for several groups have been completed.

IUCN Red List classifies species into several extinction risk categories, according to a range of quantitative criteria. These categories and criteria have changed over time, since their first release in 1991. Over the following 10 years, two more versions and a series of updates of the versions were published. Finally, in 2001, Version 3.1 was adopted by the IUCN Council (IUCN 2012). All new assessments from January 2001 use this latest version. Nevertheless, species previously assessed which have not been reassessed may have older categories (especially from the 2.3 version of 1994).

As mentioned before, IUCN Red List categories describe a chance of becoming extinct. A higher extinction risk implies a higher chance of extinction in the absence of effective conservation action. From lower to higher extinction risk, IUCN Red List categories (and their acronyms) are Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), Critically Endangered (CR), Extinct in the Wild (EW) and Extinct (EX) (Figure 1.3). Together, species under categories VU, EN, and CR are described as threatened species. Moreover, species may be classified as Data Deficient (DD), when information is not adequate to assess its extinction risk. Dealing with DD species is complicated and several studies have been performed with these species (Morais et al. 2013; Böhm et al. 2013; Bland et al. 2015, 2017; Bland & Böhm 2016), dealing with the issue of whether to consider these species as threatened or no and the chance of using new methodologies to address their conservation status.

Nevertheless, the IUCN Red List is not only a classification scheme. Species evaluations offer detailed information on species taxonomy, geographic range, population trends, habitat and ecology, threats, and conservation action. Several of these fields are used as criteria to establish species extinction risk. Criteria used by IUCN Red List categories are a series of quantitative values associated with risk factors of organisms and their life histories. Used for classifying species as VU, EN, or CR, meeting any one of these criteria qualifies a taxon for hierarchically classifying at that level of threat (e.g. meeting a single criterion for a higher level places the species at that level even though most criteria could be met for a lower level). These criteria refer to reductions in population size, reduced geographic range, small population size (mature individuals), and quantitative analyses of extinction in the wild. Further details on those criteria can be found in the IUCN Red List Categories and Criteria Version 3.1 (IUCN 2012).

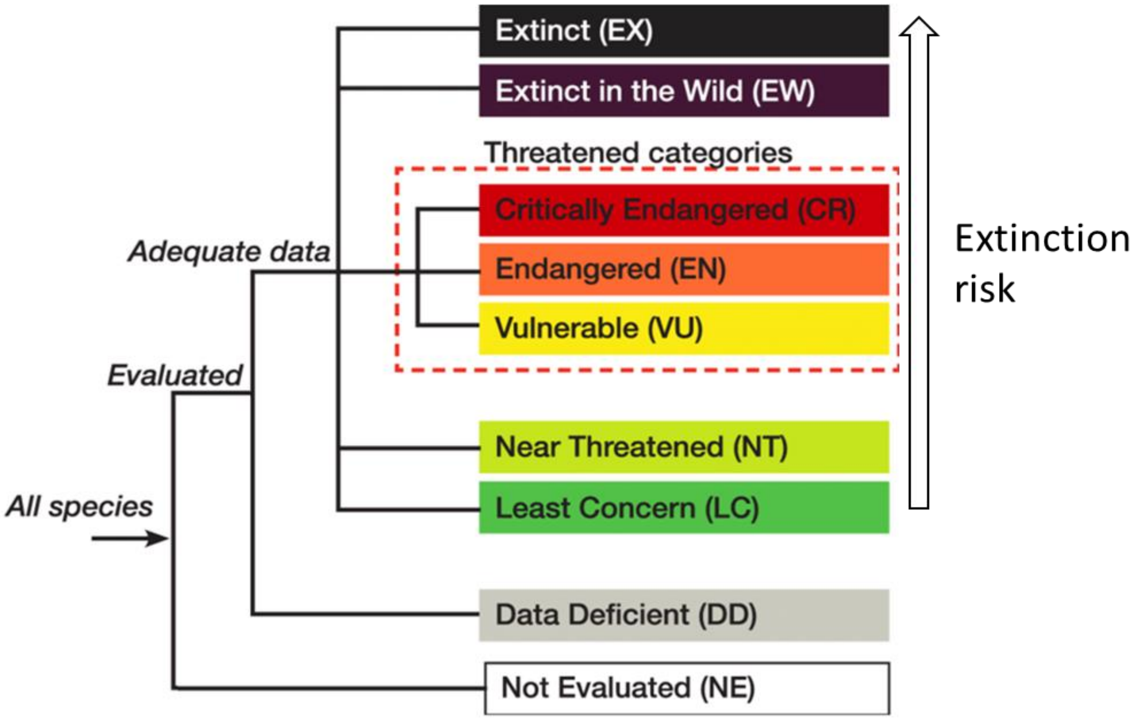

Figure 1.3: IUCN Red List categories according to IUCN Red List Categories and Criteria Version 3.1. Adapted from IUCN (2012).

Unfortunately, along the years that the IUCN Red List has been recording species data, a total of 882 species went extinct (IUCN 2020) and 77 more species were extinct in the wild (but survive in captive populations). But the problem is not only a matter of species loss but also of declines in populations and local abundances which have led to local extinctions (Ceballos et al. 2017). Vertebrate populations are declining both in terrestrial and marine ecosystems, in a defaunation process of uncertain future (Dirzo et al. 2014; McCauley et al. 2015). Reports published in the last decade state a dramatic decline in vertebrate populations, no matter the taxa, using metrics such as the Living Planet Index (LPI), a measure of the state of global biological diversity based on population trends of vertebrate species from around the world (McRae et al. 2017).

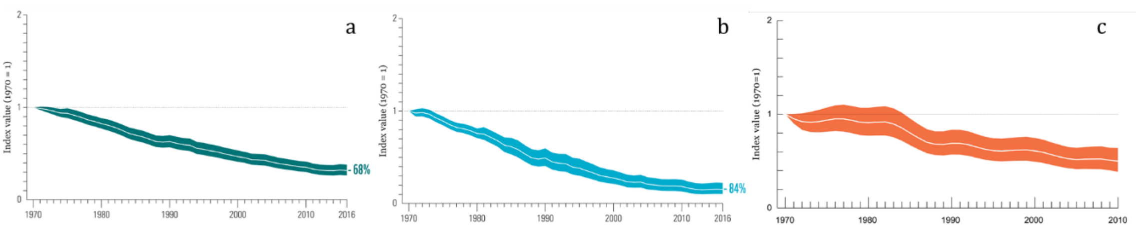

Figure 1.4: Population declines in the Living Planet Index (LPI) for a) all vertebrates, b) freshwater vertebrates and c) marine fishes. Adapted from WWF (2015, 2020).

Local and global LPI declines of populations have been reported worldwide (Figure 1.4), with an overall decline of 68% in the population sizes of vertebrates between 1970 and 2014 (WWF 2020), increasing up to 84% for freshwater vertebrates. Among the freshwater vertebrates species, fishes have suffered the greatest declines (WWF 2020) and marine fishes have also declined by 50 % (WWF 2015), calling conservation efforts in the upcoming years in order to revert such trends.

Fishes and their conservation

Fish are doubtlessly the most speciose group of vertebrates, with more than 36,000 species described so far (Fricke et al. 2020) and current description rates suggest that many more species remain undiscovered (Pelayo-Villamil et al. 2018). Diverse in morphology, physiology, behaviour, and habitats that they occupy, they are adapted to almost all aquatic environments on earth (Nelson et al. 2016). They occur in rivers, lakes, and oceans throughout the world. Some species, the *diadromous species*, can live for part of their life in freshwaters systems and part in marine environments. But many other species live in estuarine habitats or, belonging to one environment, may have populations that live in the other one. In both freshwaters and oceans, a higher diversity is found in the tropics. Higher rates of freshwater fish diversity are found in central Africa, the Amazonian basin in South America, and South-Eastern Asia (Abell et al. 2008). For marine species, fish diversity is concentrated in continental shelves, and among them, in tropical coral reefs (Snelgrove et al. 2017)

Fishes are important species in terms of food supply, but also as recreational value for naturalists, recreational fishing (Hughes 2014; Winfield 2016), and aquarists (Maceda-Veiga et al. 2013, 2016). We must recognize the value of and our dependency upon fishes and other organisms, but our threats to the integrity of the environment also pose a serious threat to fish species (Nelson et al. 2016). Both changes in distribution patterns of many fish species and the extinction of some native fish have been directly linked to human intervention. As an example, the mean freshwater fish extinction rates during the last 110 years in Europe and North American is a hundred-fold that of the calculated natural rate (Dias et al. 2017). Furthermore, fishes are described at incredibly high rates (Nelson et al. 2016; Fricke et al. 2020), and many species are likely left to be discovered in most diverse regions (Reis 2013).

The importance of fish diversity and its conservation has resulted in a set of databases where fish information is stored and made accessible to stakeholders, such as ichthyologists, conservationists, and even the general public. Among them, we could cite two outstanding databases in terms of both species coverage and information they provide.

First, Eschmeyer's Catalog of Fishes stores the most up to date records of fish species, with a strongly taxonomic and systematic point of view and currently comprising 35,613 valid fish species (Fricke et al. 2020). Secondly, FishBase, a reference tool for fish study which includes a wider range of data such as geographic range, description, life traits, and reproduction for 34,300 fish species (Froese & Pauly 2019). Nevertheless, none of these databases provides us with direct metrics or estimations of species conservation status, which is a task carried out by the IUCN Red List.

Up to date, almost 21,000 fish species have been evaluated in the IUCN Red List (IUCN 2020), with more species evaluated in the marine systems than in the freshwater ones. As we will analyse in chapters 2 and 5, this number has significantly increased in the last years and plans to evaluate all freshwater fish species are being developed all over the world. Several IUCN groups have contributed with their effort to increase global coverage of fish assessments, such as IUCN's Freshwater Biodiversity Unit (www.iucn.org/theme/species/our-work/freshwater-biodiversity), the IUCN Freshwater Fish Specialist Group (www.iucnffsg.org/), IUCN Shark Specialist Group SSG (www.iucnssg.org) or the Global Marine Species Assessment GMSA (http://sci.odu.edu/gmsa/) (Arthington et al. 2016). Nevertheless, fish assessments (all together with reptiles) remain far from the assessment rates common for other vertebrates (Meiri & Chapple 2016) and further efforts are required to evaluate all fish species and ensure their conservation and protection in the future.

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CHAPTER 2:

Assessment gaps and biases in knowledge of conservation status of fishes

Capítulo 2:

Lagunas de evaluación y sesgos en el estado de conservación de peces

This chapter is based on the following journal article:

Miqueleiz, I., Bohm, M., Ariño, A.H., Miranda, R. (2020)
Aquatic Conservation: Marine and Freshwater Ecosystems

Chapter preface

Fish species are important for both humans and ecosystems. According to FishBase database records, currently, more than 33,500 fish species inhabit marine and freshwater environments, and many more remain yet undiscovered. As we have seen in the General Introduction, many of these species are threatened with extinction, and conservation measures are needed to protect them. The International Union for the Conservation of Nature (IUCN) Red List has assessed the conservation status of approximately half of current known fish species, the lowest percentage in any vertebrate group. Furthermore, many fish species remain assessed as Data Deficient, misrepresenting extinction risk levels for them. To improve further assessment strategies, we first need to know about assessment biases that could push conservation decisions, and therefore help focus evaluation efforts towards those taxa and regions that are in the greatest need of assessments.

In order to identify the variables that may underlie this assessment gap, we examined several species traits related to distribution, life-history, taxonomy, conservation, and the economic relevance of species according to their IUCN Red List assessment status. We explored IUCN Red List assessment patterns and included separate statistical analyses for freshwater and marine species.

Our results showed that several traits analysed were under the assessment bias for fish species. IUCN Red List assessments were biased towards economically developed regions, species with early description dates and species covered by current IUCN taxonomic specialist groups. Species living in remote areas or habitats were more likely to be unassessed by IUCN Red List. In particular, South America had low assessment levels for freshwater fish species. Other traits such as commercial importance did not influence the assessment status of fish species, an issue that will be addressed in the following chapter of the thesis. Fish species low assessment rates combined with an increase in species discovery resulted in a large proportion of recently discovered species not being evaluated by IUCN Red List. Altogether with other conservation initiatives, we encourage assessment in poorly assessed areas and taxonomic subgroups to prompt timely conservation action to prevent species extinctions. Further implications on how IUCN Red List assessments have been carried out will be discussed in chapter 4 of this work.

Introduction

Throughout the earth's history, aquatic ecosystems have formed both a mosaic and a continuum of habitats ranging from the freshwater springs, rivers, lakes, and wetlands of continents and islands to estuaries, shallow coastal habitats, reefs, and the seas (Arthington et al. 2016). Fishes are one of the world's most important natural resources, as they provide humans with various ecosystem services (Olden et al. 2007). Fish regulate food web dynamics and nutrient balances (Holmlund & Hammer 1999)and also contribute to health, well-being, cultural identity, and economies of societies (Hughes 2014). With more than 33,500 species currently described, fishes constitute an important part of the biomass of aquatic ecosystems (Jennings et al. 2008), with slightly more fish species in freshwater than marine ecosystems (Carrete Vega & Wiens 2012; Fricke et al. 2020). However, population declines, mainly caused by habitat loss and degradation, invasive species, overexploitation, pollution, and climate change (Dudgeon et al. 2006), are increasing the risk of global or local extinctions of species (Darwall & Freyhof, 2016). Over the current century, marine and freshwater organisms will face a suite of environmental conditions that have no analogue in human history (Harnik et al. 2012; Garcia-Moreno et al. 2014).

Fish continue being described at very high rates, with about 3,900 new species described between 2005-2014 (Nelson et al. 2016). The most comprehensive database on fish species is FishBase (Froese & Pauly 2016), which provides information about species distributions, taxonomy, and biological traits and indices for species, However, this database does not provide an estimation of species' extinction risk (Miranda 2017). To evaluate a species' extinction risk, and assess its current, past, and future threats, we need to access the reference guide on extinction risk over the last 50 years (Rodrigues et al. 2006), the IUCN Red List of Threatened Species (IUCN 2017). Having failed to reduce the rate of biodiversity loss by 2010 (Butchart et al. 2010), the Convention on Biological Diversity determined that during the past decade there was insufficient policy-specific scientific information to aid the decision-making process (Costelloe et al. 2016). Given the global threat to a large proportion of species (Pimm et al. 2014), the IUCN Red List and the Red List Index (Butchart et al. 2004) are essential indicators to track progress towards meeting Aichi Biodiversity Target 12: that "by 2020 the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained" (SCBD 2010). Besides, the IUCN Red List directly inputs in several conservation and policy instruments, such as the development of Key Biodiversity Areas (KBAs; Langhammer et al., 2007), the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (Rodrigues et al. 2006) and dissemination of biodiversity and threat information to researchers, conservation planners and business as an environmental impact tool.

Several specialist groups and assessment projects exist under the umbrella of the IUCN's Species Survival Commission (SSC), such as the Marine's Biodiversity Unit's Global Marine Species Assessment (GMSA), several marine fish Specialist Groups, and the Freshwater Fish Specialist Group (FFSG), which have so far assessed the extinction risk of half of all known fish species (IUCN 2017). This is much lower than assessment levels in other vertebrate groups (e.g. almost 99% in mammals and birds) (Meiri & Chapple 2016), although fish are far richer (e.g. six times the number of mammal species and three times the number of birds). Knowledge of aquatic biodiversity is also lower than that of terrestrial groups due to bias in conservation research toward charismatic terrestrial species (Darwall, Holland, et al., 2011). Assessment processes are currently struggling to catch up with fish discovery rates, resulting in incomplete knowledge of fish biogeography, population density, and threats (Arthington et al. 2016).

In addition, many fish species have cryptic or remote distributions, such as tropical freshwater fishes (Alofs et al. 2014), thus lacking sufficient information to assess their extinction risk. An additional consequence of this knowledge gap is the high number of species assessed as Data Deficient (DD). Data deficiency may be caused by a lack of information on population status and trends, outdated information, or because a species is known only from the type specimen (Bland & Böhm 2016). With over 20% of fish species on the IUCN Red List currently classified as DD, there is a dangerous misrepresentation of risk levels in this group and overlooking many species in conservation efforts (Morais et al. 2013) even though they may require them. In a context of limited resources and funding for species assessments (with half of it coming from philanthropic sources) (Juffe-Bignoli et al. 2016), many species remain unassessed by IUCN. However, the affordability of assessments when considered at a global scale has been demonstrated (Turak et al. 2016; Juffe-Bignoli et al. 2016) and constitutes a best-value knowledge product into which money should be invested.

Considering that only half of all fish species are assessed, how representative of the broader fish fauna is this subset of assessed species? Complex reasons may account for certain species being systematically overlooked while others are more likely to be assessed. Species presumed to be at high risk of extinction may be assessed first, such as species with small range size, which is one of the main criteria used by IUCN to establish a risk category for a species (Meiri & Chapple 2016). Other traits like short generation times and small body size associated with fast life histories, should enable species to increase their resilience from the effects of human activities, thereby reducing their extinction risk according to ecological theory (Olden et al. 2007) and becoming less prone to assessments. However, assessment exercises are often driven by funding availability and are often first applied to better-known regions or specific taxa (Bland et al. 2017; Tapley et al. 2018). This will leave some areas or species unevaluated and introduce potential geographical and taxonomic biases. Olden et al. (2007) reported that as larger marine species face higher rates of extinction, they might be likely better evaluated than smaller ones. Knowledge about these biases in assessed species traits may steer conservation and funding decisions, and therefore help focus efforts towards the taxa and regions that are in the greatest need of investigation and determination of their conservation status (Meiri & Chapple 2016).

Here we assess whether distributional, ecological, life history, or taxonomic biases exist in IUCN assessments of marine and freshwater fishes. We hypothesise that higher assessment rates will be found for (1) species inhabiting developed regions with high levels of research activity (*i.e.* Europe, North America, Mediterranean region); (2) larger species in the marine environment because of higher perceived extinction risk (Olden et al. 2007); and (3) species that are easier to study (e.g., large, long-lived), have commercial importance, are considered more vulnerable to threats, and have been long known (i.e. described earlier). The results should serve as a guide to research efforts, conservation planning, and funding to improve the knowledge of species and areas that are in the highest need for research and assessment of their conservation status.

Methods

In this study, the 2016 version of FishBase was analysed (Froese & Pauly 2016). This database, a reference tool for fish study, includes information about the extinction risk of the species on the IUCN Red List. The status of the species was updated, where possible, according to the IUCN Red List classification (IUCN 2017). Old Red List categories were translated into current categories following the latest IUCN standards (IUCN 2012): therefore, LR/nt was renamed as Near Threatened, NT; LR/lc as Least Concern, LC; and LR/cd was merged into NT. Analyses were performed on the five classes of fishes (Actinopterygii, Chondrichthyes, Myxini, Petromyzontida, and Sarcopterygii) as recognised by FishBase.

Data on fish traits and other species information were collected from FishBase and grouped into the following five categories: 1) distributional traits, 2) life-history traits, 3) vulnerability index, 4) taxonomic traits, and 5) commercial importance. In terms of distributional traits, the presence of species in each FAO Major Fishing Area (henceforth FAO area) was collected. Preferred habitat for each species was recorded as assigned in

FishBase (bathydemersal, bathypelagic, benthopelagic, demersal, pelagic, pelagic-oceanic, pelagic-neritic, and reef-associated). For life-history traits, there were considered: maximum length (in mm) of the longest individual recorded for the species; maximum weight (in g) recorded for the species; longevity (oldest age recorded for the species); and generation time (time from birth to the average age of reproduction for the species). The vulnerability index (Cheung et al. 2005), originally developed for marine fishes but now applied to all species in FishBase, is used to establish the vulnerability of a species to fishing pressure. This index assigns each species a value between 0 (low vulnerability) and 100 (high vulnerability) based on species life-history traits, including maximum length, age at first maturity, longevity, natural mortality rate, fecundity, the strength of spatial behaviour, and geographic range. Three relevant taxonomic traits were considered: The phylogenetic index (Faith et al. 2004), that uses phylogenetic patterns of evolutionary diversification to predict feature diversity of sets of species, is calculated as a sum of phylogenetic differences present in an assemblage (Tucker et al. 2016) and takes values ranging from 0.5 (low uniqueness of the species) to 2.0 (high uniqueness) (Froese & Pauly 2016) to check whether the phylogenetic uniqueness of a species could be a trait driving IUCN Red Lists assessments. Secondly, fish order according to FishBase to see if there were certain orders which could be potentially over or under-represented in Red List assessments. Finally, in the case of the year of description (based on species authorship), it was assumed that more-recently described species were less susceptible to being assessed than previously described species. FishBase commercial importance reflects whether the species is regularly targeted by fisheries or regularly found in aquaculture activities.

FishBase did not contain data on all of the above traits for all species (Table 2.1). Rather than inferring data from similar species, species without direct data for a specific trait were classed as non-available (NA) for this trait. Our data were analysed across three groups of species: 1) all species present in FishBase (including species both assessed and non-assessed by IUCN, hereafter referred to as the full dataset), 2) species assessed by the IUCN and included in the IUCN Red List, and 3) species assessed by the IUCN excluding those classified as Data Deficient (DD). Analyses were performed separately for freshwater and marine fish.

Table 2.1: Number of fish species evaluated for each trait in each group. Only FAO (Food and Agriculture Organisation) Area, order, and year of description were available for all species. Population refers to the full dataset of all species present in FishBase. Assessed refers to those species assessed by IUCN Red List. Assessed non-DD refers to those species assessed by IUCN Red List excluding those classified as Data Deficient.

Trait	Population	Assessed	Assessed non-DD
Distribution			
FAO Area	32568	15029	11931
Life History			
Length	27967	13579	11092
Weight	1737	1104	990
Longevity	1264	865	825
Generation time	25490	12413	10095
Conservation			
Vulnerability Index	32541	14990	11892
Taxonomy			
Phylogenetic Index	32338	14977	11881
Order	32568	15029	11931
Year of description	32568	15029	11931
Commercial			
Commercial importance	7362	4376	3735

We firstly did multiple logistic regression models (generalized linear model (GLM) with binomial errors) where the status of IUCN Red List assessment ("no" or "yes") was the response variable. Sample sizes for different variables were very unequal (Table 2.1). Only those variables for which data were available for >85% of species were used as predictors: Habitat, length, Vulnerability Index, Phylogenetic Index, description year, and order. In these analyses, there were not considered body mass, tightly correlated to length (Froese et al. 2011), longevity, and generation time (due to the insufficient percentage of species having data for these traits).

Then differences in the assessment were tested (assessed vs. non-assessed) between the three groups through chi-square tests for analyses of frequencies (*e.g.* the number of assessed species in the FAO areas, commercial or non-commercial species and orders) and Wilcoxon rank-sum test with continuity correction (due to non-normal distributions of the variables) for the numeric data (*e.g.* length, weight, description year), with log transformations for length and weight. All statistical analyses were performed with R software version 3.3.3 (R Development Core Team 2019). Each trait was analysed twice to identify biases: full dataset vs. assessed species (comparison 1) and assessed vs. assessed non-DD species (comparison 2).

As assessment levels vary across vertebrate groups, with fish potentially being among the least assessed (Hermoso et al. 2017), it was tested whether there was a decline in assessment level over time. The year of species description for fish was contrasted with that from other vertebrate groups (Amphibians, Reptiles, Birds and Mammals) obtained from Catalogue of Life (http://www.catalogueoflife.org/), distinguishing between non-assessed, assessed-DD and non-DD by year to analyse how IUCN evaluations changed with time.

Results

The IUCN Red List 2017.1 has assessed 15,029 fish species (7,984 freshwater and 7,457 marine), which is 46% of the species listed in FishBase. Different FAO areas had varying proportions of species assessed, both when comparing all evaluated species and when excluding species assessed as DD (Table 2.2). South America (19% of species assessed) and Antarctic Ocean (12%-24 % depending on the FAO Area) had the lowest level of assessment, followed by the Arctic and the Pacific Ocean, (Figure. 2.1, Supplementary Data 2.1). The Atlantic Ocean (including the Mediterranean and the Black Sea) was the best-assessed area in the marine realm, while Africa and Europe had the highest levels of assessment among inland areas; however, Africa had a higher proportion of DD-species than Europe. Both the Indian and Pacific Oceans remained relatively poorly assessed (24%-40% and 12%-62% respectively). The proportion of species assessed differed significantly among habitats, in both comparisons (Table 2.2). Bathydemersal and bathypelagic habitats were least assessed, while reef associated-habitats were the best-evaluated habitats and with a relatively low proportion of DD-species. In contrast, in bathydemersal habitats, the proportion of species assessed was reduced from 32% to 18% assessment if DD-species were excluded (Supplementary Data 2.2).

Table 2.2: Chi-square results for the comparisons between global and assessed species included on the IUCN Red List (Total vs RL) and excluding Data Deficient species (RL vs RL non-DD) for each FAO area, preferred habitat, the number of species assessed in each taxonomic order in all the environments, and commercial categories. Original data can be found in Supplementary Data 2.1, 2.2 and 2.4.

	Total *vs* RL			RL *vs* RL non-DD		
	χ2	df	p	χ2	df	p
FAO areas	16894.4	25	< 0.001	801.0	25	< 0.001
Habitats	9521.4	7	< 0.001	706.7	7	< 0.001
Orders	10319.0	61	< 0.001	782.4	61	< 0.001
Orders (Freshwater species)	4476.4	61	< 0.001	393.8	61	< 0.001
Orders (Marine species)	6011.6	61	< 0.001	407.3	61	< 0.001
Commercial importance	1214.8	5	< 0.001	100.2	5	< 0.001

Commercial importance differed in both comparisons (Table 2.2): commercial species were not the best-assessed ones, despite having the biggest number of assessed species. Even excluding DD species, species of minor commercial interest were better assessed than other species (56% vs 52%) (Supplementary Data 2.3).

Regarding biological traits, assessed species tended to be larger than the average of the full dataset (Table 2.3). Heavier species were better assessed in marine habitats when analysing total and assessed species, but not in the assessed vs non-DD comparison; weight was a non-significant factor for freshwater fish. Assessed species had shorter lifespans when compared to the full species set (marine and freshwater combined), but this difference was not observed when analysing freshwater and marine species separately. Assessed species had longer generation times (Table 2.3), but this could not be seen in the comparison between assessed and non-DD species in the freshwater environments.

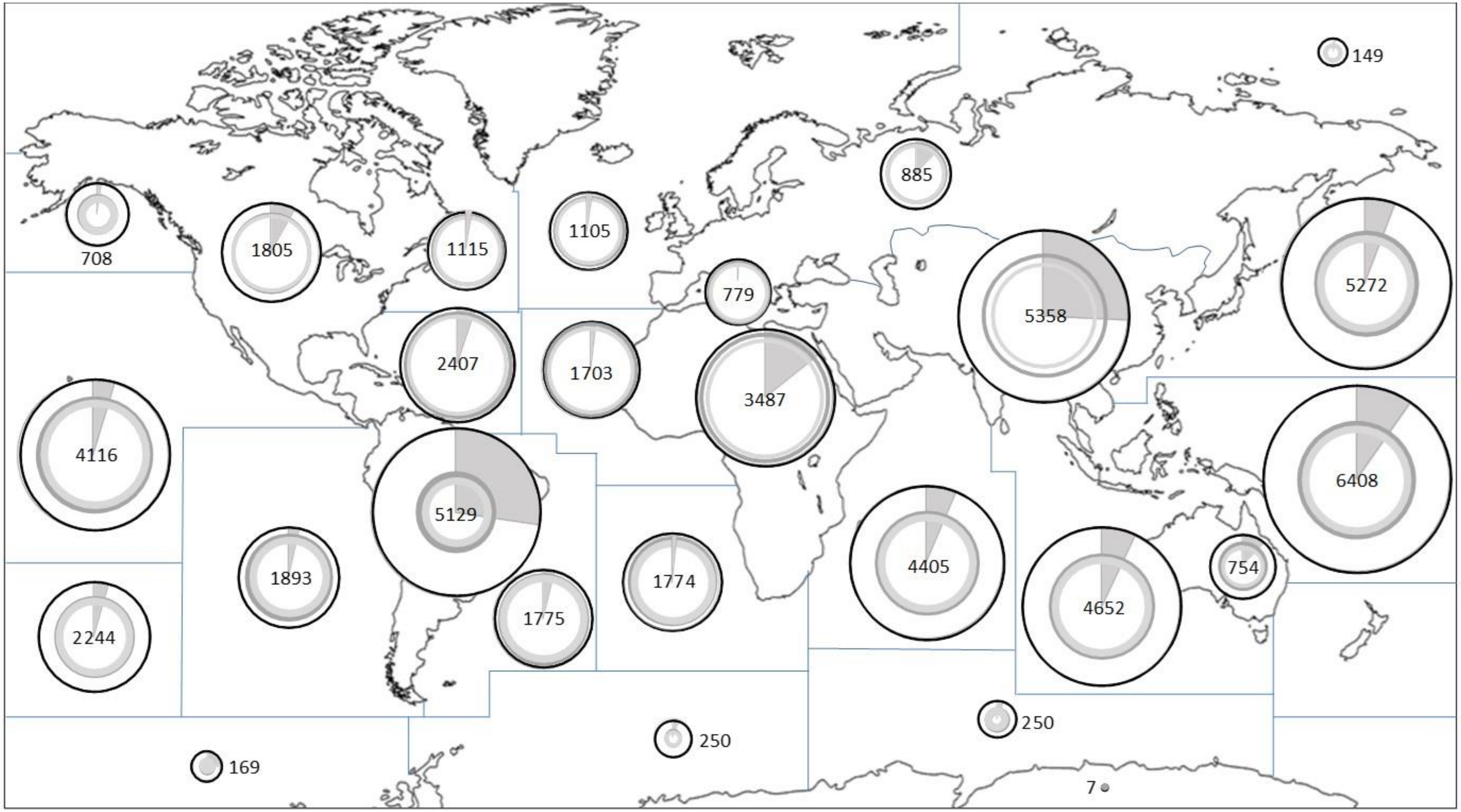

Figure 2.1: Total number of fish species included on FishBase 2013 (outer black circles), and relative number of assessed species (dark grey circles) and assessed and non-Data Deficient species (light grey circles) in the IUCN Red List, by FAO Major Fishing Area. Grey sectors: Proportion of species described in the Fishing Area after 1994. Full data in Supplementary Data 2.1. Figure by R. Miranda.

Table 2.3: Values and biases of life-history traits in the three groups: Total, assessed species included on Red List (RL), and assessed excluding data deficient species (RL non-DD) were compared. All values are reported as the median and interquartile range in brackets. Wilcoxon rank-sum test with continuity correction statistic (W) and associated probability (p assoc.) are shown.

Trait	Length (log cm)	Weight (log g)	Longevity	Generation Time	Vulnerability Index	Phylogenetic Index	Year of description
Overall							
Total median	1.1 (0.8-1.5)	3.6 (3.0-4.1)	10.0 (5.0-18.0)	1.8 (1.1-3.1)	21 (10-34)	0.5 (0.5-0.5)	1928
RL median	1.2 (0.9-1.5)	3.7 (3.1-4.3)	8.0 (4.0-15.0)	1.8 (1.2-3.1)	23 (12-36)	0.5 (0.5-0.5)	1917
RL not DD median	1.2 (0.9-1.5)	3.6 (3.1-4.3)	8.0 (4.0-15.0)	1.8 (1.2-3.1)	23 (12-35)	0.5 (0.5-0.5)	1911
Total *vs* RL	177330000	887440	591610	154800000	228120000	245890000	268090000
p assoc.	< 0.001	0.001	0.001	0.001	< 0.001	0.001	< 0.001
RL *vs* RL not DD	74322000	554770	360770	62998000	88381000	88220000	94615000
p assoc.	0.076	0.548	0.693	0.479	0.233	0.138	< 0.001
Freshwater							
Total median	1.0 (0.8-1.3)	3.5 (2.8-4.0)	7.0 (4.0-12.0)	1.5 (0.9-2.6)	15 (10-27)	0.5 (0.5-0.5)	1935
RL median	1.0 (0.8-1.3)	3.5 (3.0-4.1)	6.0 (4.0-11.0)	1.6 (1.1-2.7)	17 (10-30)	0.5 (0.5-0.5)	1927
RL not DD median	1.1 (0.8-1.4)	3.5 (2.9-4.1)	6.0 (4.0-11.0)	1.6 (1.1-2.7)	18 (11-31)	0.5 (0.5-0.5)	1921
Total *vs* RL	48165000	175230	169280	37545000	57670000	64586000	70037000
p assoc.	< 0.001	0.272	0.371	< 0.001	< 0.001	0.004	< 0.001
RL *vs* RL not DD	20605000	108340	134060	17632000	24065000	24640000	26409000
p assoc.	< 0.001	0.788	0.927	0.182	< 0.001	0.222	< 0.001
Marine							
Total median	1.3 (1.0-1.6)	3.7 (3.2-4.2)	12.0 (7.0-25.0)	2.2 (1.3-3.5)	26 (14-39)	0.5 (0.5-0.5)	1918
RL median	1.4 (1.0-1.7)	3.8 (3.2-4.4)	12.0 (7.0-22.5)	2.2 (1.3-3.7)	27 (15-42)	0.5 (0.5-0.5)	1904
RL not DD median	1.4 (1.0-1.7)	3.8 (3.2-4.4)	12.0 (7.0-22.0)	2.1 (1.3-3.5)	27 (15-41)	0.5 (0.5-0.5)	1897
Total *vs* RL	43493000	380090	174280	42631000	59736000	63703000	71410000
p assoc.	< 0.001	0.002	0.197	0.042	< 0.001	0.286	< 0.001
RL *vs* RL not DD	18896000	238810	88981	15984000	22672000	22037000	23622000
p assoc.	0.094	0.714	0.848	0.017	0.049	0.402	< 0.001

Assessed species had higher vulnerability indices in both freshwater and marine environments (Table 2.3), with no difference in vulnerability indices when comparing assessed and non-DD species. In terms of taxonomic traits, phylogenetic index values of all fish ranged from 0.5 (low) to 2 (high), although most species had low values (0.5). The only significant difference in this comparison was that assessed species had higher phylogenetic indices compared to the full dataset, in both the full comparison and for freshwater fish only.

The level of assessment varied significantly across different orders, in both freshwater and marine habitats, as well as in the global analysis (Table 2.2 and Supplementary Data 2.4). Among the richest orders, Squaliformes and Rajiformes appeared to have most species assessed (90% and 92% species assessed respectively), whilst other orders such as the marine orders Scorpaeniformes (15% assessed) and Gadiformes (21%), were relatively poorly represented in the IUCN Red List. Among freshwater fish, Gymnotiformes (11% assessed non-DD), Characiformes (21%) and Siluriformes (26%) had the lowest assessment levels.

Assessed species had generally been described earlier, both for freshwater and marine species (Table 2.3). Fish were (together with reptiles) the least assessed vertebrate taxa, with hundreds of species described in recent years but often not yet included in the Red List. When examining the proportion of non-DD vertebrate species according to their description date, it was observed that while all vertebrate groups had a lower proportion of recently-described species assessed, fish described in the last thirty years have generally not been assessed yet on the IUCN Red List. The ratio of species assessed to species described (excluding those years with less than 10 species described) showed that lower percentages of assessment were associated with higher numbers of discovered species in reptiles, amphibians, and especially in fish (Figure 2.2). Many fish species discovered since 1996 (2,782 freshwater species) occurred in South America and Asia, two areas with relatively poor assessment levels (Figure 2.1).

The best model for species assessments among those models for which data on >85% of species were available included the positive effects of length and Vulnerability Index. On the other hand, Phylogenetic Index and description year had a negative influence on species assessment probability, confirming the results obtained in the individual analyses (Tables 2 and 3). Considering fish orders, certain orders were positively associated with the probability of assessing a species (Carcharhiniformes, Chimaeriformes, Squaliformes, Rajiformes, and Syngnathiformes) whereas others had a negative association (Characiformes, Gadiformes, Gymotiformes). The full result of this model is presented in Supplementary Data 2.5

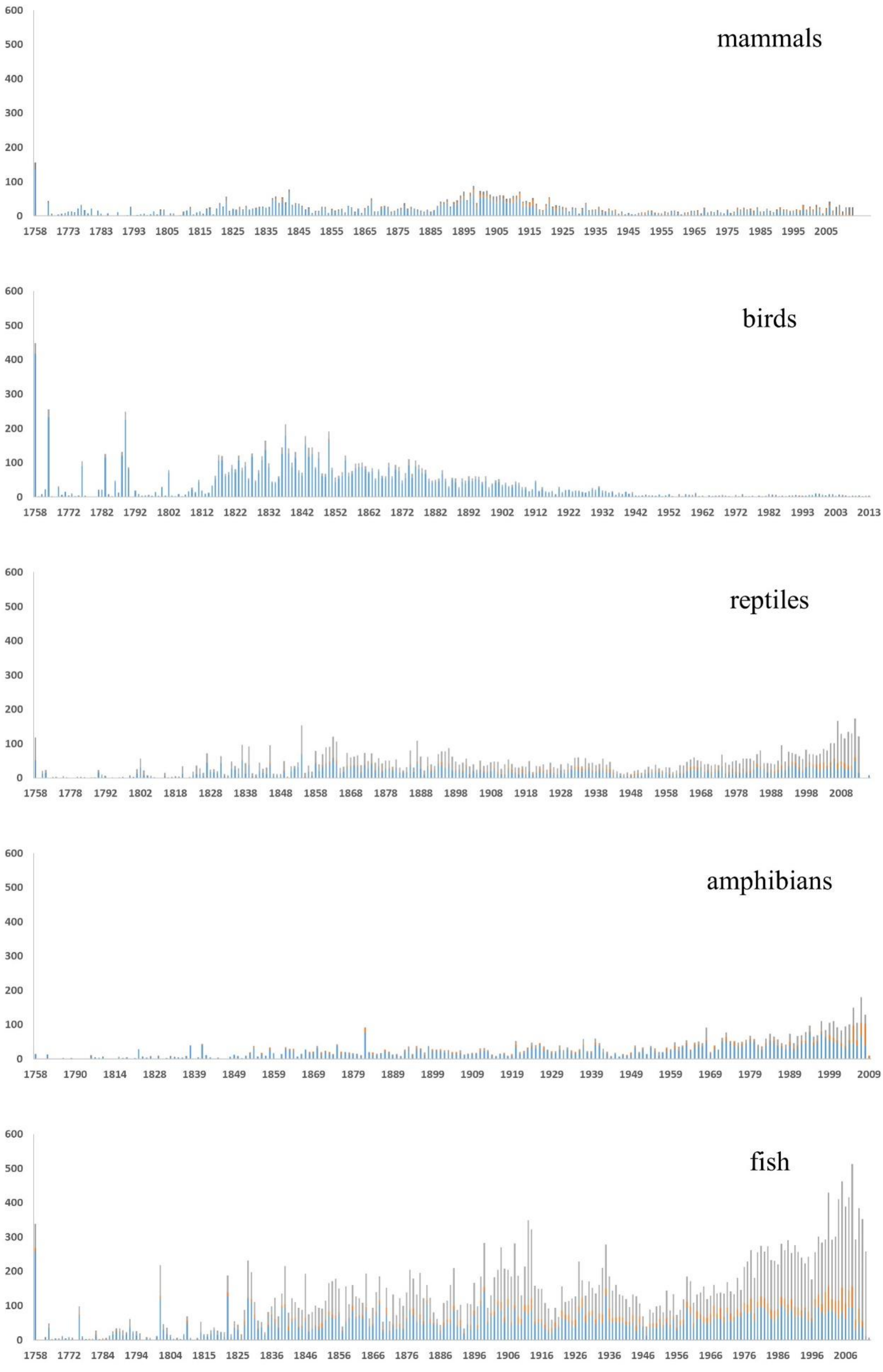

Figure 2.2: Number of species described per year assessed by IUCN as non-DD (blue) and DD (orange), and Not Evaluated (grey), in main vertebrate groups. From Miqueleiz et al. (2020).

Discussion

Our study highlights certain areas and habitats on Earth where additional assessment efforts for fish are needed to ensure that levels of threat to fish species are adequately represented within the IUCN Red List and that fish feature in subsequent conservation and policy instruments. Longer (but not heavier) species tend to be better assessed, as are short-lived species - but not those with shorter generations, i.e. those that reproduce earlier. Assessed species have a higher vulnerability index (VI, the vulnerability of a species to fishing pressure) than non-assessed ones. Certain fish orders are better assessed, such as sharks and rays (Dulvy et al. 2014), while others lack sufficient assessment (Scorpaeniformes, Gymnotiformes). Species assessed had been described earlier than unassessed ones, resulting in an assessment gap for fish species described during the most recent decades, comparable to a similar gap observed in reptiles (Meiri & Chapple 2016) and amphibians (Tapley et al. 2018). Finally, no evidence was found to support the hypothesis that assessment rates are higher in species with higher commercial interest or value.

As predicted, fish from developed regions (e.g., Mediterranean, Europe, and the Atlantic Ocean) had higher rates of assessment. The higher levels of freshwater fish assessment in Europe are due to a comprehensive European assessment programme that exists for freshwater fish (Freyhof & Brooks 2011). However, such exhaustive assessments are not confined to developed regions only: the higher levels of freshwater fish assessment in Africa compared to other developing regions are the result of an exhaustive assessment by IUCN in 2011 (Darwall, Smith, et al., 2011). South America and Asia, on the contrary, require further attention in freshwater fish assessment efforts (Darwall & Freyhof, 2016), although some Asian regional assessments have focussed on the Western Ghats, and the Indo-Burman and Eastern Himalayan regions (Allen et al. 2010; Molur et al. 2011). These regions might be subject to particularly high extinction risk, as they represent hotspots with high threat status (tropical regions), small species ranges (Albert et al. 2011), and high data deficiency, especially in South America (Alofs et al. 2014). Around 40% of freshwater fish species occur in the Neotropical region (Albert et al. 2011); given that only 19% of the more than 5,000 South American freshwater fish species are assessed on the IUCN Red List, the definition of key biodiversity areas for freshwaters in South America are likely inadequate for fish, due to a lack of fish representation. (Collen et al. 2014) showed that there was little congruence in the patterns of species richness, endemic species richness and threatened species richness between different groups of freshwater species, so that one freshwater taxon group is unlikely to be an adequate surrogate for another in analyses of priority areas for conservation. Initiatives like the Alliance for Freshwater Life aim to place freshwater species and their associated ecosystems on the global agenda as legitimate targets for conservation action (Darwall et al., 2018).

In the marine realm, it was surprising to see that the Atlantic Ocean was far better assessed than areas of the Indian and Pacific Oceans that belong to economically developed regions, such as the Eastern Pacific (Figure 2.1). In this case, we consider that our hypothesis is not truly valid for oceans, as more factors may be affecting fish assessment rates. Similarly, species assessment was not equally distributed among habitats. Coral reefs, which are known to provide several ecosystem services to humans (Moberg & Folke 1999) were better assessed than other habitats (Table 2.3). Their ease for survey and charismatic image (Duarte et al. 2008) is combined in this case with a high risk, as reef-associated fish face habitat-degrading threats originating from land, such as coastal residential and commercial development (McClenachan et al. 2016) and coral bleaching induced by climate change (Alvarez-Filip et al. 2009). Assessments of deep water benthic species are lagging behind that for neritic species, likely due to better information availability for neritic species, and possibly due to lower perceived threats affecting these species (Halpern et al. 2007). However, deep-sea habitats are often found in international waters with fewer restrictions and regulations; areas around hydrothermal vents, for example, are likely targets for deep-sea mining (Van Dover 2011) and the impacts of such activities are at present vastly overlooked in conservation planning and policy. Non-assessed marine fish species were consistently smaller than those assessed by the IUCN, but there was no size bias in freshwater fish assessments (Table 2.3). Threats affect freshwater species in a complex manner, not always related to body size (Dudgeon et al. 2006). An assessment bias towards species of commercial interest was expected, as the most significant threat for marine fishes is associated with direct mortality from human fishing activities targeting large-bodied species (Olden et al. 2007), often with slow population growth (Reynolds et al. 2005), and those species may be prioritised for conservation assessment. No evidence of commercial fish being better assessed than other species was found (Table 2.2). Species of commercial interest were expected to be better assessed as a result of the fishing pressure they are subjects of.

Assessed species generally had higher vulnerability indices (Table 2.3). Previous studies have compared this index and IUCN Red list categories (Strona 2014; Miranda 2017), and Red List categories were found to be more suitable for conservation purposes than the VI (Miranda 2017). Both measures are equally valid because they are considering different threat processes (VI measures the intrinsic extinction vulnerability due to being fished, based on biological traits of fish species whilst the IUCN Red List evaluates the extinction risk of species considering a wide range of threat processes that are affecting species, and including data on symptoms of extinction risk, such as populations declines, distribution size, population size, etc.). With aquatic systems being affected by several different threats (Reis et al., 2017), including emerging threats such as climate change and plastic pollution, the understanding of species vulnerability needs to be expanded to the wide spectrum of threat processes, e.g. through assessment processes such as climate change vulnerability assessments (Chin et al. 2010). Vulnerability assessments allow to highlight those species potentially vulnerable to a specific threat and act on safeguarding these before the threat may take full effect, i.e. lead to population declines and hence higher extinction risk. On the contrary, IUCN Red List gives an estimate of the extinction risk at present, given the threats already affecting or about to affect a species. Furthermore, previous results of species of commercial interest (more vulnerable to fishing pressure) do not show similar patterns. Therefore, this incongruity in the results will be subject to study in further research about the relationship between VI and commercial interest in chapter 3.

As predicted, the assessment of threat status in fish is taxonomically biased (Table 2.2). The presence of several Fish Specialist Groups (https://www.iucn.org/ssc-groups/fishes) may skew IUCN efforts towards certain groups or species. The IUCN Shark Specialist Group (http://www.iucnssg.org) published significant work in 2014 (Dulvy et al. 2014) assessing the conservation status of all sharks, rays, and chimaeras, resulting in higher assessment levels than in other orders. Such levels respond to an increasing concern over the past decades on shark conservation, with the change in perception, from one of needing to protect humans from sharks to that of needing to protect sharks from humans (Simpfendorfer et al. 2011). However, a closer look at these groups showed that there was a large proportion of DD species (51% in sharks, 44% in rays, and 40% in chimaeras), slightly improved in the 2017 Red List. Thus, despite it being better to have a DD assessment than not being assessed, further investigation is required in these and other highly DD orders to obtain data that will allow scientists to classify their extinction risk (Bland et al. 2012).

Regarding marine orders, Scorpaeniformes (10% assessed non- DD) and Gadiformes (15%) had the lowest levels of assessment (Supplementary Data 2.4), despite including many species of commercial importance in certain areas of the world (Winfield 2016). In the case of Scorpaeniformes, their low growth rate and long generation time make them especially sensitive to overexploitation, which has resulted in the disappearance of many stocks in the Atlantic (Ricard et al. 2012). Unfortunately, these results are consistent with data obtained for commercial fishes, suggesting that human consumers may be largely unaware of the conservation status of the consumed marine fish. Many of these commercially fished species may also be of importance to subsistence fishermen, endangering important food stocks and protein availability in areas around the world.

Freshwater tropical species are possibly within the least assessed groups compared to other Red List assessed fish, requiring in-depth research to evaluate their conservation status. Characiformes, freshwater-restricted species distributed in tropical Africa and South America, had a low assessment rate (21% if DD species are excluded). Considering that over 300 of the 2022 characiform species have been described as recently as the 2000-2010 decade (Oliveira et al. 2011), a combination of high description rates and few evaluations has led to a significant assessment gap in this order. Gymnotiformes (11% non-DD) and Siluriformes (26%) from South America, Africa, and South-Eastern Asia (only Siluriformes) (Cordiviola et al. 2009) inhabit extensive and difficult to sample habitats such as deep river channels and flood-plain floating meadows (Albert 2001), which severely hamper initiatives for their conservation.

In this study, we have demonstrated that most of the non-evaluated species were only recently described (Figure 2.2). Since the mid-1990s, IUCN's capacity to provide assessment for newly-described species seems to be decreasing as observed in the time-dependent rates of assessment. As new species are being described in those areas which already have low assessment rates, such as South America, Asia, or tropical oceans (Figure 2.1; Nelson et al., 2016) the gap between described and assessed species widens. South America is the sole FAO Major Fishing Area where more species were described between 1994 and 2013 than were included in the Red List for that area (Figure 2.1). Current rates of species discovery and publication suggest there are likely more than 8,000 Neotropical freshwater fishes (Reis, 2013), urging the need for an exhaustive effort to sample and study South American inland waters. This is of particular importance given the threats of naturalised species (e.g. non-native fish; Pelicice, Vitule, Junior, Orsi, & Agostinho, 2014), and damming (Reis et al., 2017), amongst others, which are likely to impact a large number of freshwater species in South America. In addition, these threats have the scope to impact the freshwater community structure, leading to a homogenisation of the fauna, loss of genetic diversity, etc. and thus impacting wild fish stocks which may play a major part in protein provisioning along inland waters.

Furthermore, comparing data from fish with other vertebrate groups, fish species have been suffering from an evaluation decline since the 1980s which, combined with an increase in species discovery, resulting in a large proportion of recently discovered species not being evaluated, a trend shared with reptiles (Meiri 2016) and amphibians (Tapley et al. 2018). In the case of amphibians, for which previously complete global assessments had been carried out, assessments are now rapidly becoming out-dated with an increasing proportion of non-evaluated species (Tapley et al. 2018). Previous studies with lizards and snakes (Meiri & Chapple 2016; Böhm et al. 2017) have found that those species easier to study (large range sizes, temperate latitudes) are described earlier and are better assessed, whilst species with small ranges and inhabiting tropical regions remain unassessed or even undiscovered, with a higher risk of extinction as a result of their rarity (Pimm et al. 2014). The tropical biodiversity data gap may influence certain indicators established by the Convention on Biological Diversity more than others (Collen et al. 2008) and, despite recent efforts led by IUCN (Tognelli et al. 2016), further research and investment in this area is needed to ensure the effective protection of species dwelling there. Implications of lower assessment rates for recently described species will be discussed further in chapter 4 of this thesis.

Recommendations

Since conservation efforts to date have resulted in only 46% of fish species being formally assessed by the IUCN Red List at the time of the study, completing the assessment for the remaining ones seems a colossal task, complicated by the rate of new species discovery. With a cost of US$38 million, having 160,000 species evaluated by 2020 seemed hardly feasible in the context of funding shortfalls (Juffe-Bignoli et al. 2016). Thus, we suggest focusing efforts in the following key areas:

1) Develop working groups for under-assessed areas: We strongly recommend the creation of a working group on Central and South American fish species. Several regional initiatives have been developed by IUCN in Europe (Abdul Malak et al. 2011; Freyhof & Brooks 2011; Nieto et al. 2015), Africa (Darwall, Smith, et al., 2011), and Asia (Allen et al. 2010, 2012; Molur et al. 2011). However, only a partial report of North and Central America Chondrichthyans (Kyne et al. 2012) and an assessment in the Andean region (Tognelli et al. 2016) have been carried out on the continent so far. To fulfil this aim, collaboration with local organisations and investment in local institutions is essential to develop the infrastructure and expertise for long-term monitoring (Collen et al. 2008) and study not only individual species but also species assemblages and interactions. The Global Freshwater Fish Assessment has been developed by IUCN Freshwater Unit to evaluate all discovered fish species by 2021, and has already improved assessments in many of the areas in need of assessment detected in this chapter. Further considerations on the Global Freshwater Fish Assessment project will be discussed in the next chapters of this work.

2) Increase knowledge of fish distribution, ecology, and life history to combat Data Deficiency: Only 37% of fish species have been assigned an IUCN category, excluding DD species, which are often known from type specimens or type localities only. More resources should be directed to research those Data Deficient species (Hoffmann et al. 2008), where field surveys are likely to bring about an immediate increase in knowledge and hence expedite a non-DD assessment, i.e. species where a lack of population data or knowledge about threats are affecting a DD status. The application of environmental DNA (eDNA) sampling can provide greater probabilities of detection of aquatic species when compared with the use of traditional sampling procedures (Antognazza et al. 2019). Machine-learning techniques may also help to classify the most likely extinction risk category for those DD species that are more difficult to survey (Bland, Collen, Orme, & Bielby 2015). Furthermore, we cannot underestimate the risk of outdated assessments, that combined with unassessed areas should drive conservation priorities (Hermoso et al. 2017).

3) Explore the role played by Protected Areas (PAs) and Key Biodiversity Areas (KBAs) in fish conservation (especially freshwater fish), congruently with Aichi target 11 (SCBD 2010). The establishment of PAs to benefit fish populations relies on improved knowledge on fish distribution (Hermoso et al. 2016) and knowledge on species extinction risk, distribution and endemism is vital to inform at least some of the criteria for definition of a KBA (KBA Standards and Appeals Committee 2019). Up until now, in many regions of the world fish species have played a limited role in the designation of protected areas or KBAs. Thus, further studies on both the ability of the current network of PAs to adequately protect freshwater fish (Abraham & Kelkar 2012) and on gaps within the PA/KBAs network are urgently needed (Pino-del-Carpio et al. 2011, 2014). This task is even more urgent in under-assessed areas like the Andean region of South America, where 88% of the species are not adequately represented in any protected area (Tognelli et al. 2019). This question will be addressed in chapter 5 of this thesis.

4) Enhance the role played by national Red Lists: IUCN Red List and Criteria are being increasingly used for regional and national red lists (Rodríguez 2008; Zamin et al. 2010). Several measures are proposed to better link national, regional, and global Red Lists such as taxonomic uniformity and enhance data transfer between national and the global Red Lists (Brito et al. 2010). The ability to now also submit IUCN Red List Assessments in French, Spanish, and Portuguese is likely to improve coverage of assessments for regions such as South America. In addition, financial investment for national Red List development should favour those countries with the richest biodiversity but lower GDP (Zamin et al. 2010). Better linkage of global and national Red List processes also increases the pool of

experts available for global IUCN Red List assessments, through increased networking, collaboration, and capacity building. The possibility of doing national assessments of endemic species following global Red List standards also increases the value of such assessments and we should not underestimate their possible contribution to the IUCN Red List.

5) Finally, this study goes beyond a simple listing of IUCN Red List gaps. In a context of global threat to fish species, jeopardized by human and climate pressures combined, we consider that the voice of conservation initiatives like the IUCN Red List should be extensively heard by other authorities. CBD's Aichi target #12 referred to in the introduction is a call to "improve and sustain species conservation status". The results of the study fully support this target by pointing out where assessment efforts should be focused on. FAO could benefit from improved Red List evaluations, too. There is also room for improved use of IUCN outputs in FAO assessments (especially those subject to intensive fishing). For example, the 2016 SOFIA (State of World Fisheries and Aquaculture) report by FAO did not refer to the IUCN Red List (FAO 2016) whilst this collaboration is emerging in the 2018 report (FAO 2018). With insufficient funds to both expand taxonomic coverage through new assessments, and keep existing assessments up to date (Rondinini et al. 2014) a compromise solution should be achieved. This study supports others like Hermoso et al., (2017) to help guide assessment efforts and, afterwards, implement conservation actions for such species. We do not want to devaluate conservation actions, but we consider that proper assessments provide not only a status, but also valuable information required to achieve successful conservation programs.

Chapter Transparency

This chapter is based in the following article "Miqueleiz, I., Bohm, M. M., Ariño, A. H. , Miranda, R. (2020). Assessment gaps and biases in knowledge of conservation status of fishes. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **30**, 225–236", with DOI 10.1002/aqc.3282. I. Miqueleiz and R. Miranda conceived the present idea. I. Miqueleiz developed the experiment, carried out the analyses and interpretated the results. R. Miranda contributed with Figure 1 to the results. I. Miqueleiz wrote the manuscript. M. Böhm, A.H. Ariño and R. Miranda provided comments to the analysis and the manuscript.

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CHAPTER 3:

Conservation status gaps for top fished marine commercial species

Capítulo 3:

Sesgos en el estado de conservación de las especies comerciales de mayor importancia pesquera

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Chapter preface

Biodiversity loss is a global problem accelerated by human-induced pressures on the environment. In the marine realm, one of the major threats to species conservation, together with climate change, is overfishing. The future of many dependent human communities relies on the sustainability of fisheries. Harvesting marine species above safe biological boundaries limits species resilience and can contribute to extinction risk, but often regulatory policies do not effectively control overfishing or even allow it to some extent. In this context, having information on the conservation status of target commercial marine fish species becomes crucial for assuring safe standards. However, we showed in the previous chapter that commercial fish species did not seem to stand out in terms in assessment among all fishes, despite the obvious interest that assessing commercial stocks has both from the economic and conservation viewpoints. A handful of commercial species carry the brunt of commercial fisheries—did they fare better or worse than the rest?

In this study, we combined fisheries statistics from the FAO, the IUCN Red List, FishBase and Sea Around Us to understand to what extent the top commercial species have been assessed in terms of their Red List conservation status. We focused the study on a subset of top commercial fish species which constitute almost half of global fish landings. We compared IUCN Red List assessments with FishBase Vulnerability Index and FAO and Sea Around Us landings to find differences among IUCN Red List categories.

Levels of assessment for top fished species were higher than those for general commercial or highly commercial species. Nevertheless, almost half of the species had outdated assessments. We found no relation between IUCN Red List traits and FishBase Vulnerability Index. Reconstructed catches as reported by Sea Around Us were 21.5% higher than those reported by FAO. Species with declining population trends according to the IUCN Red List have had their catches increased in recent years, even after evaluation in the IUCN Red List, and many other species have unknown population trends. Conservation status cannot be directly inferred from landing trends, and IUCN Red List methodology cannot easily be applied to fisheries management. Nevertheless, we suggest a closer cooperation between countries, FAO, and IUCN Red List to guarantee that reliable data are available to ensure commercial fishes assessment.

Introduction

For millennia, mankind has had an especially close bond with the sea as it provides people with food (Schröder 2013), as well as other ecosystem services (Worm et al. 2006) that contribute to health, well-being, cultural identity, and to the economy of societies (Hughes 2014). Billions of the world's poorest people rely on healthy oceans to provide "livelihoods, jobs and food and the range of goods and services that flow from coastal and marine ecosystems" (WWF 2018), and the oceans contribute significantly to the support of many of the Sustainable Development Goals (SDGs) (FAO 2018; Singh et al. 2018).

Marine fisheries are the main contributors of seafood (referred as finfish and marine invertebrates) for human consumption (Pauly & Zeller 2016), with almost 6 billion tons of fish and invertebrates taken from the oceans since the 50s (Pauly et al. 2020) contributing to 17% of global human protein intake (FAO 2017) and sustaining millions of jobs (FAO 2014). Nevertheless, their importance is closely linked to their long-term sustainability. The Convention on Biological Diversity (CBD), through the Aichi targets, aims to achieve both sustainable management of existent fish stocks (target 6) and prevention of the extinction and improvement of the conservation status of threatened species (target 12) by 2020 (SCBD 2010). In the same line, SDG14 on "Life below water" has the same goal of effectively regulating overfishing and rebuilding stocks to levels that produce maximum sustainable yield by 2020 (sub-target 14-4).

Historically, humanity has failed in preventing fish population collapses and has not taken conservation biology of marine fishes seriously enough (Hutchings & Reynolds 2004), resulting in declines in species diversity and abundance (Butchart et al. 2010). However, the number of sustainably harvested stocks is, in fact, increasing. This apparent paradox has been explained by some studies as those stocks being offset overall by several heavily exploited fisheries that are unmanaged (Froese et al. 2012, 2013). Food and Agriculture Organisation (FAO) reports a global fishing decline since the '90s (Pontecorvo & Schrank 2012), which seems to have stabilized in recent years (2011-2015 period) at around 80 million tonnes annually (FAO 2016, 2017). However, this stability can be affected by an underestimation of the amount of fish extracted from the sea (Pauly & Zeller 2016, 2017) as it may be misled by the omission of small-scale (Pauly 2006) and recreational fisheries (Pauly & Zeller 2016), as well as manipulated or highly questionable statistics that locally increase catches (Pauly & Zeller 2017).

Beyond this evidence lies a low concern about marine fish species conservation in the fishing industry (Worm et al. 2009; Fitzgerald et al. 2020) and/or an institutional failure during the past century (Acheson 2006). Globally, a few fish species dominate catches owing to several factors such as natural abundances, consumer preference, geography, history and ease to catch (Sadovy de Mitcheson et al. 2013). Overfishing not only affects these target species, but it also has a cascade of effects on other species and population assemblages (Duffy 2003; Springer et al. 2003). For example, the selective extraction of species and individuals of higher commercial value leads to the disappearance of higher trophic levels of the marine food webs, implying an increased fishery reliance on organisms at the low levels of the food webs (Pauly et al. 2002; Szuwalski et al. 2016). Overfishing is also identified as one of the main threats to marine biodiversity (Jackson et al. 2001; Morato et al. 2006). Population declines as deep as 90% have been reported for pelagic fish species (Myers & Worm 2003), which can cause a range of ecological impacts, restructuring communities with top-down effects (Hutchings 2000; Myers et al. 2007).

The IUCN (International Union for Conservation of Nature) is the institution responsible for assessing the global conservation status of plants and animals through their periodically reviewed Red List of Threatened Species (Rodrigues et al. 2006). Overfishing is considered by the IUCN Red List as a threat to many marine fish species under the “fishing & harvesting aquatic resources” category, acknowledging that it can lead to population declines, which is one of the criteria to classify species under the IUCN Red List Categories (IUCN 2012). Despite this, the status of only a small fraction of described marine animal species has been evaluated by the IUCN (McCauley et al. 2015). FishBase (Froese & Pauly 2019), the most comprehensive database compiling fish species information, has more than 40% of “commercial” and “highly commercial” species unassessed in the IUCN Red List (see Chapter 2).

Considering the existing level of overfishing in marine commercial species, together with the direct extinction risk, and the indirect impacts on communities, we considered monitoring of the IUCN Red List conservation status of top fished marine commercial species a priority. The objective of the present study was, therefore, to explore how most important marine commercial species are categorized within the IUCN Red List and to understand the degree of knowledge we have on marine commercial species conservation status.

Methods

We explored fisheries statistics extracted from databases compiled by FAO, IUCN Red List, FishBase, and Sea Around Us. The datasets had information about fishing trends, species conservation status, and other traits. We first identified the most fished species globally from FAO statistics. Then we collected information on IUCN Red List status for these highly fished species using assessments made between 1996 and 2019. Finally, we explored the trends in landings in the data from Sea Around Us. We then statistically analysed the relationships between conservation status and landing trends.

FAO data

In the late 40s, the FAO began collecting global fishing statistics (Pauly et al. 2002). In recent years, FAO has produced several Yearbooks of Fishery Statistics and reports about the State of World Fisheries and Aquaculture (SOFIA). Based on this work, we used the 2017 FAO Yearbook of Fishery and Aquaculture Statistics (FAO 2019) that identified the top 70 fished species at the global level based on their landings. The subset of data analysed represents almost half (46.5%) of the global landings in 2017 according to FAO statistics, considering not only fish *sensu stricto* but also squids and crustaceans. Most of these species corresponded to marine species, with only three freshwater-restricted fish. Henceforth, we will refer to this subset of most important commercial species as “top fished species”.

IUCN Red List and FishBase

For these top fished species, we extracted information from the IUCN Red List (IUCN 2019). The IUCN Red List establishes the extinction risk of species assigning them to a category according to their conservation status. From lesser to greater risk, these categories are Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), Critically Endangered (CR), Extinct in the Wild (EW), and Extinct (EX). Moreover, there is a category for those species with insufficient information to assess their conservation status, Data Deficient (DD). These assessments are regularly updated (IUCN Red List recommends revaluating species every 10 years) and contain information relevant for species conservation (population trends, biogeography, threats, or conservation actions). From the IUCN Red List database, we obtained four variables: 1) Current conservation category; 2) Assessment date; 3) Population trends (increasing, stable, decreasing or unknown); and 4) Current threats, focusing on Threat 5.4 “fishing & harvesting aquatic resources” (henceforth “fishing pressure threat”). We focused only on global scale evaluations and did not consider regional assessments (e.g. European or Mediterranean) or separate stocks for any given species.

From FishBase (Froese & Pauly 2019), we obtained the Vulnerability Index of top fished species, which estimates intrinsic extinction vulnerabilities of marine fishes to fishing (Cheung et al. 2005). This index assigns each species a value between 0 (low vulnerability) and 100 (high vulnerability). We also obtained from FishBase a list of fish species classified as “commercial” or “highly commercial” interest, based on FAO catches data. For these subsets of species, we obtained their Vulnerability Index values and their IUCN Red List status.

Sea Around Us

FAO landing data have been suggested to be not completely accurate (Froese et al. 2012; Pauly & Zeller 2017). To avoid this problem, the Sea Around Us project reconstructs data for major fished species, adding reported FAO data and estimations of unreported catches. Pauly and Zeller (2016a) suggested that reconstructed data from Sea Around Us project were overall 53% higher than the reported data. Thus, we collected reported and unreported data for top fished species in the 1996-2014 period from Sea Around Us at the global level.

All data used in this study can be found in Supplementary Data 3.

Analysis

We compared the proportion of assessed species from the subset of top fished species with the assessment rates of FishBase commercial categories (commercial and highly commercial) through chi-square tests for analyses of frequencies. We also analysed differences in the Vulnerability Index between the three species subsets (top fished, commercial, and highly commercial) trough Kruskal-Wallis tests.

Focusing on the subset of top fished species, we examined the proportion of top fished species within each IUCN Red List category over the last 20 years, the fishing pressure (IUCN Red List threat 5.4), and also the species population trends. We performed Kruskal-Wallis tests to assess differences in Vulnerability Index (VI) for the different conservation status, population trends and IUCN Threat 5.4 for top fished species.

We analysed fishing trends for the top 70 species, from both reported (FAO) and reconstructed data (Sea Around US). We decided to examine fishing trends grouping them according to the IUCN Red List categories and population trends. We also examined the change (increasing or decreasing) in the catches between the most recent assessment date and 2014.

Results

We compared the top fished species with the larger commercial species groups (commercial and highly commercial species). No association was found between IUCN Red List assessment rates and commercial categories trough the chi-square test ($p>0.05$) (Table 3.1). Vulnerability Index values were also not significantly different among top fished species and those considered to have a commercial or highly commercial interest ($p=0.065$). Nevertheless, values for top fished species tend to be lower than in the other categories (Table 3.1).

Table 3.1: Number and proportion of IUCN Red List assessed and unassessed species for each species sub-set, and their average vulnerability indices.

	Top fished species	**Commercial species**	**Highly commercial species**
Total species (n)	70	2056	225
IUCN Red List assessed species	49 (70%)	1217 (59.2 %)	126 (56%)
Unassessed species	21 (30%)	839 (40.8 %)	99 (44%)
Vulnerability Index (mean and SD)	39.8 (±19.5)	42.9 (±18.1)	49.25 (±20.9)

From the 70 top fished species, twenty-one (30%) were not assessed by the IUCN Red List (IUCN 2019) (Table 3.2), including two of the ten most fished species (*Theragra chalcogramma* and *Micromesistius poutassou*). Within the assessed species, we also found cases of deficient evaluation, with six of them (five fish and one cephalopod) classified as data deficient (DD), and two species with dated assessments (from 1996) that do not have complete information. Most of the assessed species, 35 out of 49 (71.4%), were reported under fishing pressure (IUCN threat 5.4). Almost all assessed species (47 out of 49) had information on population trends, but many of them (25, 53.2%) had unknown trends. Assessment dates ranged between 1996 and 2019, with most species having been assessed between 2010 and 2011 (Figure 3.1).

No significant differences were found in the Vulnerability Index for different IUCN categories ($\chi2=0.49$, d.f.=4, p=0.92) , populations trends ($\chi2=1.13$, d.f.=4, p=0.77) or IUCN Red List fishing pressure threat ($\chi2=0.24$, d.f.=1, p=0.63).

Reconstructed catches for the top fished species tended to be higher than reported catches for all the cases in our analysis, with an increase of 21.5% in the total amount of fish extracted for these species in the 1996-2014 interval (Figure 3.2).

Table 3.2: Number and percentage of top fished species assessed in the IUCN Red List, and their population trends and vulnerability indices. DD: Data Deficient, LC: Least Concern, NT: Near Threatened, VU: Vulnerable, NE: Not Evaluated.

Conservation status	**DD**		**LC**		**NT**		**VU**		**NE**
Top fished species	6 (8.6%)		34 (48.6%)		5 (7.1%)		4 (5.7%)		21 (30.0%)
Fishing pressure threat	4 (66.7%)		24 (70.6%)		5 (100%)		2 (50%)		
Vulnerability index (VI)	43.4 (+- 25.5)		40.0 (+-20.21)		41.6 (+-20.6)		47.5 (+- 13.4)		33.7 (+- 17.7)
Population trends	**N**	**VI**	**N**	**VI**	**N**	**VI**	**N**	**VI**	
Increasing	0	.	3	39.7	0	.	0	.	
Stable	0	.	9	38.4	0	.	0	.	
Decreasing	0	.	4	55.2	5	41.6	1	50.0	
Unknown	6	43.4	18	36.9	0	.	1	65	
NA	0	.	0	.	0	.	2	37.5	

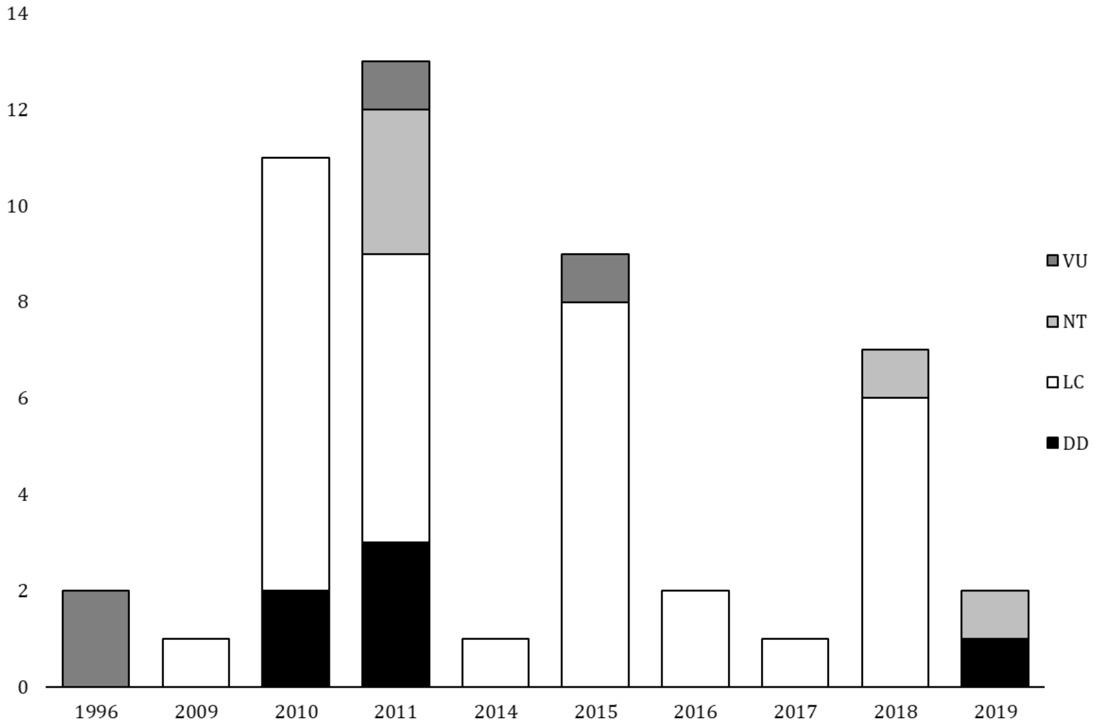

Figure 3.1: IUCN Red List assessment dates and resulting categories for the top-fished species.

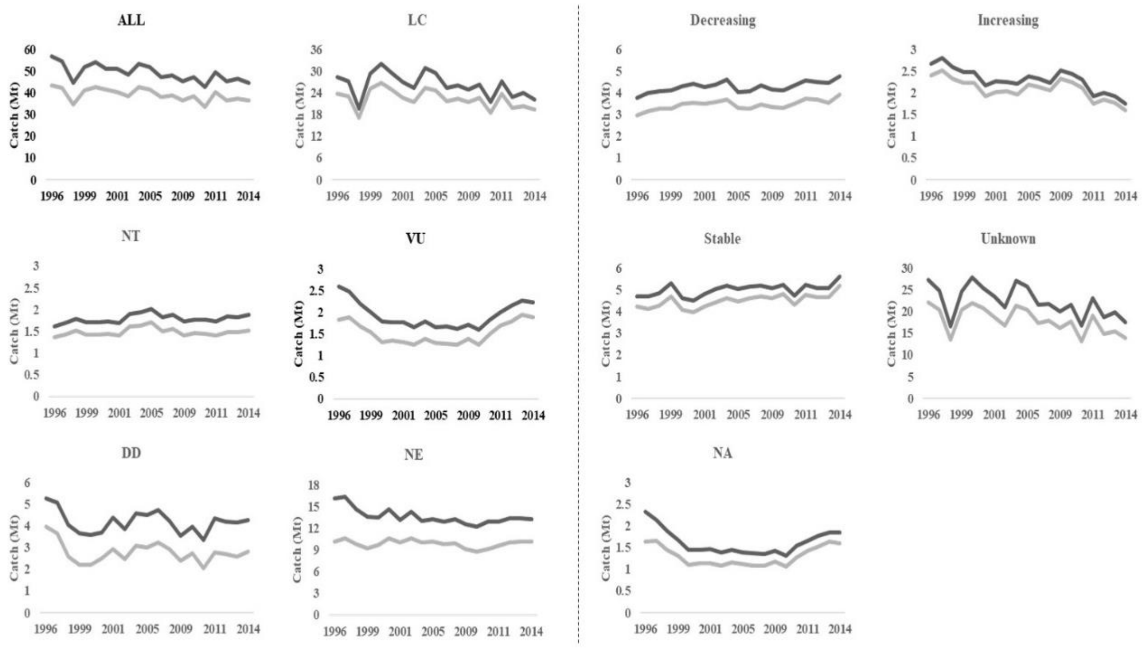

Figure 3.2: Catch trends for top fished species (ALL), by IUCN Red List conservation status (LC, NT, VU and DD, and NE) on the left, and by population trends (Decreasing, Increasing, Not Available, stable and Unknown) on the right. Black lines for reconstructed data (SAU), grey lines for reported data (FAO).

The top 70 species suffered significant declining catches in the 1996-2014 period (Figure 3.2-ALL and Table 3.3). Nevertheless, this trend was not shared for all assessed groups. Catches of species evaluated as LC declined significantly in both reported and reconstructed data (Table 3.3), whereas non- evaluated species only had significant declining trends for reconstructed data. Concerning population trends, significant declining catches were found for increasing and unknown population trends, whereas catches significantly increased in stable and decreasing populations (Table 3.3), suggesting a direct effect of fishing catches/landings on the species population trends.

Table 3.3: Linear models for catch trends in the 1996-2014 period for IUCN Red List categories and population trends. Results are given for reconstructed and reported data, with black lines for reconstructed data (SAU), grey lines for reported data (FAO).

		Slope	t statistic	P assoc	Adjusted R^2
IUCN Red List Category	LC	- 332,263	-2.716	**0.015**	0.262
		-251,843	-2.594	**0.019**	0.241
	NT	8,069	2.064	0.055	0.153
		2,163	0.561	0.582	-0.04
	VU	- 10,349	0.807	0.431	-0.020
		6,082	0.561	0.582	-0.04
	DD	- 24,882	-1.162	0.261	0.019
		-28,032	-1.437	0.169	0.056
	NE	- 138,844	-4.088	**<0.001**	0.466
		-26,386	-1.235	0.234	0.029
IUCN Red List Population Trend	Increasing	-38,478	-5.456	**<0.001**	0.615
		-31,374	-4.429	**<0.001**	0.508
	Stable	28,746	2.941	**0.009**	0.298
		38,307	4.289	**<0.001**	0.492
	Decreasing	29,187	3.665	**0.002**	0.409
		27,343	3.806	**0.001**	0.423
	Unknown	-365,110	2.902	**0.01**	0.292
		-308,543	-3.081	**0.007**	0.321
	NA	-13,769	-1.161	0.262	0.019
		2,638	0.276	0.786	-0.05
All species		- 498,269	-4.067	**<0.001**	0.4634
		- 298,016	-2.918	**<0.001**	0.2945

We finally analysed how species catches had varied after having been evaluated in the 1996-2014 period. In other words, we looked at the potential effect of conservation status listing in landings. We found that all species categorized as having decreasing populations, according to their IUCN evaluation, had actually increased their catches in the period comprised between their evaluation and 2014 (Table 3.4).

Table 3.4: Species assessed before 2014 and change in catches after evaluation.

Species	Category	Date	Fishing trend	Change in the assessment date-2014 period (tonnes) according to SAU
Clupea harengus	LC	2010	Increasing	-482,541.20
Dosidicus gigas	DD	2010	Unknown	326,834.34
Engraulis ringens	LC	2010	Unknown	-882,668.62
Ethmalosa fimbriata	LC	2010	Unknown	133,432.04
Euthynnus affinis	LC	2011	Unknown	13,534.02
Gadus morhua	VU	1996	NA	-207,420.31
Homarus americanus	LC	2009	Unknown	62,241.58
Illex argentinus	LC	2010	Unknown	433,027.24
Katsuwonus pelamis	LC	2011	Stable	214,342.17
Melanogrammus aeglefinus	VU	1996	NA	-288,299.65
Merluccius productus	LC	2010	Unknown	103,723.46
Oncorhynchus nerka	LC	2011	Stable	26,882.82
Opisthonema libertate	LC	2010	Stable	182,360.40
Rastrelliger brachysoma	DD	2011	Unknown	16,016.82
Rastrelliger kanagurta	DD	2011	Unknown	-158,248.19
Sardinella longiceps	LC	2010	Decreasing	137,119.90
Sardinops sagax	LC	2010	Unknown	-296,688.53
Scomber colias	LC	2011	Unknown	79,004.09
Scomber japonicus	LC	2011	Stable	235,471.27
Scomber scombrus	LC	2011	Decreasing	366,914.44
Scomberomorus commerson	NT	2011	Decreasing	29,454.15
Tenualosa ilisha	LC	2014	Decreasing	18,570.26
Thunnus alalunga	NT	2011	Decreasing	9,781.26
Thunnus albacares	NT	2011	Decreasing	120,560.38
Thunnus obesus	VU	2011	Decreasing	1,215.94
Thunnus tonggol	DD	2011	Unknown	8,097.14
Todarodes pacificus	LC	2010	Unknown	12,822.69
Trachurus murphyi	DD	2010	Unknown	193,919.08

Discussion

The revision of the conservation status and population trends of the main fish species of commercial interest is urgent and mandatory. Solutions for restoring marine ecosystems and the fish species that live in them are still under debate (Worm et al. 2009), but scholars and international organizations agree in that sustainable management is becoming more and more urgent for several fish stocks (Froese et al. 2019). With a horizon of human population increase in the coming years, assessing species conservation status is more important than ever, and only possible if all players do their part to manage fisheries sustainably and sustain the oceans and their biodiversity.

We found progress in the higher assessment rates for top fished species, but no significantly better conservation assessment coverage as compared with the commercial or highly commercial counterparts (Table 3.2). As stated in chapter 2, one reason could be that commercial species may not have been given priority in the IUCN Red List conservation assessment (Miqueleiz et al., 2020). The absence of significant differences in the Vulnerability Index among IUCN Red List categories had already been noticed by Miranda (2017), and our results support those findings. We also demonstrated that the categorisation of a species under fishing threat, or a declining population trend, were unrelated to a higher Vulnerability Index. In this sense, we consider that the Vulnerability Index may not be accurately measuring the extinction risk of a species. Biological traits may not be the most reliable predictor for extinction risk due to fishing pressure as other factors are also present (Sadovy de Mitcheson et al. 2013). We consider that IUCN Red List categorisation provides us with more accurate information about species extinction risk.

Among the assessed species, *Gadus morhua* (cod) and *Melanogrammus aeglefinus* (haddock) have extremely outdated assessments, classified as Vulnerable in 1996 (24 years ago). After the Atlantic stocks collapsed in the late 1980s and early 1990s (Hutchings & Myers 1994; Fogarty & Murawski 2008), some recent studies have found that cod stocks have not yet recovered from the collapse in northwest Atlantic (Neuenhoff et al. 2019) while IUCN Red List Europe assessment classifies *G. morua* as LC with increasing populations in some stocks (Cook et al. 2015). Therefore, we consider that urgent global evaluations of Atlantic cod and haddock are necessary as conditions may have evolved since 1990s, and there is a need to combine fisheries and conservation assessments to understand the status of marine biodiversity.

Apart from these two species assessed in 1996, all remaining assessments dated from 2009 onwards. IUCN estimates that assessments to be outdated after 10 years (Rondinini et al. 2014), so priority reassessments should be done in the following years for 50% of the top fished species (most of them classified as LC or DD). Data deficiency not only implies "inadequate information to make a direct, or indirect, assessment of its risk of extinction based on its distribution and/or population status" (IUCN 2012) but also affects conservation priorities, which rely upon threatened species lists (Bland & Böhm 2016). The uncertainty associated with data deficiency affects extinction risk patterns (Bland et al. 2012) and should be solved through a reassessment of DD species.

Not all assessed species were considered to be under fishing pressure (Table 3.2). Certain species may indeed have abundant populations or be subjects to sustainable fishing or fishing quotas, but examples of stocks overexploitation are abundant (Mullon et al. 2005) and several models state that the percentage of overexploited stocks has increased in recent years (Pauly & Zeller 2017). We should not lower the guard even with those species classified as LC (not to mention DD), as these species show declining catch trends, that could hint to declining population trends (Table 3.4). Previous studies have stated the importance of analysing together IUCN Red List assessments with stock assessments, such as RAM Legacy Stock Assessment Database, resulting in a high agreement in the conservation of exploited marine fishes (Davies & Baum 2012).

Almost all species assessed (96%) had information about population trends in the IUCN Red List, with haddock and cod lacking these data because of their outdated assessments. Many species had unknown population trends, and as subjects of intensive fishing, we consider that they should be reassessed in the short term to examine if current data allow us to establish their trends. Recent IUCN evaluations, such as the one done for *G. morhua* in Europe, show detailed information about population trends in the different stocks (Cook et al. 2015) and can be an example to follow. Nevertheless, the chance of landings data being underestimated (Pauly & Zeller 2016) may turn them into a non-reliable source of information to establish stocks viability and population trends. We also urge to analyse whether those data are reliable and if so, proceed to establish whether those species are suffering or not from overfishing and take the resulting conservation measures.

FAO's stable catching trends in recent years have been missed in doubt because unreported or manufactured data have been detected in previous studies (Pauly & Zeller 2017). Since the 90s, it has been observed a global decline in industrial fishing at an average rate of 1.2 million tons per year, even excluding those countries which have established quota management systems (Pauly & Zeller 2016). Reconstructed catches in our study were in average 21.5% higher than those reported by FAO, far from the 53% stated by Pauly & Zeller, (2016a). In this sense, FAO data for these top fished species seem to be more accurate, probably owing to their commercial importance. Furthermore, since the year of peak catches in 1996, reconstructed catch declined strongly at a mean rate of almost 0.5 mt per year, whereas FAO showed a less pronounced decline (almost 0.3 mt per year).

Only IUCN Red List categories LC and non-evaluated showed significant catch declines although the trend for the latter could not be observed in FAO reported data. Assuming that conservation status cannot be directly inferred from catching trends (Branch et al. 2011), we consider that this difference for trends for unassessed species highlights the necessity for this species to be assessed by the IUCN Red List, as reconstructed catches suggest that they are being more fished than reported ones.

IUCN Red List population trends provided us with relevant information for species status. Especially surprising was to observe how species with decreasing population trends according to IUCN Red List (10), had significantly increased their captures in the 1996-2014 period, with higher increase rates for the reconstructed data. Scombridae assessed in 2011 with declining populations had increased their catches after the assessment, even though this family has shown population declines up to 74% between 1970 and 2010 (WWF 2015). Examples like *Scomber scombrus* (Atlantic mackerel) and *Thunnus albacares* (yellowfin tuna), whose catches widely increased after their IUCN Red List evaluations should call attention on how can we know the true status of stocks. Science-based recommendations, despite their uncertainty, cannot be neglected by the fishing industry, as management of overfished stocks is essential for their sustainability (Fromentin et al. 2014).

Our study does not intend to infer stock status or collapses from landing data or use landing data as a direct indicator of species conservation status. Several papers in the last decade have pointed out the potential flaws of using FAO and Sea Around Us catch statistics to assess the state of marine ecosystems (Branch et al. 2011). Landings frequently do not track changes in biomass; thus, collapses estimated on the basis of landing data do not directly report an actual stock collapse. The IUCN Red List classifies the extinction risk of species whereas the reference points used in fisheries management relate to the productivity of a stock. This results in the IUCN assessments mostly addressing rates of decline in fish populations, while the fisheries assessments address the status relative to biomass target and/or limit reference points (Millar & Dickey-Collas 2018).

Climate change and global warming affect fish populations viability and compromise the subsistence of human communities linked to them (Cheung 2018; Morley et al. 2018). In a context of a global threat to marine species, where human and climate pressures combine to jeopardize them, we consider that the voice of conservation initiatives, like IUCN Red List, should be extensively heard by fishing authorities. Despite IUCN Red List categories and criteria posing problems when evaluating marine fish species (Collen et al. 2016), they have proven to provide evaluations congruent with those done by fishing authorities (Davies & Baum 2012). Having failed in meeting most CDB Aichi targets (Tittensor et al. 2014; UNEP-WCMC et al. 2018; Visconti et al. 2019), the sustainability of one of our main food sources is at stake. If the IUCN approach is incorporated into fisheries management, it is important to recognise that the two approaches have been developed for different purposes. The two approaches may therefore lead to different outcomes and their integration may require the adoption of further decision rules (Millar & Dickey-Collas 2018). The last SOFIA report states that collaboration efforts between FAO, CITES, and IUCN are taking place (FAO 2018), but unless urgent measures are taken, the overexploitation of our seas can lead again to stock depletion and compromise not only species conservation but also food security and the way of life in many regions.

Chapter Transparency

I. Miqueleiz conceived the present idea. I. Miqueleiz developed the experiment, carried out the analyses and interpretated the results. E. Ojea contributed with the structure of the manuscript to better organize ideas and concepts. I. Miqueleiz wrote the manuscript. R. Miranda, A.H. Ariño and E. Ojea provided comments to the interpretation of the results and the manuscript.

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CHAPTER 4:

Trends and perspectives in the knowledge of conservation status of fishes

Capítulo 4:

Tendencias y perspectivas en el conocimiento del estado de conservación de los peces

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Chapter preface

As described in the General Introduction of this thesis, freshwater and marine fish species face numerous anthropogenic threats, causing a worldwide decline in their populations. Populations of the world's fish have worsened and their extinction risk has increased in the last decades. In chapter 2 we studied how IUCN Red List has evaluated fish species and the underlying biases of the resulting assessments. At the time of this study, assessed fish species number about 20,000 but they are a far smaller fraction than that of comparable assessment rates for other vertebrate groups. Furthermore, fish species description rates remain high and efforts must be prioritised when acknowledging new assessments.

In this study, we aim to address global trends on IUCN Red List fish assessments and to evaluate the role of individual countries in fish assessments according to their economic capacity. We compiled a list of all fish species described until 2019 and analysed their conservation status. We also extracted subsets of newly discovered species (described between 1996 and 2019), species with dated assessment (IUCN Red List assessment dating more than 10 years back), and reassessed species, and analysed the resulting dataset. Finally, we correlated species richness, assessment rate, out-of-date assessments, and new species by country with the economic power (GDP power per capita) of the country.

Our results showed an increasing IUCN Red List assessment effort for fish in the past years, but also higher levels of threat and more data deficiency for the more recently described species. They also suggest that these new species should be prioritised in further assessment programs. On the other hand, we found that higher-income countries list a large proportion of out-of-date assessments, suggesting a redirect towards the reassessment effort. Finally, several countries of South America, had both a large gap in assessments, and a high proportion of newly described species, clearly indicating a need to step up the assessment effort in the region, including the development of retrospective assessments for those recently assessed species. Globally, in view of those trends we recommend the development of long-term plans for national Red Lists as an essential tool to ensure the quality of Red List assessments and enhance the conservation perspectives for fish species. The role of national Red Lists will be further discussed and examined in chapter 6.

Introduction

Fish inhabitants in aquatic environments are numerous, with more than 35,000 valid species in total (over a half of all vertebrate species) and half of them living in freshwater habitats (Fricke et al. 2020). They constitute a large fraction of biomass in aquatic ecosystems (Jennings et al. 2008) and provide us with various ecosystem services (Worm et al. 2006; Green et al. 2015). Nevertheless, in a rapidly changing world, fishes are facing several threats that jeopardize their survival. Human activities have globally increased in the last century, overexploiting natural resources (Garcia-Moreno et al. 2014). Nowadays, freshwaters receive impacts from habitat loss and fragmentation, water pollution, extensive wetland drainage, groundwater depletion, the establishment of introduced alien species, and overfishing of native ones (Dudgeon et al. 2006; Strayer & Dudgeon 2010; Vörösmarty et al. 2010). Concerning the marine realm, main threats emerge from overfishing, pollutant, sediment, and nutrient input (Halpern et al. 2007, 2008), habitat loss (Dulvy et al. 2003), and invasive alien species (Bax et al. 2003)., with a strong impact on critical ecosystem services such as fisheries or nutrient cycling (Selig et al. 2014). Furthermore, climate change is very likely to be a driver of freshwater and marine fish physiological changes, species turnover, local extinction, and invasion (Cheung et al. 2009; Woodward et al. 2010; Poesch et al. 2016). In the last decades, vertebrate populations have declined worldwide, with freshwater (84% decline) (WWF 2020) and marine fishes (50%) (WWF 2015) at high risk.

Conservation of the world's freshwater and marine fishes requires management and restoration strategies, focused on species at the greatest risk of extinction (Arthington et al. 2016). In 2010, the Convention on Biological Diversity (CBD) developed the Strategic Plan for Biodiversity, which included 20 time-bound, measurable targets to be met by the year 2020. Among them, target 12 was established in 2010 to prevent species extinction and improve and sustain their conservation status (SCBD 2010). To measure species extinction risk, the International Union for the Conservation of Nature (IUCN) developed the Red List of Threatened Species, which has turned into the reference guide to identify threats and prioritise conservation efforts (Rodrigues et al. 2006; Rondinini et al. 2014). This tool not only provides a classification of each species into a category of threat (IUCN 2012a) but also supports it with information on species range size, population trends, habitats, conservation actions, and past assessments (IUCN 2020). Aiming to be a "Barometer of Life", IUCN Red List expects to reach a milestone of 160,000 species assessed by the end of 2020. Nevertheless, IUCN Red List coverage remains unbalanced among different taxa assessed. Thus, in the case of vertebrate species, while almost all extant mammal and bird species have been assessed, the remaining vertebrate groups have lower levels of assessments

(Meiri & Chapple 2016; Tapley et al. 2018). Similar trends have been observed when assessment rates of terrestrial and freshwater species have been compared (Collen et al. 2014). In the case of fish, recent studies estimate that little more than a half of described the fish species have been assessed in the IUCN Red List, resulting in the poorest representation of all vertebrate groups (Miqueleiz et al. 2020).

In this sense, IUCN Red List efforts to address this fish assessment gap and increase our knowledge of fish conservation status are noticeable. Over the last years, several IUCN Species Specialist Groups (SSG) have increased fish evaluations focusing on specific groups (Sadovy de Mitcheson et al. 2013; Dulvy et al. 2014). Furthermore, under the IUCN Freshwater Biodiversity Unit (FBU), regional assessments have increased knowledge in eastern Himalaya (Allen et al. 2010), Africa (Darwall et al. 2011), Europe (Freyhof & Brooks 2011), Indo-Burma (Allen et al. 2012) Western Ghats (Raghavan et al. 2016), Andean region (Tognelli et al. 2016), Brazil (Instituto Chico Mendes de Conservação da Biodiversidade 2018) and Mexico (Contreras-MacBeath et al. 2020). According to the most recent data (IUCN 2020), almost 21,000 fish species are currently assessed in the IUCN Red List.

In parallel to this increase in fish evaluations, new fish species are being described at the highest rate among all vertebrates (Miqueleiz et al. 2020). Over the last two decades, an average of 400 new fish species have been described every year (Fricke et al. 2020) and added to the list of species in need of assessment. Furthermore, IUCN Red List assessments should be regularly updated (according to IUCN Red List, after 10 years) to avoid evaluations become obsolete. Considering economic and human resources constraints, several proposals have been previously made to prioritise fish conservation efforts (Rondinini et al. 2014; Hermoso et al. 2017) for out of date assessment or geographic areas. Certainly, fish biodiversity is not evenly distributed across freshwaters and seas (Selig et al. 2014; Pelayo-Villamil et al. 2015; Tedesco et al. 2017), nor are the resources devoted to its conservation. Previous studies have analysed the changes in conservation status at the global level looking at each country's contribution to terrestrial vertebrates' conservation (Rodrigues et al. 2014), but fish have remained out of such analyses. With the end of the UN Decade for Biodiversity, it is time to look back to evaluate how fish conservation status has been evaluated worldwide in recent years and propose new solutions for the upcoming ones.

We aim here to address global knowledge on fish conservation status, focusing on assessment rates, species descriptions, and out of date assessments. Furthermore, we aim to evaluate the role of individual countries in fish conservation assessments according to their economic capacity and propose solutions to improve IUCN Red List coverage and quality.

Methods

In January 2020 we compiled a list of all fish species included in FishBase, the reference tool for fish study (Froese & Pauly 2019), with species described until 2019. From this list, we extracted the description year (according to species authority) and selected the species described between 1996 and 2019 (henceforth called *recently described species*). We realised that species described in 2018-2019 in FishBase were fewer than those from previous years. To check whether this was caused by a lag in the species included in the database, we obtained the number of species described per year in the Eschmeyer's Catalog of Fishes data (a more taxonomy-focused fish database) (Fricke et al. 2020), which compiles descriptions per year for the last two decades. We also analysed the IUCN Red List 2019.3 version (IUCN 2019) to address how many species had been assessed per year between 1996 and 2019. Furthermore, for the recently described species, we obtained the lag-time (in years) between each species description and its assessment (if it had been done so).

Concerning evaluated species, we checked the number and proportion of Data Deficient (DD) and threatened (Vulnerable, Endangered, and Critically Endangered) species for all assessed species and recently described species. We calculated proportions of threatened species (Prop thr) by assuming that DD species will fall into threatened categories in the same proportion as non-DD species:

$$\text{Prop thr} = (CR+EN+VU)/(N-DD),$$

where N is the total number of species. To incorporate uncertainty introduced by DD species, we calculated upper and lower bounds of threatened species proportions by assuming that (a) no DD species were threatened (lower bound), and (b) all DD species were threatened (upper bound):

$$\text{Lower bound: Prop thr} = (CR+EN+VU)/(N)$$

$$\text{Upper bound: Prop thr} = (CR+EN+VU+DD)/(N)$$

Furthermore, we retrieved those species with outdated assessments according to IUCN Red List standards (species that have not undergone an assessment in the last ten years) (Rondinini et al. 2014). We also used the IUCN Red List database to obtain historical evaluations for those species assessed two or more times and to find changes in conservation status along time. In these cases, we looked at IUCN data on species changes to address whether such changes had genuine reasons (a real change in species conservation status) or, on the contrary, had a different origin. As described in IUCN Red List guidelines, non-genuine reasons for changes in the conservation status include (new information available, taxonomic revisions, errors in previous assessments, or older criteria). We measured changes in conservation status as changes in the Red List Index (RLI) (Butchart et al. 2004) for those species that had undergone genuine changes.

We calculated fish richness for each country as the sum of non-evaluated species (obtained when comparing all described fish species from FishBase to the assessed fish species in 2019.3 IUCN Red List) and of assessed native species (we excluded introduced species from our analysis). We obtained data on purchasing power parity from the 2019 World Economic Outlook database calculated as estimated Gross Domestic Product (GDP) per capita in US dollars. We classified countries into four categories according to their GPD per capita (Table 4.1). We analysed the relationship between the 2019 GPD per capita and the performance of each country in fish conservation, evaluating three aspects: a) percentage of assessed species vs total number of species; b) percentage of out of date assessments vs total number of species and c) percentage of assessed species vs newly described species. We analysed data for all fish species and separately for freshwater ones.

Table 4.1: Country classes according to their 2019 GDP per capita (in US$)

Category	Number of countries	Lower bound	Upper bound
1	47	727$	4,275$
2	47	4,454$	14,028$
3	46	14,102$	31,808$
4	46	32,455$	134,622$

Results

The description rates of new species have remained more or less constant since 1996, with a mean of 317 (maximum of 510) new species described per year according to FishBase, with lower values in 2018 and 2019 (39 and 2 respectively). Nevertheless, data from Eschmeyer's Catalog of Fishes reflects that more species have been described in these years and not included in FishBase, and description rates since 1996 raise to an average of 400 species described per year (Figure 4.1).

When examining the number of total evaluations performed by IUCN Red List in the 1996-2019 period, more fish species have been evaluated in such period than the ones being described, being able to start filling in the gaps caused by previous years of insufficient assessment effort. Concerning recently described species, after 2006, evaluations have constantly increased leading to a decreasing disparity between species descriptions according to FishBase and subsequent assessments. Whereas in 2010 only 10.8 % newly described species had been assessed, the percentage increased to 20.1 % in 2015, and in 2019 reached a 35% assessment of recently described species.

Assessed Data Deficient species represent 20.2% of all evaluated fishes. For recently described species, this percentage rises to 36%. Among all evaluated fish species 17.5% are threatened with upper and lower estimates of 34.2% and 13.9% when including or excluding DD species. In the case of recently described species had 32.6% of assessed species were classifies as threatened, with upper and lower estimates between 56.9% and 20.8% (Figure 4.2).

Considering all species included in FishBase, 47.1 % of fish species had never been assessed by IUCN Red List. When incorporating species with out-dated (before 2010) evaluations, this percentage went up to 52.3% of fish species without an effective assessment.

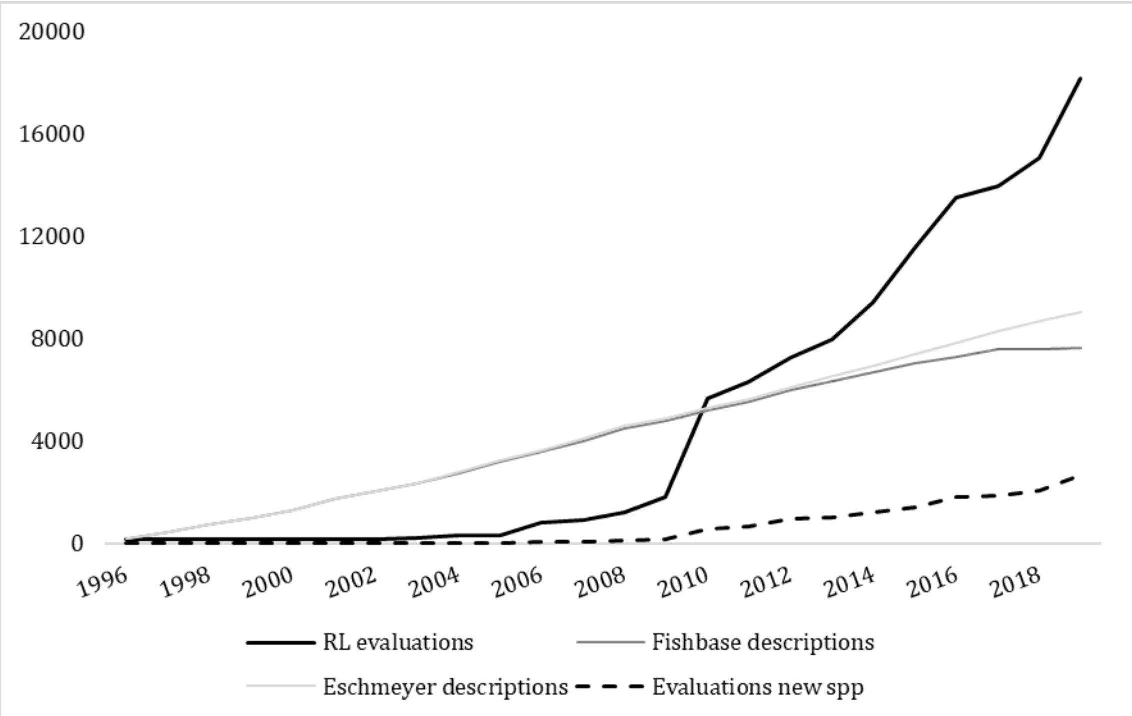

Figure 4.1: Described vs assessed fish species between 1996 and 2019. Cumulative IUCN Red List fish evaluations per year (solid black), cumulative recently described fish species per year in FishBase (dark grey), Eschmeyer Catalogue of Fishes (light grey), and cumulative IUCN Red List assessments of recently described fish species (dashed).

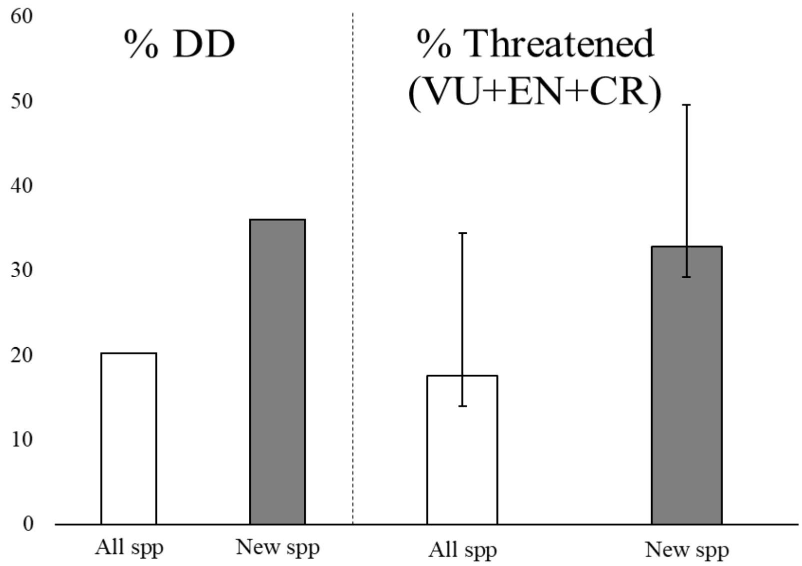

Figure 4.2: Percentages of DD and threatened (Vulnerable, Endangered and Critically Endangered, with upper and lower bounds) species for all fish species and recently described species(from 1996 to 2019).

The mean lag-time between species description and Red List assessment for species described between 1996 and 2019 was 9.7 years. There was a positive correlation between description year and mean assessment lag time (Spearman's ρ =0.9). Assessment lag-time had increased since 2006, when the mean lag-time was 6.9 years, reaching a mean lag-time of 12 years in 2019 (Figure 4.3).

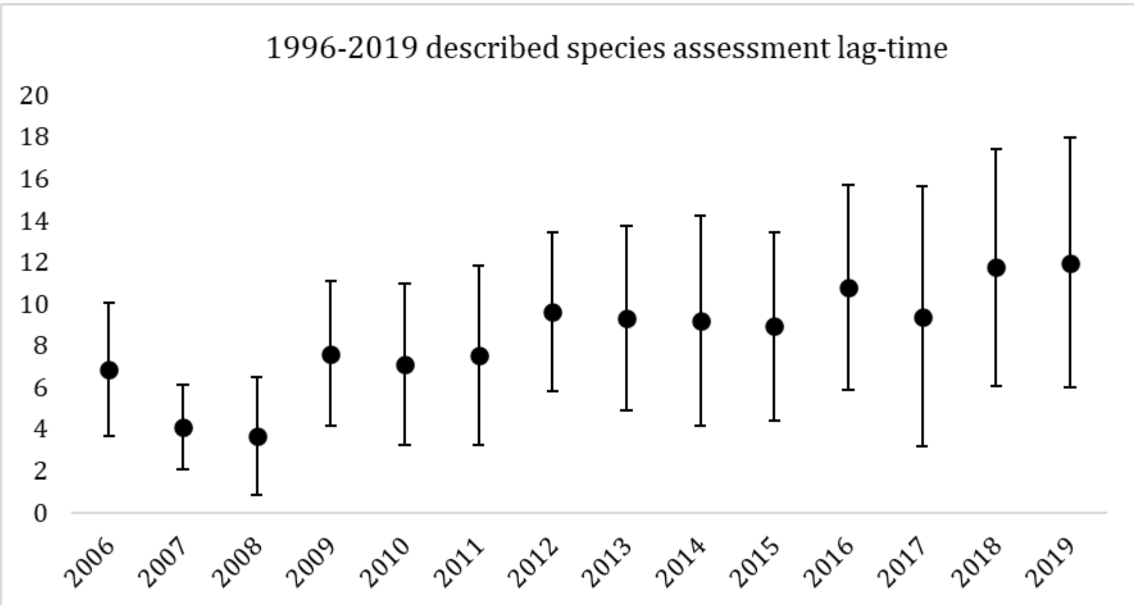

Figure 4.3: Mean (black dots) and standard deviation (error bars) of the assessment lag time for recently described species (1996-2019).

The number of fish species that have been assessed more than once in the 1996-2019 period was 3,309 (17.3% of the total of species assessed) from which 3,003 species (15.7% of total) changed their IUCN Red List status. Nevertheless, when examining closely at these changes we observed that most of them were non-genuine changes and only 110 species (0.57%) had undergone genuine changes. These changes showed an average decline in the conservation status of 1.3 points in the RLI, with only 13 species having genuinely improved their conservation status.

Richer countries had significantly better assessment rates of freshwater fishes, but no difference was found for assessment rates of all fishes (Figure 4.4). Countries in South America had the lowest number of freshwater assessed species, including Brazil, the most fish-diverse country in the world and the worst-assessed one. Similarly, no differences were observed for the percentage of out of date assessments among the four country classes for all fish species (Figure 4.5). However, the two richest country classes had significantly higher rates of out of date assessments of freshwater fish species. New species are being principally described in countries with low assessment rates; a trend more acute in the freshwater environment (Figure 4.6).

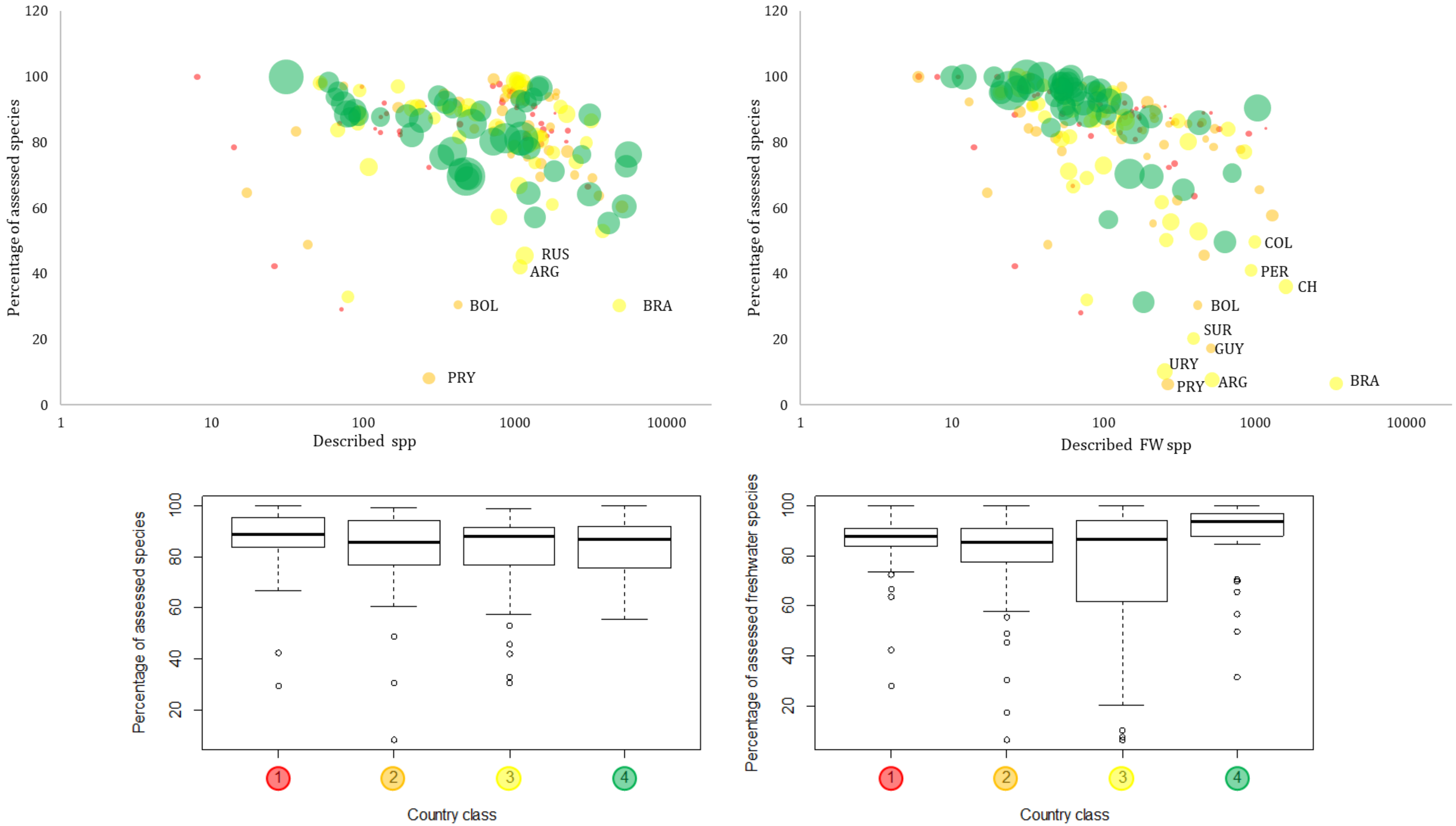

Figure 4.4: Top: Described and assessed species (left: total, right: freshwater only) per country according to country classes 1 (red), 2 (orange), 3 (yellow) and 4 (green) from lower to higher income (GDP per capita). Bottom: Mean percentage of assessed species and interquartile range for country clases. Dot radius prportional to countries GDP per capita. See Supplementary Data 4 for country codes.

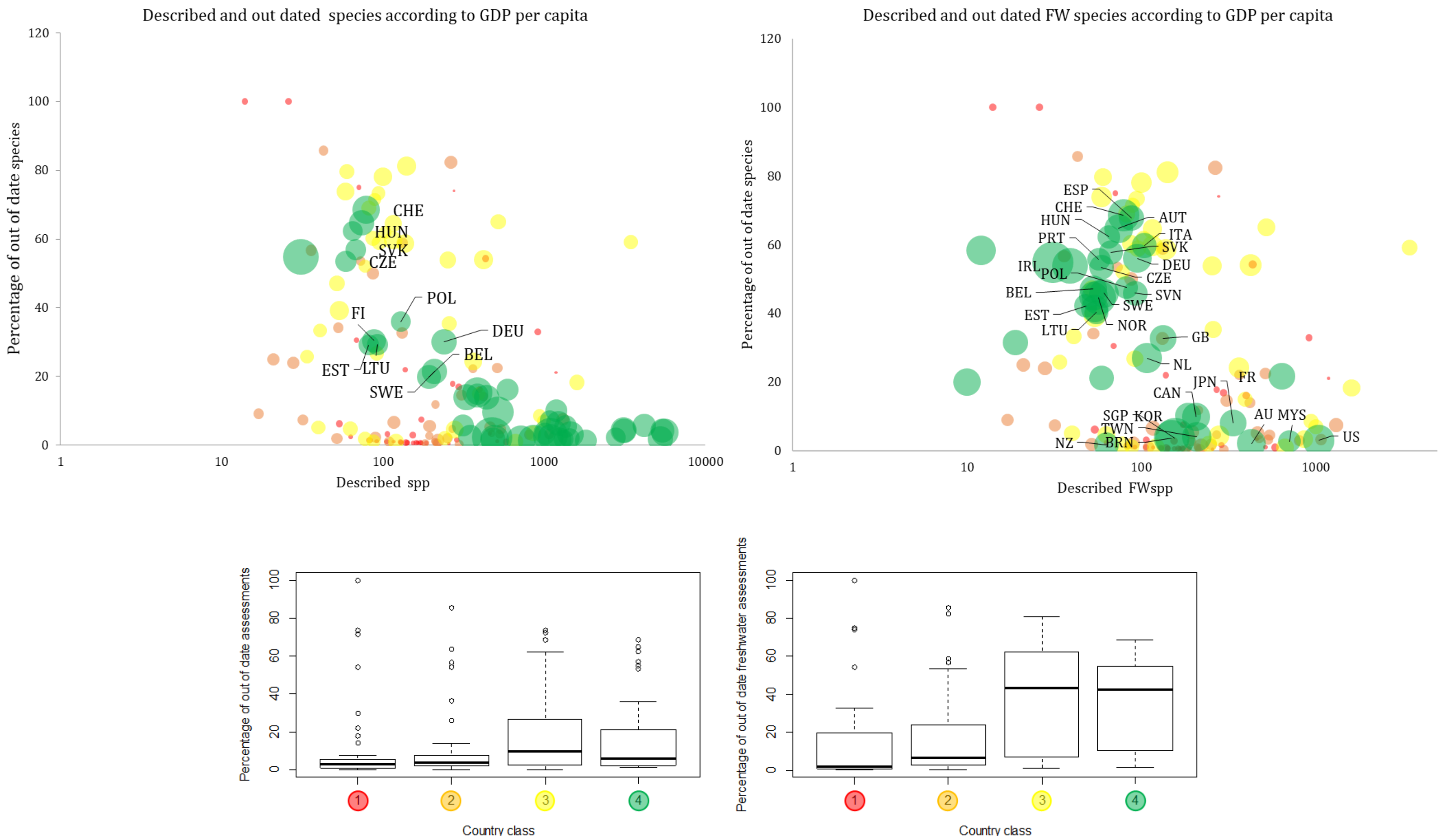

Figure 4.5: Top: Described species and out of date assessments (left: total, right: freshwater only) per country according to country classes 1 (red), 2 (orange), 3 (yellow) and 4 (green) from lower to higher income (GPD per capita). Bottom: Mean percentage of out of date assessments and interquartile range for country clases. Dot radius prportional to countries GDP per capita. See Supplementary Data 4 for country codes.

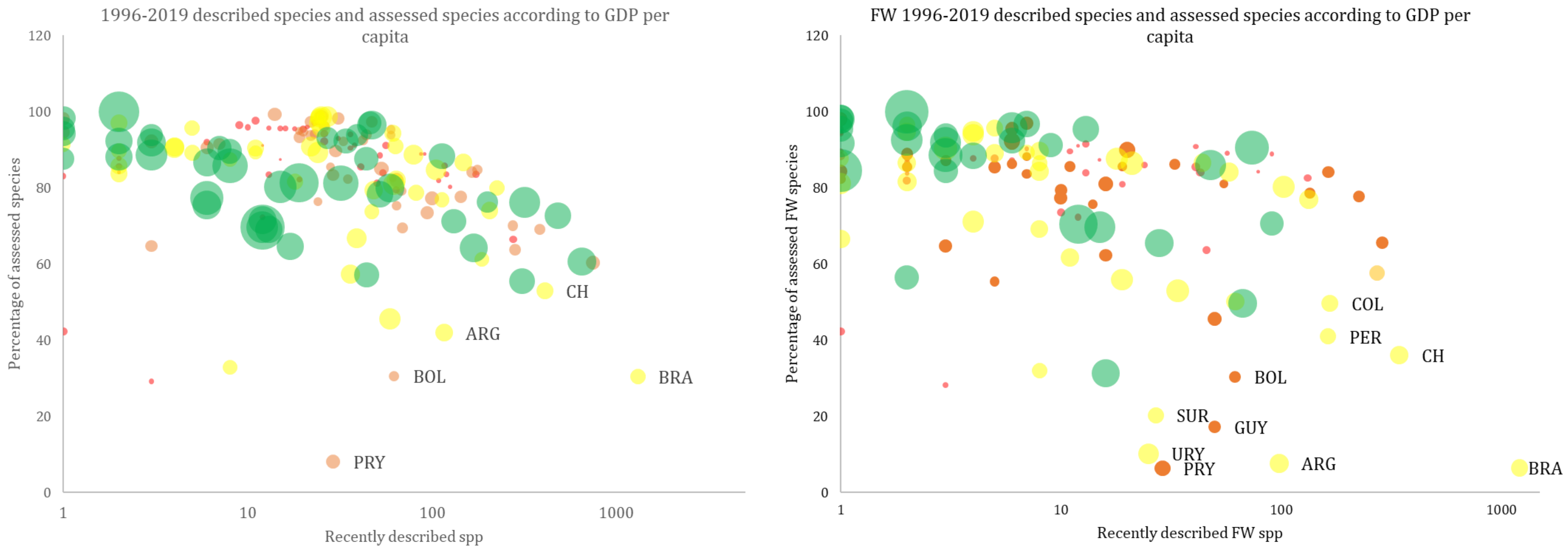

Figure 4.6: Upper: Recently described and assessed species (left: total, right: freshwater only) per country according to country classes 1 (red), 2 (orange), 3 (yellow) and 4 (green) from lower to higher income (GPD per capita). Dot radius prportional to countries GDP per capita. See Supplementary Data 4. for country codes.

Discussion

Thanks to IUCN Red List efforts and the work of SSG and other initiatives, fish assessments have extraordinarily improved in the last years, both in number and quality. Nevertheless, several considerations must be made when planning and developing assessment processes in the upcoming years.

Our study suggests that more attention should be paid to the conservation of newly described species. Most countries have not completed their fish inventories (Pelayo-Villamil et al. 2018) and data suggest that we have not flattened the accumulation curve of described species (Figure 4.1). In the case of recently described species, the scientific community has been unable to effectively assess them, even though, potentially, they could be disproportionately threatened (Pimm et al. 2014). The fact that many of those newly-described species are not included in FishBase (Figure 4.1) reflects a first delay in the knowledge of these species, which further pushes down their appearance in the IUCN Red List and hampers the development of assessments for its conservation. In fact, higher rates of threat for recently described fish species (Figure 4.2) represent a strong argument to afford them increased assessments efforts. Fishes, altogether with amphibians (Tapley et al. 2018), are a group with low assessment rates and high threat levels, overall and in the freshwater realm (Collen et al. 2014). With increasing assessment lag times, priorities should shift towards swiftly assessing newly described species. In this sense, we emphasize the role that authors, and the descriptions that they write, can play in the facilitation of IUCN Red Lists assessments. Authors could enhance taxonomical descriptions with useful data for the assessment process, including habitat and demographic information, as well as observed or projected threats (Tapley et al. 2018), and with genetic markers that could allow using further research tools such as environmental DNA (eDNA) for conservation purposes (Antognazza et al. 2019; Itakura et al. 2019). Furthermore, free-flowing communication from authors to IUCN Red List could enable the latter to become more readily aware of the new species that need to be assessed and better allocate resources and efforts.

Recently described fishes are more frequently assessed as Data Deficient compared with all assessed fish, probably because less information is available for them. Data deficiency has seldom meant being left aside of main conservation efforts (Bland et al. 2017). Significant progress has been done in predicting IUCN Red List status of Data Deficient species (Bland et al. 2015; Bland & Böhm 2016), but more resources and funds need to be allocated to clarify the extinction risk of DD species and facilitate future assessments. Until then, we support recommendations by Jaric et al. (2016) of considering

Data Deficient species as "Potentially Threatened", which in our case means that up to one half of newly discovered fish species could also be threatened with extinction (Figure 4.2).

IUCN Red List reassessment process has proved to be extremely useful for fishes. Despite most fish species having only been assessed once (owing to their recent descriptions), those that were reassessed showed high rates of non-genuine changes. This means that the reassessment process has much improved the quality of fish assessments, updating species' status with the current knowledge. Nevertheless, many species have not been reassessed ever since the 1990s, and their conservation status could likely have changed (either because of a real change or because of a non-genuine one), therefore requiring need urgent reassessment. Some studies have inferred past species status based on current knowledge (Bohm et al. unpublished work) and observed deteriorations in the conservation status of species. Our results support these trends, as most reassessed species with a genuine change worsened their conservation status. Further studies in this area could provide us with more robust estimations of fish conservation trends in the last years. These reassessments seem to be essential in lower diversity, developed countries, where out of date assessments are common among freshwater fish species (Figure 4.5). Our data suggest that with little reassessment effort, these countries could update their freshwater fish assessments and thus achieve high levels of both assessed species and up to date assessments. The next step for these countries could be the development of stable, long-term national Red Lists, where experts trained in the assessment process could provide continuous updates on species conservation status at the national level (which would become global level for endemic species).

Fish species are not evenly distributed around the world (Nelson et al. 2016), and neither is the individual responsibility of each country in their conservation. Richer countries showed better assessment rates for their freshwater fish species (Figure 4.4), but this trend was not observed for all fish species. Nevertheless, per-capita wealth was not a driver of conservation improvement for terrestrial vertebrates (Rodrigues et al. 2014). Future studies may be able to analyse the contribution of each country to the global trends of fish conservation as a change in the RLI, but in this study we found two constraints to do so: First, the lack of complete assessments for fish, which prevented us establishing a time gap to analyse, and the high proportion of non-genuine changes. Second, most fish species have been recently described and IUCN's main assessment efforts are now focused on evaluating unassessed species. Thus, we suggest that retrospective assessment processes could be very useful to stablish a retrospect time reference to address changes in the fish RLI.

We identified several South American countries that showed both high levels of diversity and low levels of assessment (Figure 4.4). Furthermore, many of these countries were among the ones where more species had been recently described, for which it has been demonstrated that their extinction risk is higher. The most outstanding case of low assessment rates was found in Brazil. Nevertheless, their Instituto Chico Mendes for the Conservation of Biodiversity (ICMBio) is currently finishing the Brazilian Red List and these results are expected to be incorporated soon in the global IUCN Red List (Instituto Chico Mendes de Conservação da Biodiversidade 2018). Brazil's terrestrial vertebrates conservation status has had a small deterioration in the last decades (Rodrigues et al. 2014) and further studies are required to address whether the current conservation status of their freshwater fish is following a similar trend.

The IUCN Red List has already taken in charge of many of these problems. For instance, the Global Freshwater Fish assessment is already underway, in the frame of the wider aim of increasing representation in the IUCN Red List of key underrepresented taxonomic groups. This project aims to evaluate all freshwater fish species by the end of 2021, focusing on underassessed regions, such as the ones detected in this study. Moreover, IUCN Red list aims to enhance the role of national Red Lists to provide assessments for endemic species (Brito et al. 2010; IUCN 2012b), allowing the upload of assessments in several languages, but the process needs to be reviewed under global IUCN Red List standards.

Having failed in preventing the extinction of many fish species, we are still in time to avoid the disappearance of many others. In 2021 CBD will set up new goals for 2030 that expect to reduce species threatened with extinction and increase species abundance, but it requires deep compromise from all parties to reverse current trends and improve fish conservation status and knowledge.

Chapter Transparency

I. Miqueleiz and M. Böhm conceived the present idea. I. Miqueleiz developed the experiment, carried out the analyses and interpretated the results. M. Böhm contributed with the accession to the IUCN Red List database. I. Miqueleiz wrote the manuscript. M. Böhm, R. Miranda and A.H. Ariño provided comments to the interpretation of the results and the manuscript.

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CHAPTER 5:

Spatial priorities for freshwater fish conservation in relation to protected areas

Capítulo 5:

Prioridades espaciales para la conservación de peces de agua dulce en relación con las áreas protegidas

Miqueleiz, I., Ariño, A. H., Miranda, R.

Chapter preface

Freshwater ecosystems, important for humans and nature, are under serious threats. As stated previously in this work, the creation and development of protected areas has been proposed as the most feasible way to ensure protection objectives established for the years to come. However, traditional protected areas have not effectively protected freshwater ecosystems and their fauna, especially fish, and conservation priorities have been established based on terrestrial biodiversity. Previous studies have identified the most irreplaceable terrestrial locations to achieve conservation aims. We aim here to complement these analyses addressing how the current network of protected areas covers irreplaceable rivers for fish.

Based on IUCN Red List distribution maps, we have calculated the irreplaceability of rivers in the major basins of the world, taking into consideration the proportion of IUCN Red List assessed fish species in them. We have also evaluated the overlap between irreplaceable rivers and the current network of protected areas. Finally, we have compared the irreplaceability values of protected areas for freshwater fish with that for terrestrial vertebrates.

Our results highlighted the conservation value of tropical rivers, apart from other hotspots in temperate regions. Furthermore, protected areas did not seem to afford protection to rivers, especially those considered as irreplaceable. Irreplaceable, protected areas in the terrestrial and freshwater domains did not generally match. Urgent work is required to fill the neotropical freshwater fish biodiversity knowledge gap and improve the protection of the ecosystems where they inhabit. Advances in IUCN Red List proposed in previous chapters could improve the quality of our analysis. Our study complements other endeavors seeking to identify priority conservation sites through informed decision-making for an increasingly effective setting od protected areas.

Introduction

Freshwaters occupy a tiny fraction of the Earth's surface, representing only a very small proportion of the available volume of liquid water (less than 0.01%) yet containing perhaps as much as 12% of all known species, including one-third of all vertebrate species (Mittermeier et al. 2010). They also provide humans with various ecosystem services (Darwall et al. 2011b), ranging from water provision, water security and nutrient flow to recreational activities and spiritual values or food and fibre production (Carpenter et al. 2011; Green et al. 2015).

However, freshwater ecosystems may rank among the most jeopardized on Earth, being truly endangerment hotspots (Dudgeon et al. 2006; Vörösmarty et al. 2010). The progressive concentration of people and settlements around freshwater systems and increasing human demands for water are leading to high levels of degradation and threats to freshwater biodiversity (Strayer & Dudgeon 2010; Arthington et al. 2016), including habitat loss and degradation, invasive species, overfishing, climate change, and water pollution among others (Freyhof & Brooks 2011). Aware of the necessity of protecting freshwater habitats, the Convention on Biological Diversity (CBD) adopted in 2010 the Strategic Plan for Biodiversity 2010-2020 and its 20 Aichi Biodiversity Targets to address global declines in biodiversity (Butchart et al. 2010). Target #11 requests that "by 2020, at least 17 per cent of terrestrial and inland water (…), especially areas of particular importance for biodiversity and ecosystem services, are conserved through (…) protected areas" (SCBD 2010).

Protected areas (henceforth PAs) play a key role in maintaining a healthy environment for people and nature. They are essential for biodiversity conservation and also provide various ecosystem services, benefits to millions of people derived from tourism, and protection from climate change and natural disasters for local communities and habitats (UNEP-WCMC and IUCN 2016). Despite the continual increase in the number and extent of PAs in the last decades, protection levels remain significantly below the CBD's 17% target when assessed global and regionally (Abell et al. 2017). Trends in freshwater biodiversity show a continuous increase in the number of endangered freshwater species (Reid et al. 2019), and the low protection they receive in the current network of PAs often stems from their design and management (Linke et al. 2019). Often seen as elements of a landscape mosaic, rivers constitute a heterogeneous landscape in their own right (the riverscape) with its ecological processes, complex and dynamic (Wiens 2002). Traditional notions cannot be applied to freshwaters as they have received inadequate protection (Abell et al. 2007), and have been largely neglected in global priorities of biodiversity conservation (Abell et al. 2011). Effective protection of freshwaters within PAs needs a paradigm shift, incorporating the processes that sustain the functioning of wetlands and the ecosystem services they provide (Hermoso et al. 2016). Models as the one proposed in Abell et al. (2007) not only consider freshwaters as focal areas but establish management zones surrounding these areas, exceeding the limits of PAs and considering basins as conservation units (Hermoso et al. 2011). Also, the International Union for Conservation of Nature (IUCN) has developed the Key Biodiversity Areas (KBA) program to identify such places (Darwall et al. 2015; KBA Standards and Appeals Committee 2019).

Despite these signs of progress and some examples of the positive effects that PAs can have on freshwater biodiversity abundance (Hermoso et al. 2016), species in freshwater systems are under serious threat and in decline, with one in three species threatened with extinction worldwide (Collen et al. 2014; WWF 2018). Among freshwater fauna, fish are good indicators of the state of the ecosystem because 1) they are highly susceptible to changes in their freshwater environment and habitat degradation, with restricted-range species often facing quick and complete extinctions (Closs et al. 2016); 2) consequently, they are severely affected by obstacles in river connectivity and habitat fragmentation (Poff et al. 2007); and 3) rivers are tightly dependent on the surrounding catchments, acting as impact collectors (Dudgeon 2011). Freshwater fish are also important as a food resource for human communities, (FAO 2018), critically important in Africa, Amazonian basin and parts of Asia (Darwall & Freyhof 2016).

Unfortunately, studies based on global trends of freshwater fish have to deal with problems associated with provisional information, data scarcity, and biases in databases (Pelayo-Villamil et al. 2015; Rodeles et al. 2016). Around 50% of the total freshwater fish species (Froese & Pauly 2019) have been assessed by IUCN's Red List (IUCN 2019), the reference guide over the last 50 years on species extinction risk (Rodrigues et al. 2006). IUCN's Red List data on freshwater fish show that more than 25% of species fall within some threat category of IUCN (IUCN 2019). Furthermore, 21% of freshwater fish are considered as data deficient (DD), with a potential risk of leaving them out of the main conservation efforts (Bland et al. 2015).

Several biases affect freshwater fish protection in PAs: conservation priorities driven by terrestrial biodiversity patterns (Abell et al. 2011), existing PAs network biased towards remote places (Butchart et al. 2012), and deficit in the degree to which PAs cover areas of particular importance for freshwater biodiversity (Juffe-Bignoli et al. 2016a). Finally, data gaps in species distribution data, mainly located in tropical areas (Miqueleiz et al. 2020), may influence certain indicators (Collen et al. 2008) which could potentially be used to identify where PAs should be established or the extent to which current PAs are protecting freshwater biodiversity.

Up until now, in many regions of the world fish species have played a limited role in the designation of PAs or KBAs (Juffe-Bignoli et al. 2016a). Thus, further studies on both the ability of the current network of PAs to adequately protect freshwater fish (Abraham & Kelkar 2012) and on gaps within the PA/KBAs network are urgently needed (Pino-del-Carpio et al. 2014). We need specific indicators to measure the progress through CBD 2020 goals, connected with essential biodiversity variables. In this sense, the concept of irreplaceability, defined as "the extent to which spatial options for conservation targets are reduced if the site is lost" (Rodrigues et al. 2006), appears as a valuable way to detect those high-value areas where urgent conservation measures are required, presenting several choices for achieving conservation targets (Knight et al. 2013). Irreplaceability has been used in previous studies (Le Saout et al. 2013; Tognelli et al. 2019), and despite sometimes being considered that comprehensively assessed taxonomic groups can act as surrogates for broader vertebrate diversity (Rodrigues et al. 2014), other studies confirm that freshwater uniqueness cannot be measured using terrestrial vertebrate data (Darwall et al. 2011a). Thus, freshwater fish-based irreplaceability remains unexplored and can offer new insights on inland waters biodiversity conservation.

The aim of this study is the application of the irreplaceability index to identify priority conservation freshwater areas owing to their fish fauna. Studying the relation between this index and PAs we aimed to address two main questions: 1) Is the current network of PAs adequately protecting irreplaceable areas for fishes? 2) Do irreplaceable areas for freshwater fish agree with those identified as irreplaceable for terrestrial vertebrates? Answering these questions would enable us to inform about where freshwater fish conservation efforts and resources should be focused on.

Methods

We chose to study river irreplaceability at *reach level*, defining reach as the segment between two nodes in a river system. By using these small units, we avoided biases towards large ecoregions or areas masking the truly irreplaceable (and generally smaller) areas that our study aimed to detect. River irreplaceability was defined in our study, following Le Saout et al. (2013), as "a measure of the degree of dependence of species on a given river reach", in other words, the importance of each river reach to prevent global species' extinction owing to the distribution patterns of its freshwater fish fauna. This measure is calculated from the proportion of each species' global distribution overlapping each river reach. The metric provides us with spatial priority areas for effective biodiversity conservation based on species distribution patterns but does not consider other species extinction drivers such as habitat modifications, exploitation, or biological invasions.

We extracted 3,200,000 reaches with 30 arc-seconds resolution from the HydroSHEDS project web page (http://hydrosheds.org/) (Lehner et al. 2008) between the parallels 60º latitude North and South because of the lower quality of HydroSHEDS data in higher latitudes. In the case of the Southern Hemisphere, it excludes Antarctica and in the Northern Hemisphere, higher latitude areas of North America, Greenland, Europe, and Siberia.

Data on freshwater Actinopterygii (ray-finned fish) fish species distributions and global conservation status were obtained from the IUCN Red List (IUCN 2019). Distribution maps comprised information about the known, inferred, or projected sites of occurrence for the species although they often are, by the nature of their build, imperfect generalizations. As in previous studies that used similar data (Le Saout et al. 2013), we only included those areas of each species' distribution where it was considered to be extant (either confirmed or probable) and where the species was either native or reintroduced. Besides, we kept those areas of migratory passage or seasonal presence, even though they might not be regarded as distributional, as we considered that they also constitute important areas for fish species that may include longitudinal and horizontal movements in their life histories. We followed the description of the categories of origin, presence, and seasonality in the metadata document Digital Distribution Maps on The IUCN Red List of Threatened Species (IUCN 2017). From the available distribution data, we compiled distribution maps for 7,848 freshwater Actinopterygii species.

Unfortunately, as we have previously shown (chapter 2), the IUCN Red List assessment is incomplete for freshwater fishes, and there are regional assessment coverture differences. We decided to hypothesize the possible effect in the irreplaceability index of 100% of freshwater fish with the IUCN Red List assessment. Based on data from Tedesco et al. (2017), we extracted a list of fish species for the major basins of the world and calculated the percentage of the list that was actually assessed in the IUCN Red List. In this scenario, we removed from the analysis those basins where no species were evaluated, as well as those where more species were evaluated by the IUCN Red List than were described in Tedesco et al. (2017) owing to taxonomic uncertainties.

We defined the irreplaceability score, Ip, of each river reach, p, as a weighted species richness, the sum across species i of weights w_{ip} for each species in each site p.

$$Ip = \Sigma_i w_{\underline{ip}} / (np/Np)$$

In this analysis, we overlap each species distribution map with the river layer. This intersection calculates which species are present in a river reach and in how many river reaches a species is present in. Then, for each river reach *p* and each species *i* we calculated the proportion of the species distribution that falls within that reach (1/number of river reaches where the species is present), a rarity value for the species, w_{ip}. We then added the rarity value of all the fish species present in a river reach *p* to obtain the irreplaceability value for that river. Finally, we divided the irreplaceability value by the proportion of species assessed in the river *p*, where *np* is the number of fish species assessed in the basin to whom *p* belongs and *Np* is the number of fish species present in that basin according to Tedesco et al. (2017).

We chose to use direct distribution proportions, as we wanted to focus our study unit on the river reach as a single unit. If we had normalised the *Ip* value of the river reach considering its size, as in the previous studies (Le Saout et al. 2013), we would have biased longer rivers and weakened shorter ones. With our procedure, we were considering equally all river reaches where the species was present. Regarding that no information about other factors (habitat quality, dams, river width, river branching) was included in the study, we considered that discriminating shorter rivers would potentially underscore areas with species located in small river reaches.

We extracted PAs from the World Database on Protected Areas (WDPA) (www.protectedplanet.net) in February 2020 and considered only PAs with national designation (IUCN codes I to VI) (Venter et al. 2018). We excluded those corresponding to marine PAs. For PAs lacking a polygon representation in the database, we created a circular buffer of its specified area around its central coordinates. We analysed the proportion of rivers within PAs by freshwater ecoregions (Abell et al. 2008), evaluating which ecoregions have fulfilled Aichi Biodiversity Target number 11 for those rivers containing fish species. Then, we identified those rivers with high *Ip* value (*Ip*>=0.05) that remained outside PAs.

We obtained the mean *Ip* value for PA and compared those PAs with higher *Ip* value (mean *Ip*>=0.025) with the ones considered as irreplaceable because of their terrestrial biodiversity. The values for the latter ones were obtained in Le Saout et al. (2013), based on birds, amphibians, and mammals distributions. Similar approaches have also been used in previous studies to compare freshwater and terrestrial biodiversity at a broader scale (Abell et al. 2011).

All calculations were done with R software (R Development Core Team 2019) and geographical information packages rgeos and rgdal. Maps were produced with ArcGIS software (ESRI 2014).

Results

We observed that higher *Ip* values were obtained in South-eastern Asia, Ganges basin, Western Ghats, African Great Lakes, Congo basin, lower Niger-Benue basin, Eastern Mediterranean basin, Andean region and the Eastern Mississipi Basin (Figure 5.1), apart from other small areas in Mexico and Melanesia. See Supplementary Data 5 for descriptive (average and standard deviation) *Ip* values in major freshwater basins.

Irreplaceable rivers and PAs

Only 10.3 % of rivers worldwide fall inside PAs. Furthermore, 75% of freshwater ecoregions do not fulfil Aichi Target 11 (17% of their rivers protected) (Figure 5.2). We found that Europe and lower areas of the Amazonian basin have good coverage (over Target 11 threshold) of protected rivers but wide regions of Asia, North America, South America, and Africa have low values of rivers inside their current network of PAs. We detected that 25,857 of 30,041 river reaches with *Ip*>=0.05 (86%) were outside PAs (Figure 5.3). Maps showed a patchy coverage of PAs in the Western Ghats or South-Eastern Asia and regions where no protection is applied (African Great Lakes, Anatolian Peninsula, or Andean Amazon Piedmont region). The latter case was quite remarkable, with big PAs in the lower areas of the Amazonian Basin, but scarcer protection in higher altitudes.

Terrestrial and freshwater irreplaceable PAs

We found 1,084 freshwater PAs with *Ip*>=0.025. However, only 314 freshwater PAs were also part of the terrestrial subset of terrestrial PAs with *Ip*>=0.025, with the rest (71% of the total) not overlapping with any of the most valuables terrestrial areas.

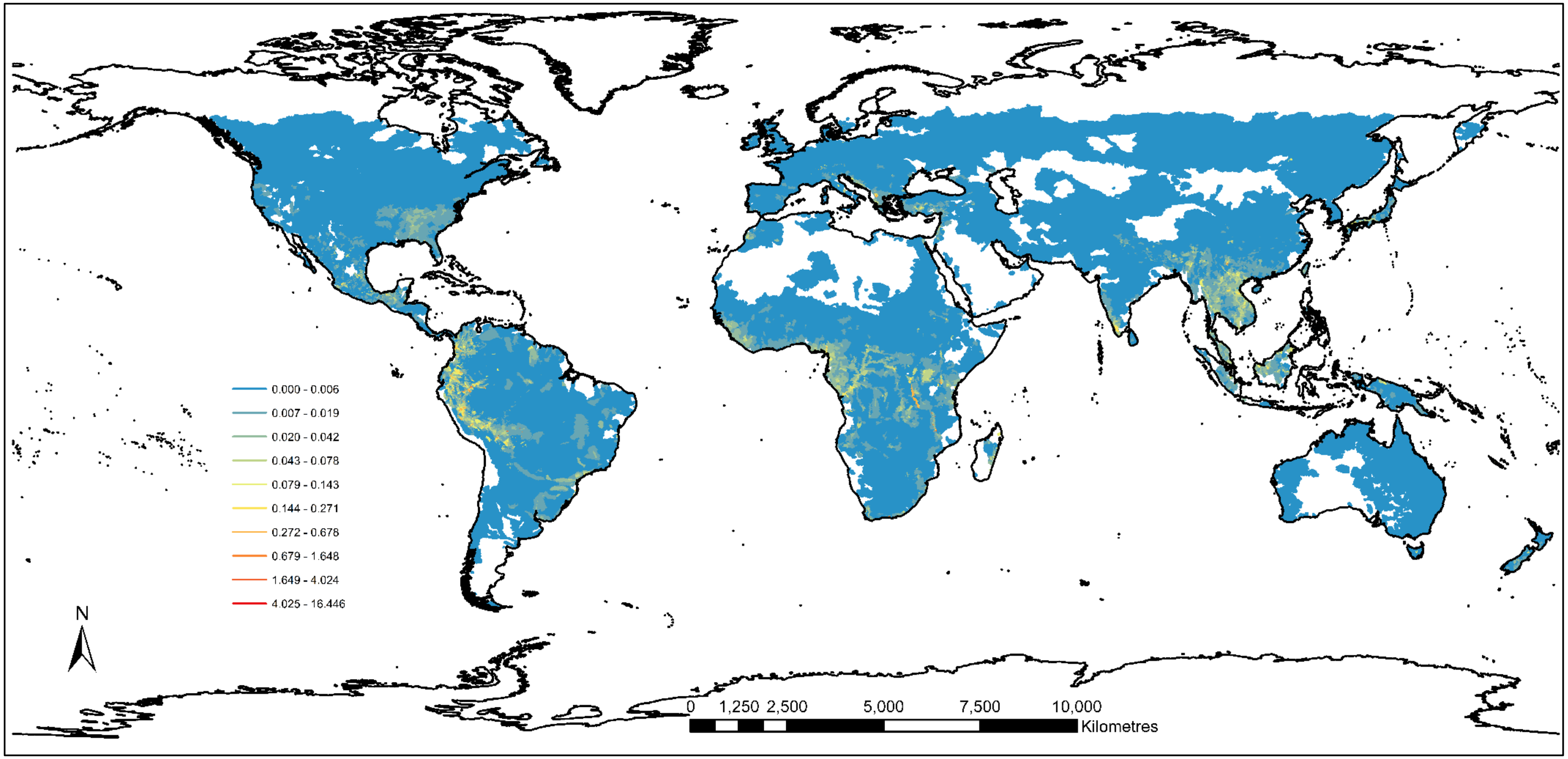

Figure 5.1: *Ip* index values from lower (blue and green) to higher (yellow and red) values from rivers in major river basins of the world.

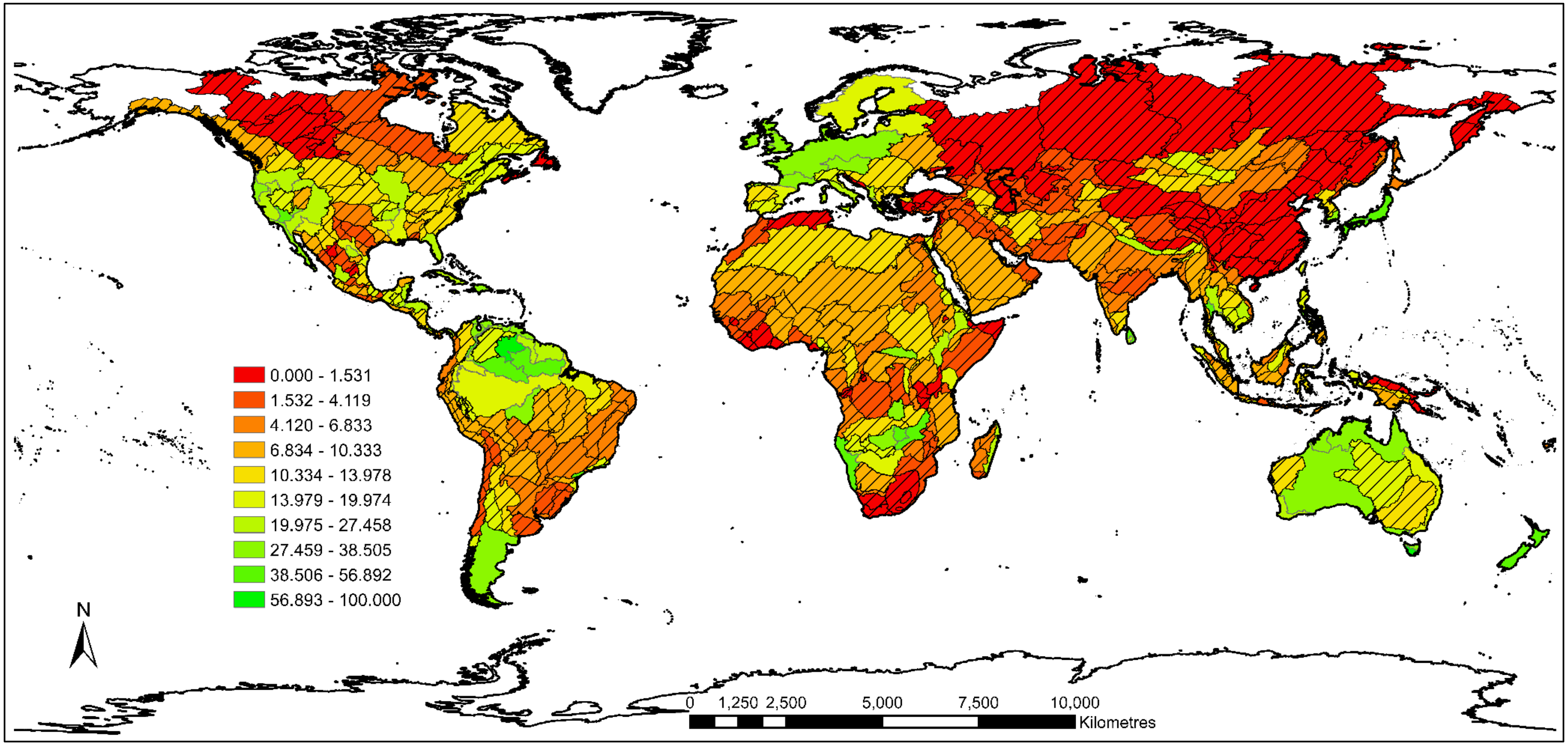

Figure 5.2: Proportion of rivers inside PAs in major Freshwater Ecoregions. Shaded areas have values under the 17% goal of CBD 2020 target number 11 (proportion of rivers protected).

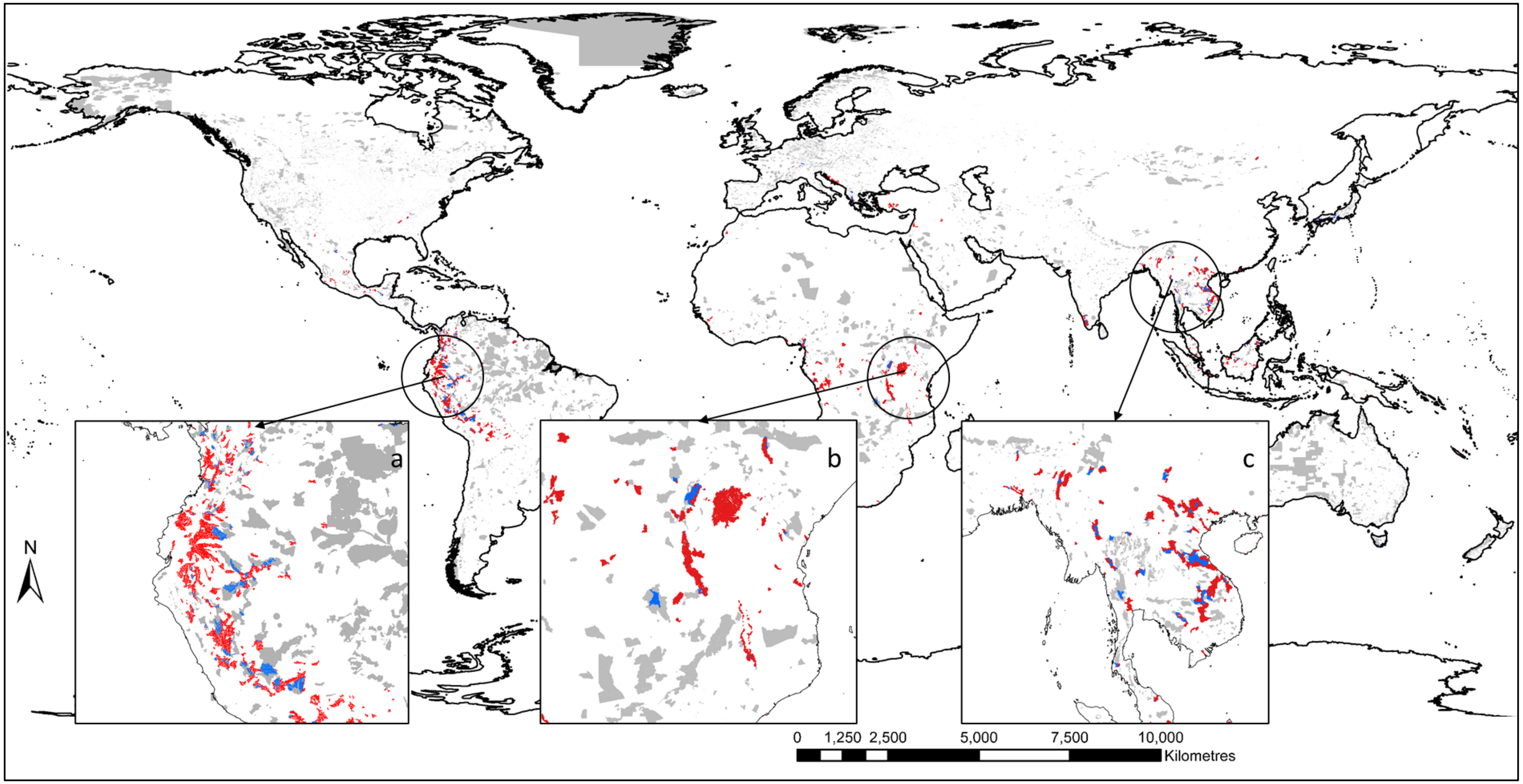

Figure 5.3: Map of Protected Areas (PAs) of the world (grey) and most irreplaceable areas (*Ip* value>=0.05), showing those places in (blue) and outside (red) PAs. Detail maps from the Andean Amazon Piedmont (a), African Great Lakes (b), and south-eastern Asia (c).

Discussion

Our results support the existence of irreplaceable freshwater rivers in tropical areas, owing to their unique freshwater fish fauna. However, the protection of highly irreplaceable areas is far from being adequate, with a high proportion of irreplaceable rivers outside PAs. Furthermore, the distribution of PAs important for freshwater fish conservation and terrestrial vertebrates is highly unbalanced, resulting in potential under-consideration of freshwater fish needs in PAs design and management. Results obtained could be improved in the following years if new distribution maps and species descriptions are developed to obtain more accurate distribution data and irreplaceable rivers.

Our study confirmed highly irreplaceable areas in regions which had been previously identified as freshwater biodiversity hotspots (Abell et al. 2008; Collen et al. 2014; Pelayo-Villamil et al. 2015; Jézéquel et al. 2020a), with particular importance for tropical areas of South America, Africa, and Asia, as well as areas of North America and Europe (Figure 5.1). Previous studies (Abell et al. 2011) had identified several biodiverse freshwater ecoregions where effective protection of freshwater fauna was unlikely because the relative importance of freshwater and terrestrial biodiversity were not matched. Examples of such areas were central Europe or the lower Amazonian rainforest. However, our results did not support that concept as these areas ranked low in the freshwater fish irreplaceability when played at the river reach scale. We could attribute the discordance to a large number of freshwater fish species that might occur over a single ecoregion and nowhere else, but that within it were relatively widespread across most reaches. Conversely, we found that our results precisely highlighted irreplaceable regions such as the Mediterranean region, where a high number of species remain confined to a few river basins, which entails a much more vulnerable situation (Darwall et al. 2015). Therefore, the use of high-resolution data allowed us to better identify those truly irreplaceable areas where opportunities for maximum conservation of biodiversity could be found (Arthington et al. 2016).

The role of PAs in irreplaceable river conservation

PAs offered low protection to freshwater systems in general and to highly irreplaceable areas in particular (Figure 5.2 and 3). The CBD target of 17% of freshwaters protected seems far from being met in most freshwater ecoregions. Our analysis has proved that much further work is required towards that goal, as most of the irreplaceable river reaches worldwide (83.7%) falling now outside PAs. Patchy protection is not effective, as core principles for freshwater PAs effective design emphasize that preserving upstream-downstream and lateral connections are essential to protect freshwaters (Hermoso et al. 2016). Furthermore, areas like the Andean Amazon Piedmont, where PAs currently protect some irreplaceable rivers, are under the threat of a dam construction boom (Closs et al. 2016; Carvajal-Quintero et al. 2017), which can alter water flow regimes and affect river connectivity, essential for freshwater fish. In this area, our results agree with others published recently, reinforcing the irreplaceable value of higher reaches in the Amazonian basin, whereas lower areas and the main river have lower irreplaceable values (Jézéquel et al. 2020a). As PAs in the Amazonian region are mostly located in the lowlands, it seems evident that future efforts should be directed towards design and establishment of PAs in the higher reaches.

Concordance between terrestrial and freshwater PAs

In our study, we found that a high proportion (71%) of PAs with higher *Ip* value were not part of those PAs considered also as highly irreplaceable for their terrestrial biodiversity in Le Saout et al. (2013). Established PAs have generally afforded low protection to freshwaters, because their specific needs often received poor consideration at the design phase as compared to the needs of the terrestrial portion (Roux et al. 2008). A high proportion of the most irreplaceable rivers fell outside PAs (Figure 5.3) and among the few of them that were actually protected, most were not inside a highly irreplaceable terrestrial PA, resulting in a double jeopardy for the most irreplaceable freshwater fish communities.

Limitations and perspectives

According to (Collen et al. 2014), "the extent to which terrestrial protected areas protect freshwater species is unknown, but they are likely to be insufficient". In our study, we have confirmed this conjecture for freshwater fish. However, disc the effectiveness of using a single group (freshwater fish) to establish the value of rivers for conservation is open to debate. Previous studies have studied whether terrestrial vertebrates may act as surrogates for each other (Moore et al. 2003) but they cannot act as surrogates for freshwater fauna (Darwall et al. 2011a). On a global scale, fishes have not acted as good surrogates of other vertebrates (Tisseuil et al. 2013) but some examples of effective surrogacy exist when examined in catchments (Lessmann et al. 2016). Unlike other freshwater vertebrates, fish are strictly restricted to water bodies. As they are better assessed than other potential surrogates (i.e. freshwater macroinvertebrates), we believe that fish offer a good opportunity to draw spatial protection priorities. Nevertheless, when conservation planning is carried out at finer spatial resolutions, it is important to study the diversity patterns at a more detailed scale to provide the best solutions.

Our results were strongly conditioned by the knowledge gap that exists in many areas of the world (Miqueleiz et al. 2020). Tropical areas of South-Eastern Asia and South and Central America are the ones with a lower level of inventory completeness (Pelayo-Villamil et al. 2015, 2018; Tognelli et al. 2016). In the case of the Neotropic, current rates of species discovery and publication suggest that there are likely more than 8,000 Neotropical freshwater fishes (Reis 2013). Despite more species being described and better assessed every year according to IUCN Red List, the risk of undiscovered species going extinct without noticing (Costello et al. 2013; Bland et al. 2015) is high. Field surveys and monitoring programs are essential to fill knowledge gaps in the distribution of fishes and organisms in general. Despite recent efforts carried out to increase our knowledge of Neotropical biodiversity (Tognelli et al. 2016; Jézéquel et al. 2020b), this tropical biodiversity gap may be influencing indicators established by the CBD (Collen et al. 2008), and urgent work is needed to sample and study Neotropical inland waters. Recent studies have identified a set of priority regions (119 freshwater ecoregions) that could help assess one-third of all freshwater fishes that need to be assessed or reassessed by 2020 (Hermoso et al. 2017) and a Global freshwater Fish Assessment is being developed by IUCN. We hope that the results in our study, altogether with those other works, will help redirecting efforts and resource allocation to the Neotropic, resulting in new distribution maps and strengthening freshwater ecosystems protection.

Sensible decision making requires assessing the effectiveness of protected areas for sustaining species and identifying priority sites for their conservation (Tognelli et al. 2019), particularly for freshwater fishes in the Andean Amazon Piedmont. Our study highlights its value as an irreplaceable region of huge extension and its key role for freshwater fish protection in Neotropical region. A wider comprehension of freshwater fish distribution is possible (Tedesco et al. 2017), but more resources (both economic and human) are needed to achieve a global assessment of freshwater fish (Juffe-Bignoli et al. 2016b).

PAs are traditionally established in low-cost lands, a trend intensified through time (Venter et al. 2018). That is why aiming to establish some kind of protection in areas like the African Great Lakes, where conservation interests go together with the social value of those areas for fishing (Gherardi et al. 2011), is challenging. The introduction of the Nile Perch *Lates niloticus* in Lake Victoria in 1954 caused the decline of native haplochromine cichlids which constituted the basis of the local fishermen economy (Hecky et al. 2010) and replaced traditional fishery by an industrial process in the hands of a small minority of fishermen (Kasulo 2000). Establishing some kind of protection in this area could benefit both native fishes by controlling *L. niloticus* populations and native fishermen enabling them to take back the control of the fisheries. In places like the Andean Piedmont with several dams projected for the following years and many others built or under construction (Carvajal-Quintero et al. 2017), connectivity analyses provide us with a useful tool to decide where dam project should not be executed to preserve their freshwater biodiversity (Anderson et al. 2018).

With the permanent threat of climate change looming over the horizon (Comte & Olden 2017), urgent actions are needed to accomplish better knowledge and protection of freshwater biodiversity, especially in tropical countries, which host the most irreplaceable rivers but low protection is offered from them by the current network of PAs. Freshwater systems are under extreme threat; the latest Living Planet Index showed an 80 % decline in population abundance of freshwater vertebrates since 1970 (McRae et al. 2017), 89% in Central and South America. Conservation action to combat such losses is most often highly spatially explicit, focussing on areas of highest loss or threat, endemism, etc. Address these issues requires international efforts to establish protected riverine landscapes. Enhancing the capacity of freshwater PAs to adequately cover the needs of freshwater biodiversity requires actions that also make them flexible enough to avoid unrealistic PAs (Linke et al. 2019). We believe that our study goes with initiatives like KBAs to identify irreplaceable places and offer them protection, not only for the freshwater fish that dwell in them but also for the whole ecosystem. We see that sustainable solutions that benefit both freshwater ecosystems and humans are possible with thorough PAs designing and planning.

Chapter Transparency

I. Miqueleiz and R. Miranda conceived the present idea. I. Miqueleiz developed the experiment, carried out the analyses and interpretated the results. A.H. Ariño provided help with the technical calculations of the irreplaceability index. I. Miqueleiz wrote the manuscript. R. Miranda and A.H. Ariño provided comments to the interpretation of the results and the manuscript.

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CHAPTER 6:

Effective reassessments of freshwater fish species: A case study in the Mediterranean

Capítulo 6

Reevaluación efectiva de peces de agua dulce: Un caso de estudio en el Mediterráneo

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Chapter preface

Freshwater ecosystems and the species that live in them are severely affected by anthropogenic pressures. The IUCN Red List has assessed the conservation status of many freshwater species, among which fish take up an important place. As discussed in Chapter 4, many fish species have been assessed for the first time in recent years, while many others have out of date evaluations which require a reassessment to update their conservation status. Obtaining realistic distribution ranges is difficult for those species for which there is not enough information. In recent years molecular techniques have added new ways of obtaining information about species distribution or populations. Willing to wrap up the research from a more applied perspective, we propose to evaluate the Iberian Peninsula as a test case for the possibilities that environmental DNA (eDNA) offers for the reassessment of freshwater fish species with out of date evaluations.

We compiled the catalogue of freshwater fish species occurring in continental Spain and Portugal and examined their conservation status in global and national Red Lists. We obtained records for these species in the Iberian Peninsula and calculated several biological indexes. We also examined the presence of these species in reference genetic databases.

Our results showed a patchy data coverage of fish records in the Iberian Peninsula which should be improved to better establish their species distribution. Threat levels reported within national Red Lists for extant populations are higher than their global counterparts, reinforcing the necessity of maintaining up to date national Red Lists. Iberian watersheds have moderate levels of threat (based on their freshwater fish fauna conservation status) and high levels of out of date assessments. The limited distribution of many endangered species and the necessity of updating their assessments constitutes an excellent opportunity to use data obtained from eDNA to improve our knowledge about fish species and their conservation status. Future reassessment efforts should be focused on creating stable National Red Lists which ensure that correct criteria and evaluations are applied to improve conservation status of freshwater fish.

Introduction

The Earth is home of more than 1.8 million described species (https://www.catalogueoflife.org/) and many others remain undiscovered (Mora et al. 2011). At present, species extinction rates have been estimated to be 1000 times faster than those registered in the fossil record (De Vos et al. 2015) and the sixth mass extinction (Ceballos et al. 2017) is one of the most important issues occurring in the XXI century. Ecosystems are losing their biodiversity at extremely high rates mainly due to anthropogenic causes such as climate change, species invasions, and habitat alteration (Dirzo et al. 2014; Reid et al. 2019). Among all ecosystems, freshwater ones are the most affected (Strayer & Dudgeon 2010; Collen et al. 2014). Wetlands are disappearing three times faster than forests (Ramsar Convention on Wetlands 2018) and freshwater vertebrate populations are decreasing more than their terrestrial or oceanic relatives (WWF 2020). Although freshwaters cover a very restricted area on the Earth, they host almost 10% of all described species (Strayer & Dudgeon 2010) including 18,000 fishes (Fricke et al. 2020). Fishes are one of the most representative and good studied organisms who live in freshwater and their endemism level is particularly high (Pelayo-Villamil et al. 2015; Tedesco et al. 2017).

To inform about species extinction risk, the International Union for the Conservation of Nature (IUCN) has developed since 1964 the IUCN Red List, which has become an increasingly powerful tool for conservation planning, management, monitoring, and decision making (Rodrigues et al. 2006). IUCN Red List data are continuously updated and there are currently almost 10,000 freshwater fish species assessed, and approximately 23 % are currently threatened with extinction (IUCN 2020). As seen in Chapter 2, freshwater fish assessment rates in the IUCN Red List (and fish assessment rates in general) have remained below than of any other vertebrate group (Tapley et al. 2018; Miqueleiz et al. 2020). Thus, efforts in the recent years have focused on identifying priority assessment areas to optimize IUCN Rede List fish evaluations (Hermoso et al. 2017), and finally developing projects to evaluate all known freshwater fish species. The Global Freshwater Fish Assessment aims to evaluate all freshwater fish species by the end of 2021. Consequently, a large proportion of freshwater fish species has been evaluated in the last years or will be evaluated soon (IUCN 2020). Nevertheless, IUCN Red List assessments require regular updates (every 10 years at the most) to provide reliable information about species conservation status (Rondinini et al. 2014). The number of freshwater fish species with outdated assessments is high as only a few of them have been reassessed (IUCN 2020) as shown in (Chapter 4). Considering that most fish species that have undergone genuine changes in the IUCN Red List have worsened their conservation status (see Chapter 4), the reassessment of freshwater fish species remains thus a priority to ensure their future survival.

To obtain a reliable conservation status, IUCN Red List requires many parameters such as population size, distribution range, and population structure (IUCN 2020). Nevertheless, the repeated acquisition of these data for freshwater fish using classical techniques (e.g. electric fishing) is expensive and not easy (Rondinini et al. 2014). In a context of conservation underfunding, regular reassessment of freshwater fish populations might only be possible if the evaluation becomes more efficient, possibly through new assessment strategies or techniques. In the last years, the use of non-invasive molecular techniques (e.g. metabarcoding, eDNA) is raising increased attention (Taberlet et al. 2018) and their application in conservation projects has rapidly grown. These techniques may provide the opportunity to map species geographic distribution over long time periods and across large spatial scales (Sales et al. 2020) and could also offer greater probabilities of detection of cryptic aquatic species when compared with the use of traditional sampling procedures (Antognazza et al. 2019; Itakura et al. 2019), among other benefits. Despite its limitations (Beng & Corlett 2020), there is a wide consensus that a molecular approach can become a powerful tool to ease and improve species conservation assessments.

Among the several, biodiversity hotspots where a molecular approach could be applied to improve species knowledge and reassessment (Myers et al. 2000), in this work we focused on the Iberian Peninsula, in the eastern Mediterranean basin. The Iberian Peninsula sits between the Atlantic Ocean and the Mediterranean Sea and, from the hydrological point of view, became fairly isolated from the rest of Europe since the rise of the Pyrenees (80-20 million years ago). At the same time, the region could be considered as a representative model of the Mediterranean area since it shares whit other European countries around the Mediterranean basin not only climatic, biodiversity and landscape characteristics but also the same pressures (Cuttelod et al. 2008). The Iberian river net is complex, comprising a high number of independent river basins where the different species' populations are strongly isolated (Clavero et al. 2004). As a consequence of this isolation, the native freshwater fishes of the Iberian Peninsula are characterized by a low number of families, a high degree of diversification at the species level, and the greatest European percentage of endemism (80%) (Doadrio et al. 2011). Despite its uniqueness, Iberian freshwater fish are jeopardized by various threats. Water extraction (including hydrological infrastructures) and introduced species, followed by climate constraints, pollution and overexploitation have been identified as the main threats for the native Iberian freshwater ichthyofauna (Maceda-Veiga 2013), a trend shared with other Mediterranean regions (Hermoso & Clavero 2011) . The IUCN Red List has evaluated the conservation status of many Iberian freshwater fish species, resulting in a high number of species being threatened by extinction, similarly to other regions around the Mediterranean (Darwall & Smith 2006). Nevertheless, they require reassessment efforts that must be done not only at global scale but also locally, to allow specific conservation actions at national level.

The objective of this study is to propose some guidelines to optimize freshwater fish reassessment efforts in the Iberian Peninsula. In this study, we use information on species distribution, conservation status and availability of genetic information on the freshwater fish of the Iberian Peninsula to suggest assessment priorities for the upcoming years.

Methods

Fish checklist (IUCN Red List in Spain and Portugal)

The Iberian freshwater fish checklist was created by merging the data from Spanish and Portuguese freshwater fish lists. The Iberian Freshwater Fish Database is a resource developed by the Iberian Society of Ichthyology (SIBIC) comprising data and occurrences from freshwater fish species present in peninsular Spain and also some present in Portugal. Data on Portuguese species were completed through consultation with Portuguese ichthyologist expert F. Ribeiro (personal communication). All native freshwater fish species from the Iberian Peninsula were considered in the study, including anadromous and catadromous species and endemic species present in coastal lagoons. We discarded duplicates and added information about species origin (native or introduced), and endemicity (whether they were endemic in Spain, Portugal, or both countries).

For each species, conservation status was checked in two databases: IUCN Red List and National Red Lists. Concerning IUCN Red List assessed species, we obtained data about conservation status and assessment date, to address the number of species with out of date assessments (before 2010). For National Red Lists, assessments were extracted from the 2011 report for Spanish fish (Doadrio et al. 2011) and the 2005 report for Portuguese fish. We compared the conservation status of both national Red List and the global one. The comprehensive list of freshwater fish from the Iberian Peninsula at species level and associated information can be found in Supplementary Data 6.1.

As single sources for biodiversity data records tend to have complementary gaps (Pino-Del-Carpio et al. 2014), we retrieved freshwater fish records for all the species in the checklist by combining records from GBIF and Spanish Freshwater List, using only records dating after 1990. We partitioned the Iberian Peninsula in a 10x10 km grid and calculated the completeness of the dataset by estimating the species richness and record density in each resulting tile and plotting the distribution of records and diversity data across tiles and computing the fraction of empty tiles (Lobo et al. 2018).

Calculations

The Iberian peninsula was segmented in basins according to data from MARS project http://www.mars-project.eu/index.php/databases.html. Following Abellán et al. (2005), we calculated several biological indexes for the Iberian basins:

- Species richness: The count of all species present in a basin.
- Rarity Index: We measured the rarity based on species range with no reference to abundance, calculated for all species in a basin by summing the inverse of all species' ranges and divided by the species richness of that basin

  $$Rarity\ index = \sum_{i=1}^{S} \frac{\left(\frac{1}{ci}\right)}{S}$$

  where ci is the number of basins occupied by species i and S is the species richness of the basin.
- Complementary Vulnerability Index: Calculated using the conservation status of the species recorded in each basin. Each species was assigned a score based on its IUCN Red List category (1 for Least Concern, 2 for Near Threatened, 3 for Vulnerable, 4 for Endangered and 5 for critically Endangered). A basin score was calculated as the sum of the vulnerability scores for each species present in that basin and divided by the species richness of that basin.

  $$Complementary\ Vulnerability\ index = 1 - \sum_{i=1}^{S} \frac{\left(\frac{1}{vi}\right)}{S}$$

  where vi is the vulnerability score of species i and S is the species richness of the grid cell.

For each basin, we also calculated the proportion of species with out of date assessments (species assessed before 2010)

We combined species richness, vulnerability and out of date assessments to find a set of priority basins where reassessment efforts should be developed in the following years.

Genetic analysis

Construction of fish genetic libraries started by querying for all fish species in the list the two most popular genetic databases: NCBI (National Center for Biotechnology Information) and BOLD (Barcode of Life Data System), using a standard barcode marker, the cytochrome c oxidase subunit I (COI). All available COI sequences for each species were downloaded from both genetic databases. Search parameters in NCBI were strict: "taxon _name" [Organism] AND COI [Gene]; database: nucleotide. BOLD did not require strict rules to download public sequences. We accessed sequences on April 3rd, 2020. To get a comprehensive genetic dataset for each species, the information of NCBI and BOLD was merged to remove duplicates originated by shared records among the main reference libraries. For each record, we preserved the dataset origin as NCBI or BOLD and for shared records, we used the nomenclature NCBI-BOLD. In the case of shared sequences, the NCBI sequence was retained. Downloaded data can be found in Supplementary Data 6.2.

All operations described above done performed using R software (R Development Core Team 2019) and the associated packages as *rentrez, readtext, stringr* and *bold*.

Results

Records were available for all species in the Iberian Peninsula. Nevertheless, they were unevenly distributed and certain regions of the Iberian Peninsula had a lower number of records (Figure 6.1).

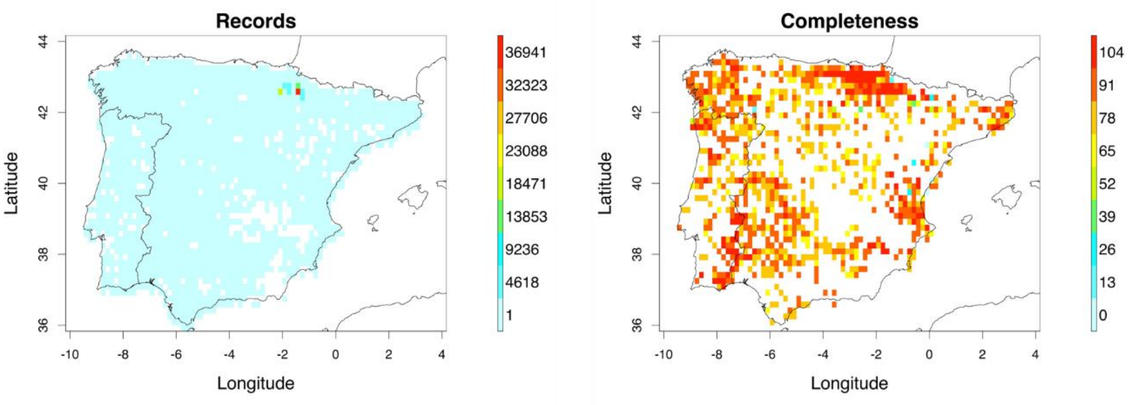

Figure 6.1: Number of records (left) and completeness (right) of Iberian freshwater fish records from GBIF and Spanish Freshwater List. Figure by T. Cancellario.

From 97 freshwater fish species listed in the Iberian Peninsula, 67 of them (69%) were native from the Iberian Peninsula and of these 61 (91%) were assessed by the IUCN Red List. The number of unassessed species was lower in Spain (2, 4 % unassessed) than in Portugal (5, 10%). Threatened species (classified as Vulnerable, Endangered or Critically Endangered) were 31 (50% of native species assessed), more than those classified as LC (29, 47%). Nevertheless, when examining National Red Lists, we found that Spanish freshwater fish are, on average, evaluated at higher threat categories than in the global list (Figure 6.2). In the case of Portugal, the absence of National evaluations for several species did not allow us to identify a similar trend, as many species are evaluated in the global list but not in the national one.

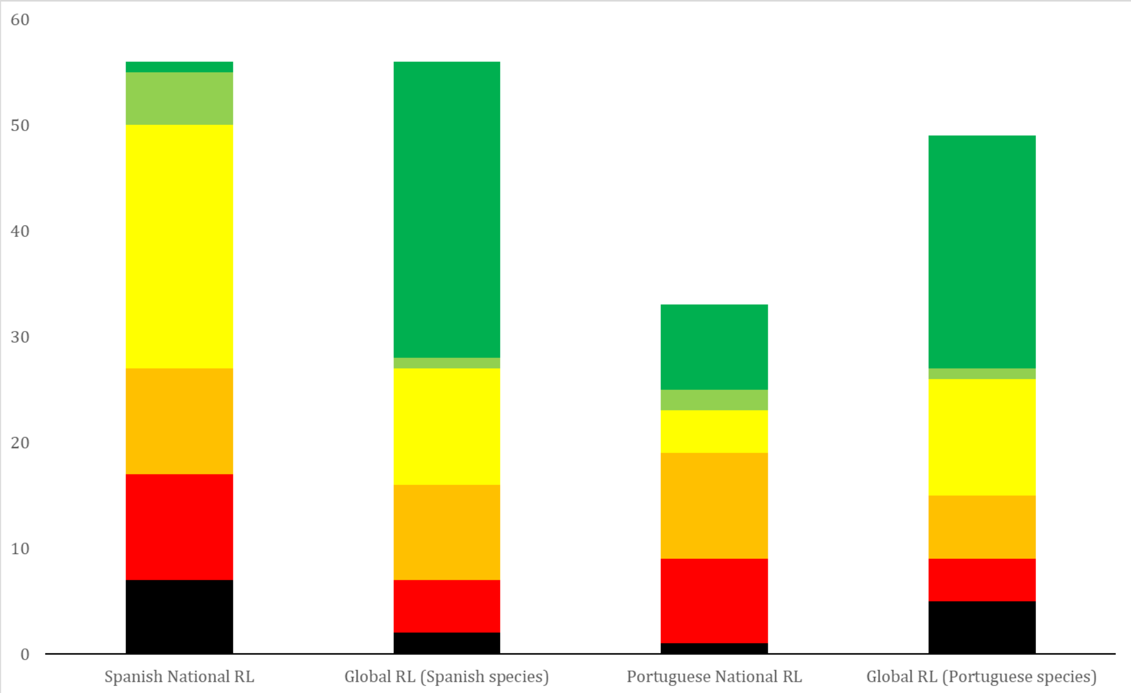

Figure 6.2 Distribution of global and National Red List Assessments for freshwater fish species present in Spain and Portugal. IUCN Red List categories are Least Concern (green), Near Threatened (light green), Vulnerable (yellow), Endangered (orange), Critically Endangered (Red) and Data Deficient (black).

Freshwater fish richness in the Iberian Peninsula is mainly concentrated in the Atlantic watersheds of the Southwestern, overall, in the Tagus and Guadiana Rivers, apart from a high diversity spot in the lower Ebro River (Figure 6.3). However, the Inverse Vulnerability Index in the Iberian Peninsula showed that higher vulnerability values were observed in the Mediterranean basins (except Ebro River), Guadalquivir, Guadiana, and Tagus basins (Figure 6.3).

Out of date assessments represent 77% (47 species) of assessed species in the Iberian Peninsula, with similar values for Spain (76%) and Portugal (75%). By basins, the highest number of out of date assessments were found in the Guadiana River basin and the lower reaches of the Ebro River Basin (Figure 6.3).

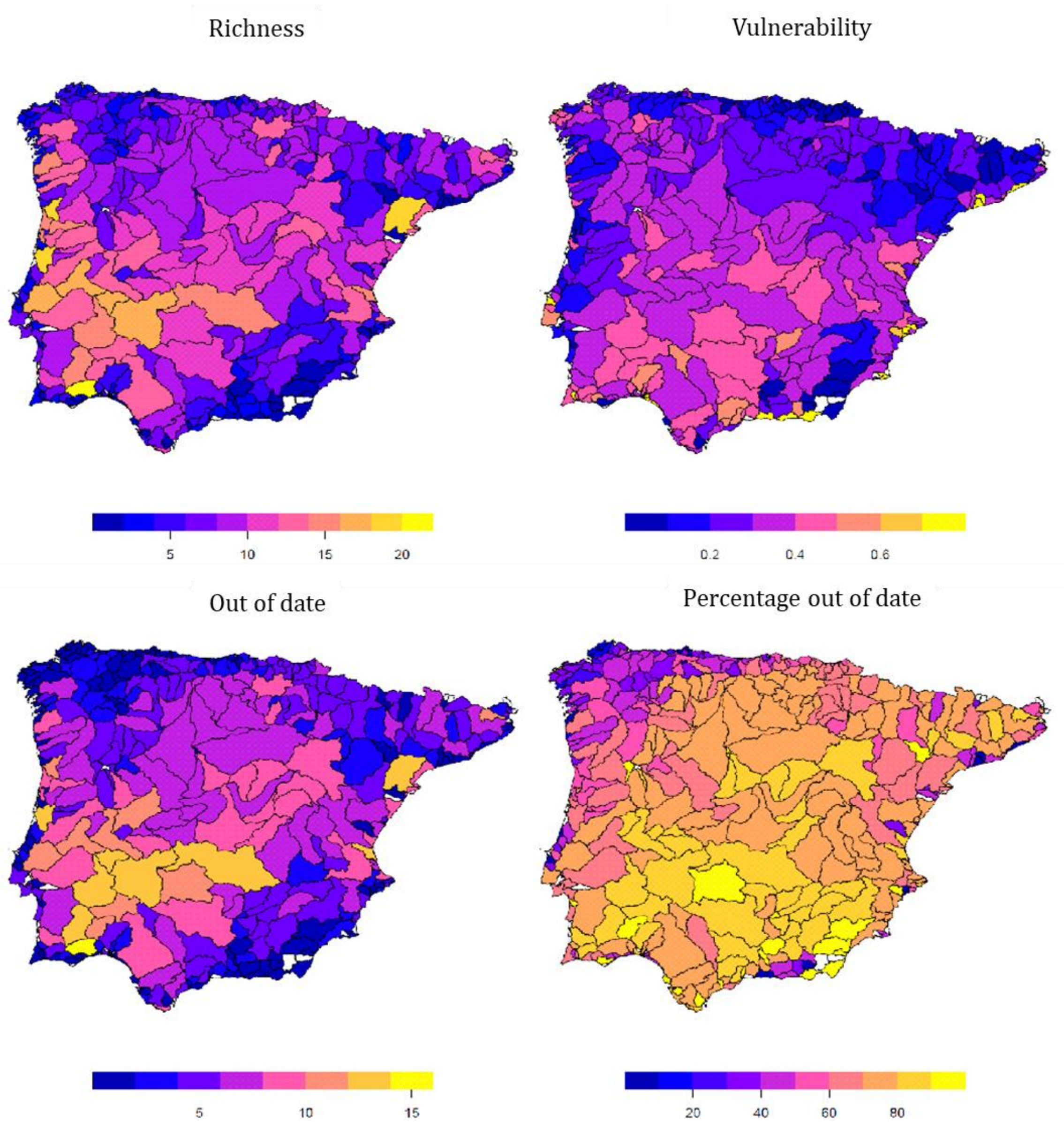

Figure 6.3: Freshwater fish indices in the basins of the Iberian Peninsula. Top left: Species richness. Top right: Complementary vulnerability index (from low to high vulnerability). Bottom: Number (left) and percentage (right) of species with out of date assessments.

Several basins were selected as priority for reassessment in the following years (Figure 6.4): Basins with low richness but with high vulnerability and out of date assessments of freshwater fish and basins with high richness and high rate of out of date assessments. We observed moderate to high levels of vulnerability in most basins.

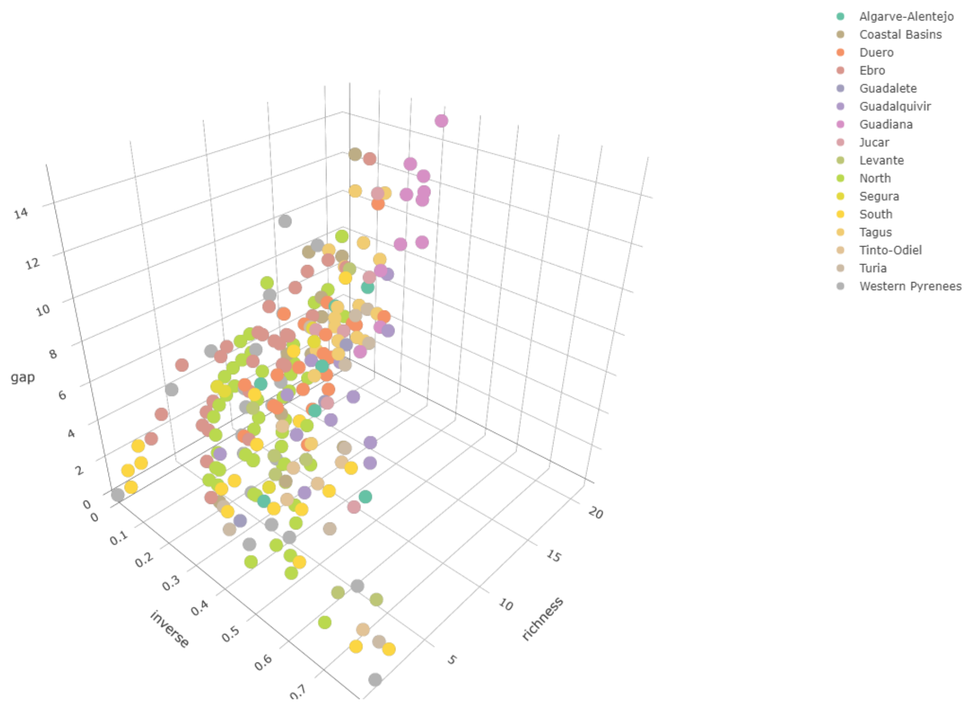

Figure 6.4: Values of richness, inverse vulnerability, and gap of out of date species in Iberian freshwater basins. Link to the online 3D plot in Supplementary Data 6.3.

Genetic information about freshwater fish in the Iberian Peninsula remains at a very good state (98% of species are represented in the genomic libraries). However, no advance has been made in this aspect since the last published studies (Múrria et al. 2020), and two native species remain absent from reference genetic libraries.

Discussion

Our study can serve as a useful tool to guide future reassessment efforts in the Iberian Peninsula. In fact, we think that similar approaches can be taken in other European countries with similar characteristics of species richness and out of date assessments, as seen in chapter 4 of this thesis.

Our results were strongly conditioned by the data coverage in the Iberian Peninsula (Figure 6.1). Despite having combined data from two sources (Iberian Freshwater Fish Database and GBIF) to achieve the most complete coverage of freshwater fish richness in the Iberian Peninsula, we consider that more efforts are needed to achieve and maintain long-term data series of species presence in Iberian freshwaters. We encourage the development of projects which use new techniques as eDNA to evaluate their efficiency against traditional electro-fishing methods (Itakura et al. 2019) and provide us with new methodologies for species sampling and monitoring. We need data to generate information and build knowledge to inform decision-makers or develop indicators to track progress towards biodiversity goals (Juffe-Bignoli et al. 2016). Furthermore, these data should be available in public repositories as sharing primary biodiversity data is fundamental to the advancement of science as it is currently practiced (Huang et al. 2012) and manage biodiversity change (Kissling et al. 2018). Primary biodiversity records on Iberian fish can not only benefit native communities but also help control invasive species. Implications of exotic species in Mediterranean environments have been widely studied (Vila-Gispert et al. 2005) and the Iberian Peninsula (Clavero & Garcia-Berthou 2006; Muñoz-Mas & García-Berthou 2020)) and efforts are being developed to increase the knowledge and awareness of the general public about these problems, such as the LIFE Project INVASAQUA (Casals & Sanchez-Gonzalez 2020).

Assessment rates of Iberian freshwater fish stay high, with a low number of native fish species out of the IUCN Red List. Nevertheless, many of these assessments date from before 2010 and according to IUCN Red List guidelines, they are out of date and should be redone shortly. Furthermore, the National Red Lists of Spain (2011) and Portugal (2005) are out of date too and, in the case in Portugal, do not assess many of the native species. National Red Lists show higher levels of threat for native species than the global one (Figure 6.2), which suggests that many species whose global conservation status is adequate could actually have populations closer to extinction in the Iberian Peninsula. However, all these assumptions must be contrasted with current and reliable evaluations, based on recent distribution and population data. Furthermore, in the case of Spain there is effort duplicity as the current National Red List is not official, whereas conservation priorities are driven by the species included in the Spanish National Catalogue of Endangered Species https://www.miteco.gob.es/es/biodiversidad/temas/conservacion-de-especies/especies-proteccion-especial/ce-proteccion-listado-situacion.aspx. We consider that a reliable and authoritative National IUCN Red List, elaborated following the IUCN Red List criteria and procedures, should be the guideline for conservation in countries, and that duplicated efforts should be avoided for the sake of species conservation.

Regarding species occurrence data, higher species richness was found in the south-western basins of the Iberian Peninsula, overall in the Guadiana Basin, which harbors a high number of endemic species (Filipe et al. 2004). Similarly, higher levels of threat in central and southern Iberian Peninsula are related to a higher level of endemism found in these rivers (Elvira 1995), especially in basins with low richness (Figure 6.3). Many basins in the Iberian Peninsula combine moderate or high levels of threat with a high proportion of freshwater fish in need of reassessment (Figure 6.4). This calls, and provides an opportunity, for developing future reassessment projects to promote endangered species conservation.

Outdated assessments in Spain and Portugal number similarly to other European countries having comparable species richness (Chapter 4, Figure 4.5). Nevertheless, the isolation of the Iberian Peninsula also implies different conservation perspectives for both endemic species and European species which lie at the edge of their range and whose conservation status is different from that in the rest of the continent (Figure 6.2). We consider that both countries have enough species to contemplate feasible projects to reevaluate the conservation status of their freshwater fish faunas. Furthermore, considering that many of the species are Iberian endemisms, this situation offers the opportunity to develop cooperative projects, as freshwater conservation should not understand of political borders. In this sense, the opportunity of using eDNA to promote species knowledge is a good opportunity to boost species information about distribution and abundances as a first step to new reassessments. Considering the high coverage of Iberian freshwater fish fauna in genetic libraries, we consider that eDNA can be effectively combined with traditional sampling methods (Takahara et al. 2019). Environmental DNA is especially useful when dealing with endangered species (the case of many Iberian species), as it does not require repeated samplings that would involve huge amounts of time and effort (Stewart 2019) and potential damage to the populations.

Significant human resources, structures, and processes are required to make continuous reassessments possible (Juffe-Bignoli et al. 2016). Without a stable financial and institutional support, there is little chance of establishing long-term monitoring policies that can help to protect both freshwater fish species and the riverine systems where they live. Previous works (Doadrio et al. 2011) have already drafted a proposal for a form of stable survey methodology in Spain and can serve as a starting point to incorporate eDNA and turn it into a stable, and overall applicable methodology to perform global and national Red Lists.

Chapter Transparency

I. Miqueleiz and T. Cancellario conceived the present idea. I. Miqueleiz developed the experiment, carried out the analyses and interpretated the results. T. Cancellario contributed with the calculations of genetic gap and Figure 1. I. Miqueleiz wrote the manuscript. T. Cancellario, R. Miranda and A.H. Ariño provided comments to the interpretation of the results and the manuscript.

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CHAPTER 7:

General discussion

Capítulo 7:

Discusión general

Conservation of fishes and the aquatic ecosystems where they inhabit, and the environment in general, is not only a matter concerning biodiversity but also has deep implications on the achievement of a more sustainable society (Convention on Biological Diversity 2016). In previous chapters, we have shown how fish conservation is far from being adequate considering the threats that fish species suffer both in inland and marine waters. The persistence of species, the management of stocks, and the sustainability of fisheries rely on a deeper knowledge and application of their conservation necessities. In 2010 Parties to the United Nations (UN) Convention on Biological Diversity (CBD) agreed to reduce the rate of biodiversity loss within a decade by achieving 20 objectives that are commonly known as the Aichi Targets (Convention on Biological Diversity 2010). In an editorial from February 2020, Nature journal warned that when targets expire at the end of this year, most of them will not have been reached (Nature 2020) and, when being reviewed, they will not be met (Juffe-Bignoli et al. 2016; Buchanan et al. 2020), so new targets will need to be developed for 2030. Willing to help and propose new ideas on fish conservation, we proceed to discuss the implications of our study on it.

The research described in this dissertation became feasible because many other scientists worked in producing and uploading data to the databases, including primary biodiversity data (PBR), Essential Biodiversity Variables (EBV) or biodiversity indices, which is an essential labour for biodiversity conservation (Kissling et al. 2018). As mentioned in the Introduction of this thesis (Chapter 1), databases continued evolving throughout the development of this project, incorporating new data and updating existing ones. Focusing on the IUCN Red List, which has been used as the main source for establishing the species conservation status, while many species had been evaluated and were included in the IUCN Red List, increasing our knowledge on fish biology and conservation, many others remained unassessed. We have observed that throughout this research (almost 4 years), fish species included in IUCN Red List have changed from slightly less than 50% (IUCN 2017) at the start of the investigation (Miqueleiz et al. 2020, Chapter 2) to 57% recently (IUCN 2020a) (Chapter 4, figure 4.1). Despite remaining worse assessed than other vertebrates, it is evident that progress is being made and our knowledge on fish conservation necessities is improving. This increase in fish species assessment rate is the result of extensive efforts carried out by IUCN Red List including several Fish Specialist Groups or the Global Freshwater Fish Assessment project. This project, which is expected to evaluate all fish species by the end of 2021, constitutes a major evaluation effort that is already producing published results (Contreras-MacBeath et al. 2020) which are improving the knowledge of freshwater fish conservation status in previously under-assessed and poorly known areas. Similar projects are being carried out to increase assessment efforts on several fish groups under the Species Survival Commission (SSC) https://www.iucn.org/ssc-groups/fishes. To support the labour done by this group and many other researchers, we consider that the future of fish assessments relies on two main courses of action:

1) Assessment of new species: Despite high species description rates, as reported in Chapters 2 and 5 (Figure 2.1) many more remain undescribed in many regions of the world (Pelayo-Villamil et al. 2018). Thus, many new fish species are expected to be discovered in the upcoming years. Several hotspots of fish descriptions have been identified (Nelson et al. 2016), which are similar to biodiversity hotspots (Myers et al. 2000), turning them in highly interesting areas not only for their current fish fauna but for the potential unknown one. Most newly discovered marine fishes have been found in the SW Caribbean, NW Indian Ocean, southern China Sea, and off the corners of Australia. In the case of freshwater fishes, they have been described in the Amazon Basin and the Parana Basin of South America, western Equatorial Africa, and south-eastern Europe, especially near Turkey, as well as in Southeast Asia (Nelson et al. 2016). These areas are already areas with low assessment rates (Chapter 2) and effort will be needed in future years to avoid assessment gaps for new species again. When assessing new fish species, we observe higher rates of threat and data deficiency (Chapter 4), and specific efforts and funds should be devoted to them. As mentioned in Chapter 4, the collaboration between taxonomists and IUCN Red List is essential for the development of reputed assessments of new species.

2) Updating assessments: Currently, IUCN Red List has assessed almost 21,000 fish species, from which 6,351 (30.4%) already require an update (IUCN 2020b). Furthermore, many of the revisions lead to non-genuine changes, which is to say that the previous assessment was not fully accurate. Given the high proportion of non-genuine changes that have been produced in the last reassessments, it is fundamental to evaluate many species whose assessments are very dated and potentially may not be accurate. As mentioned in previous Chapters, IUCN Red List assessments are considered to be out of date after 10 years (IUCN 2012; Rondinini et al. 2014). The increase in IUCN Red List assessments for fish started in 2010, so many species are expected to become out of date in the following years (Figure 4.1). In this sense, as discussed in Chapter 4, we strongly encourage the development of stable and long-term National Red List. On the one hand, we consider that countries can perform the evaluations of endemic species, thus resulting in a reduction of the assessment work for the global IUCN Red List. Thus, the assessment labour of IUCN Red List would be

limited to gather information on those species living in many countries and perform their assessments. Furthermore, we consider that implication of countries in fish conservation would be higher if they were responsible for the evaluations of their fish faunas. The development of National assessment groups would increase the awareness and knowledge of IUCN Red List assessment efforts, as well as the number of people trained in the IUCN Red List assessment process. A practical application of this suggestion is developed in Chapter 6 and discussed further at the end of this chapter.

In Chapter 2, we showed how certain groups of fishes less assessed than average for the taxonomic group. Among the traits analysed to find their relationship with different IUCN Red List assessment rates for fish, we found that, surprisingly, commercial fish species did not seem to be better assessed than non-commercial ones (Miqueleiz et al. 2020). Given the importance of these species in food consumption (FAO 2018), we considered that further analysis of commercial species was required. Results provided in Chapter 3 concerning top-fished commercial species showed that there is still a gap to fill, as many species remain unassessed or have outdated assessments (Figure 3.1, Table 3.2). Furthermore, we found a worrying trend in the family Scombridae, where many species had their catches increased even after having been assessed by the IUCN Red List with declining populations (Table 3.4). A specific group from IUCN is devoted to tunas (https://www.iucn.org/commissions/ssc-groups/fishes/tuna-and-billfish) and their assessments should be deeply considered by fishing industry and authorities. WWF reported a 74% decline in tuna populations since 1970 (WWF 2015), which attracted media attention and increased awareness about overfishing in these species (Fromentin et al. 2014). The fishing industry has developed tools to inform about stock assessments such as the RAM Legacy Stock Assessment Database to detect these trends and act accordingly. Given that such tools' outcomes usually converged with the assessments carried out by IUCN Red List (Ricard et al. 2012), we believe that all parties and stakeholders should act together in the name of commercial species conservation. The sustainability of fisheries is included within Aichi targets (Target 6) and Sustainable Development Goals (Cooke et al. 2016), but we need to apply more actions apart from improving commercial species evaluations, such as controlling discards (Zeller et al. 2018) and establish effective marine protected areas (Davidson & Dulvy 2017), also included in Aichi Target 11.

Regarding freshwater ecosystems, as described in the first chapter of this thesis, they are potentially the most endangered ones in the world (Dudgeon et al. 2006) and populations of fish species living in them have declined more than any other vertebrate

(McRae et al. 2017). In recent years, place-based approaches for conservation have gained support through the development of marine and freshwater protected areas (Loury et al. 2018). Nevertheless, target 11 will not likely be met by this year neither in the proportion of coverage nor in the representativeness of areas of particular importance (UNEP-WCMC et al. 2018). In our work, we have focused our attention on the protection offered to freshwater ecosystems, that contain perhaps as much as 12% of all known species (Garcia-Moreno et al. 2014) but which have been traditionally neglected in the design and management of protected areas (Abell et al. 2007). Even when freshwater ecosystems are included within protected areas, management is not usually focused on freshwater ecosystems, and these ecosystems may be compromised by upstream threats from outside protected areas (Thieme et al. 2016; Abell et al. 2017). Protected areas are not adequately covering rivers worldwide (Abell et al. 2007), as few freshwater ecoregions meet the Aichi 17% protection of rivers and wetlands (Chapter 5, Figure 5.2). Furthermore, protected areas do not adequately cover irreplaceable rivers for freshwater fish, resulting in ineffective protection regarding conservation needs (Figure 5.3). This problem has also been identified in the case of terrestrial vertebrates (Venter et al. 2014), and we need to reconsider the way we design and manage protected areas in the future by incorporating all available data across taxa (Pino-Del-Carpio et al. 2014). There are possibilities of finding regions or areas with high terrestrial and freshwater diversity (Abell et al. 2011), but they have to be considered equally. Global studies identifying conservation priorities have been usually driven by information on terrestrial vertebrates information (Le Saout et al. 2013; Rodrigues et al. 2014), and we contend that freshwater fish should also be considered, as they are potential surrogates of other freshwater taxa (Lessmann et al. 2016). New CBD targets are to be established to design 2030 goals. We strongly recommend, in the case of freshwater protected areas, to avoid thinking of them as isolated static units and consider them as dynamic elements within the wider landscape. As the full potential value of a protected area comes into focus, management objectives evolve over time to adapt to it (Flitcroft et al. 2016). There are many more freshwater areas that need to be protected than are manageable (Tognelli et al. 2019). Thus, it is important to identify priority areas for conservation action that provide networks of freshwater conservation with a connection between them. In this context, results provided in Chapter 5 reinforce the existence of many irreplaceable rivers which should be the cornerstone for future protected areas design.

Several recommendations should be considered for post-2020 targets. Many protected areas have been established in locations that are disproportionately unimportant for biodiversity (Venter et al. 2018). Some of them are ineffectively managed (Watson et al. 2014) and metrics can be improved to achieve a more adequate management (Visconti et al. 2019). Furthermore, in some cases, managers are unaware of important information regarding the freshwater biodiversity or lack sufficient resources for freshwater management activities (Thieme et al. 2012). It also is important to make the general public aware of the importance of the freshwater fauna that lives in protected areas, as an opportunity to find new resources and support from them (Hermoso et al. 2016).

It is time now for governments to learn lessons from the past and decide the way they want to face the upcoming years. Certain indicators such as the Living Planet Index (Collen et al. 2009) or the Red List Index (Butchart et al. 2007) allow us to track progress in species conservation along time. In the case of the latter one, we consider that retrospective assessments of recently assessed species can provide us valuable information regarding past status and trends of long-known species but that have been assessed only in recent times. Regarding the improvement of assessing species conservation status, we suggest that little effort can be done by many developed countries (mostly located in Europe) to improve the quality of their IUCN Red List assessments for fish, most of them dating from many years ago (Chapter 4). Using the Iberian Peninsula as an example that can surely be applied in other countries (Chapter 6), we suggest that the use of eDNA, combined with traditional sampling methods (Evans et al. 2017) could provide useful information about species distribution and abundance. Having more information is the start point to plan and develop National Red Lists, which would benefit freshwater fish conservation both at national and global levels. We believe that both Spain and Portugal have an excellent opportunity to develop high-quality evaluations that drive conservation actions for Iberian freshwater fish in the next decade. We strongly suggest the recognition of the IUCN Red List as an authoritative source of knowledge for conservation and a reference tool, and to follow its procedures and assessment process to establish countries' conservation priorities and strategies. We also suggest that reassessment efforts could benefit from the application of molecular techniques as eDNA to better monitor species distribution and abundances, as in previous works (Taberlet et al. 2018; Antognazza et al. 2019; Itakura et al. 2019; Pont et al. 2019).

We believe in the need for a mindset shift to protect biodiversity in the upcoming years. Aichi Targets did not fail solely because they were not measurable. They also failed because countries did not need to report what they were doing to achieve them, and they produced biodiversity action plans rather than achievement records (Nature 2020). We need countries to commit to protecting biodiversity and develop realistic targets towards which they can compromise. Several recommendations have already been made to suggest that new or revised targets should be clearly and unambiguously worded (Green et al. 2019;

Buchanan et al. 2020), and SMART (specific, measurable, achievable, realistic and time-bound). The work done in this thesis emphasizes the necessity of having the best available data and evaluations to develop conservation strategies that follow the previous named principles. 2030 CBD targets constitute an unbeatable opportunity to include knowledge provided by this thesis and similar studies and lay on the table fish necessities to ensure their protection.

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CHAPTER 8:

General conclusions

Capítulo 8:

Conclusiones generales

In this dissertation, the conservation status of fish species is analyzed and new insights on freshwater protected areas and species assessments are developed. The main conclusions of this research are the following:

1. Aquatic environments are severely threatened, and populations of fish species that live in them have continuously declined along over the last decades. Thus, urgent action is needed to improve fish species evaluations and promote their conservation.
2. Previous IUCN Red List assessments for fish wee biased towards economically developed regions, species with early description dates and species covered by current IUCN specialist groups.
3. Despite recent efforts, IUCN Red List assessment rates for fish have remained lower than other vertebrate groups, while fish description rates remain high. This poses a challenge to evaluate these newly described species, as they are more vulnerable than the total of fish species.
4. Top-fished species, which have been subject to intense fishing pressure for many years, are not better assessed than those of general commercial interest, and their reported catches may not be reliable.
5. Reconstructed catches for top fished species are 21.5% higher than those reported by FAO and increasing in several species having known declining population trends. Fisheries sustainability is at risk, and urgent cooperation between stakeholders is needed to achieve future sustainability.
6. A high proportion of those rivers considered as irreplaceable because of their unique freshwater fish fauna falls outside protected areas, reinforcing this way the general sense that protected areas do not effectively protect freshwaters and do not consider their special characteristics.
7. Irreplaceable protected areas in the terrestrial and freshwater domains do not generally agree and this disagreement may misrepresent the requirements for freshwater fauna needs in the planning and management of protected areas.
8. Freshwater fish may act as surrogates of the broader freshwater fauna to drive future protected areas establishment and management, although more information about species distribution is required to effectively establish river irreplaceability at a finer scale.
9. Higher-income countries have high rates of assessment for their freshwater fish fauna, but many of these assessments are out of date and should be redone promptly.

10. Non-genuine changes inform us of the necessity of update assessments to truly know species conservation status and develop more concise strategies.
11. New molecular techniques, such as environmental DNA (eDNA) have the potential to ease the acquisition of biodiversity data and improve fish conservation evaluations and strategies. There is much work that can be done to explore possibilities to extract data about species distribution, abundance, or population structure.
12. IUCN Red List criteria and guidelines should be applied at national level to create national Red lists, which can both promote specific conservation actions at country level and increase the knowledge and awareness of freshwater fish fauna. Avoiding duplicities and following IUCN Red List criteria would reduce efforts and improve results of evaluation processes.
13. Failure of CBD Aichi 2020 targets must teach us lessons to be applied in the next decade. We need to increase investment and awareness on biodiversity conservation, and leverage all the opportunities, techniques and resources to achieve a sustainable future for fish, nature and humans.

APPENDICES

Apéndices

Below these lines are listed all the appendices included in this thesis, with their metadata and a brief description of their content. All the appendices with the supplementary information relevant to this thesis are stored in electronic format in Figshare (https://figshare.com). All the information can be accessed trough the following repository https://figshare.com/projects/PhD_Tesis_Imanol_Miqueleiz/87119

Chapter 2

Supplementary Data 2: Word file with tables regarding traits and analyses carried out in the study (Supplementary Data 2.1 to Supplementary Data 2.5).

Chapter 3

Supplementary Data 3: Excel table with information on top fished commercial species.

Chapter 4

Supplementary Data 4: Excel table with country codes and GDP per capita in 2019.

Chapter 5

Supplementary Data 5: Excel table with average and standard deviation irreplaceability values in major freshwater basins.

Chapter 6

Supplementary Data 6.1: Excel table with information on Iberian freshwater fish species

Supplementary Data 6.2: Excel file with sequences downloaded from NCBI and BOLT for Iberian Freshwater Fish.

Supplementary Data 6.3: Html file with link to the 3D plot of richness, vulnerability and out of date assessments in major Iberian freshwater catchments.