Freshwater megafauna in a changing world: An alien species perspective

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Thesis outline

This thesis work was conducted between November 2019 and January 2024, under the supervision of **Dr. Fengzhi He** and **Prof. Dr. Sonja C. Jähnig** (both at the Leibniz Institute of Freshwater Ecology and Inland Fisheries and Humboldt-Universität zu Berlin), **Dr. Thomas G. Evans** (Université Paris-Saclay) and **Prof. Dr. Jonathan M. Jeschke** (Leibniz Institute of Freshwater Ecology and Inland Fisheries and Freie Universität Berlin).

1st Reviewer: **Prof. Dr. Sonja C. Jähnig**

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Declaration of Independence

Herewith I certify that I have prepared and written my thesis independently and that I have not used any sources and aids other than those indicated by me. I also declare that I have not submitted the dissertation in this or any other form to any other institution as a dissertation.

Xing Chen, January 15, 2024

Table of contents

Summary

Freshwater ecosystems, including rivers, lakes and wetlands, provide critical habitats for diverse species and support essential ecosystem services for human well-being. Meanwhile, they are under growing threats from various sources, including overexploitation, habitat degradation, flow modification, water pollution and invasive species. Consequently, monitored populations of freshwater vertebrates showed an average decline of 83% from 1970 to 2016. Freshwater megafauna (i.e., animals that spend a crucial part of their life cycle in freshwater or brackish ecosystems and have a maximum reported body mass of 30 kg) are particularly susceptible to anthropogenic impacts. Previous studies mainly focus on the impacts of overexploitation and dam construction on these large animals. The impacts of alien species on freshwater megafauna have been largely overlooked. While impacts of alien species on native freshwater megafauna are documented, many freshwater megafauna species, such as sturgeons, Asian carps, American beaver, hippo, crocodilians and the Chinese giant salamander, have been introduced outside of their native distributions. However, their impacts on native species and human well-being in the introduced regions have yet to be systematically investigated at a global scale.

This thesis aims to provide a comprehensive understanding of alien species impacts related to freshwater megafauna. I used Environmental Impact Classification for Alien Taxa (EICAT) framework to assess the environmental impacts of alien species on native freshwater megafauna. Then I took a different angle and focused on environmental impacts of alien freshwater megafauna, using megafish as an example and considering both negative and positive aspects with EICAT and EICAT+ frameworks. Moreover, I adapted the approach of nature's contributions to people (NCP) and assessed the beneficial and detrimental impacts on humans by alien freshwater megafauna.

Freshwater megafauna have been affected by a wide array of alien species group from freshwater and terrestrial ecosystems, including both vertebrates and invertebrates. Alien species impact native freshwater megafauna through mechanisms such as predation,

competition and hybridization, leading to declines in individual performance and population abundance, or even local extinction of native freshwater megafauna. In addition, native freshwater megafauna showed distinct susceptibility to alien-species impacts between life-cycle stages. Meanwhile, almost half of the 134 extant freshwater megafish species have been introduced to new freshwater ecosystems, with almost 70% of the introduced species established self-sustaining alien populations. These alien megafish caused negative impacts through nine different mechanisms. Predation is the most frequently reported mechanism, followed by herbivory and competition. More than half of the alien megafish species that have sufficient data for assessing impact magnitudes caused population declines of native species, or even species extirpation. A broad range of beneficial NCP categories have been documented for 59 alien freshwater megafauna species in 430 records, with food supply being the most frequently reported category (58%), followed by physical and psychological experiences (20%) and materials and companionship (12%). Much fewer records (154) were identified for detrimental NCP associated with 25 alien freshwater megafauna species, covering four categories including reduced food resources, damage to properties, reduced physical and psychological experiences and risk to health and safety.

This thesis emphasizes the vulnerability of native freshwater megafauna to alien species and demonstrates the profound environmental and socio-economic impacts of alien freshwater megafauna. Additionally, it highlights gaps in long-term monitoring and bias in geographical and taxonomic coverage. Long-term monitoring studies are deemed critical for a comprehensive assessment of alien species impacts, given that short-term studies may underestimate the potentially severe, population-level effects. Furthermore, there is an urgent need for monitoring the introduction and assessing impacts of alien species in the Global South. Considering the high economic values of freshwater megafauna due to their use in aquaculture, recreational fishing and pet trade, it is anticipated that more species will be introduced and established outside of their native ranges. Strict biosecurity requirements, mandatory risk assessments and management plans should be implemented when introducing alien freshwater megafauna for activities These measures will help reduce the risk of escapes or releases into natural waterbodies and help safeguard freshwater biodiversity and human well-being.

Zusammenfassung

Süßwasserökosysteme, darunter Flüsse, Seen und Feuchtgebiete, sind wichtige Lebensräume für eine Vielzahl von Arten und erbringen wichtige Ökosystemleistungen für die Menschen. Gleichzeitig sind sie zunehmenden Bedrohungen ausgesetzt, unter anderem durch Übernutzung, Habitatzerstörung, Veränderung der Wasserführung und -menge, Verschmutzung oder invasiven Arten. Infolgedessen verzeichneten ausgewählte und beobachtete Populationen von Süßwasserwirbeltierarten zwischen 1970 und 2016 eine durchschnittliche Verringerung der Populationen von 83%. Süßwasser-Megafauna (d. h. Tiere, die einen wesentlichen Teil ihres Lebenszyklus in Süß- oder Brackwasserökosystemen verbringen und deren adultes Gewicht mindestens 30 kg beträgt) sind besonders anfällig für anthropogene Einflüsse. Bisherige Studien befassen sich hauptsächlich mit den Auswirkungen von Übernutzung und Dammbau auf diese großen Tiere. Die Auswirkungen gebietsfremder Arten auf die Süßwasser-Megafauna wurden weitgehend außer Acht gelassen. Einerseits sind Auswirkungen gebietsfremder Arten auf einheimische Süßwasser-Megafauna dokumentiert, aber viele Süßwasser-Megafauna-Arten wie Störe, asiatische Karpfen, amerikanische Biber, Flusspferde, Krokodile oder der chinesische Riesensalamander wurden selbst außerhalb ihres ursprünglichen Verbreitungsgebiets eingeführt. Die Auswirkungen dieser Arten auf einheimische Fauna und das menschliche Wohlergehen in den eingeführten Regionen sind jedoch noch nicht systematisch auf globaler Ebene untersucht worden.

Ziel dieser Arbeit ist es daher, ein umfassendes Verständnis der Auswirkungen gebietsfremder Arten in Bezug auf Süßwasser-Megafauna-Arten zu erhalten. Dazu wurde die sog. EICAT-Analyse (Environmental Impact Classification for Alien Taxa) verwendet - einerseits, um die Umweltauswirkungen gebietsfremder Arten auf die heimische Süßwasser-Megafauna zu bewerten. Andererseits wurden die Umweltauswirkungen gebietsfremder Süßwasser-Megafauna mit Fokus auf Megafische für sowohl negative als auch positive Aspekte, mit den EICAT- und EICAT+-Rahmenwerken analysiert. Darüber hinaus wurde der Ansatz der Beiträge der Natur für den Menschen (nature's contributions to people - NCP) angepasst und die positiven und negativen Auswirkungen gebietsfremder Süßwasser-

Megafauna auf den Menschen bewertet.

Die Süßwasser-Megafauna ist von einer Vielzahl gebietsfremder Arten aus Süßwasser- und Landökosystemen betroffen, darunter sowohl Wirbeltiere als auch wirbellose Tiere. Gebietsfremde Arten beeinflussen die einheimische Süßwasser-Megafauna durch Mechanismen wie Prädation, Konkurrenz und Hybridisierung, was zu einem Rückgang der individuellen Leistung und der Populationsdichte oder sogar zum lokalen Aussterben der einheimischen Süßwasser-Megafauna führt. Darüber hinaus zeigte die einheimische Süßwasser-Megafauna eine unterschiedliche Anfälligkeit für die Auswirkungen gebietsfremder Arten in den verschiedenen Lebenszyklusstadien. Inzwischen ist fast die Hälfte der 134 existierenden Süßwasser-Megafischarten in neue Süßwasser-Ökosysteme eingeführt worden, wobei fast 70 % der eingeführten Arten sich selbst erhaltende gebietsfremde Populationen gebildet haben. Diese gebietsfremden Megafische haben sich durch neun verschiedene Mechanismen negativ ausgewirkt. Raub ist der am häufigsten gemeldete Mechanismus, gefolgt von Pflanzenfresserei und Konkurrenz. Mehr als die Hälfte der gebietsfremden Megafischarten, für die ausreichende Daten zur Beurteilung des Ausmaßes der Auswirkungen vorliegen, führten zu einem Rückgang der Populationen einheimischer Arten oder sogar zum Aussterben von Arten. Für 59 gebietsfremde Süßwasser-Megafauna-Arten wurde in 430 Datensätzen ein breites Spektrum an nützlichen NKP-Kategorien dokumentiert, wobei die Nahrungsversorgung die am häufigsten gemeldete Kategorie war (58 %), gefolgt von physischen und psychologischen Erfahrungen (20 %) sowie Materialien und Gesellschaft (12 %). Für 25 gebietsfremde Süßwasser-Megafauna-Arten wurden deutlich weniger Datensätze (154) für schädliche NKP identifiziert, die vier Kategorien umfassen, darunter verringerte Nahrungsressourcen, Schäden an Grundstücken, verringerte physische und psychologische Erfahrungen und Risiken für Gesundheit und Sicherheit.

Diese Doktorarbeit unterstreicht die Anfälligkeit einheimischer Süßwasser-Megafauna-Arten gegenüber gebietsfremden Arten und zeigt ökologische und sozioökonomische Auswirkungen gebietsfremder Süßwasser-Megafauna-Besiedlung auf. Darüber hinaus werden

Lücken im Monitoring und systematische Tendenzen in der geografischen und taxonomischen Erfassung aufgezeigt. Langfristiges Monitoring sind für eine umfassende Bewertung der Auswirkungen gebietsfremder Arten von entscheidender Bedeutung, da kurzfristige Studien die potenziell schweren Auswirkungen auf Populationsebene unterschätzen können. Darüber hinaus besteht dringender Bedarf, die Einführung gebietsfremder Arten (z.B. im globalen Süden) zu überwachen und ihre Auswirkungen zu bewerten. In Anbetracht des hohen wirtschaftlichen Wertes von Süßwasser-Megafauna-Arten (durch Einsatz in Aquakultur, Freizeitfischerei und den Heimtierhandel) ist zu erwarten, dass noch mehr Arten eingeführt werden und sich dann außerhalb ihrer ursprünglichen Verbreitungsgebiete etablieren. Eine obligatorische Risikobewertung und Managementpläne sollten bei der Einführung nichtheimischer Süßwasser-Megafauna-Arten umgesetzt werden. Diese Maßnahmen tragen dazu bei, das Risiko von Entweichungen oder die Freisetzungen in natürliche Gewässer zu verringern und die biologische Vielfalt der Binnengewässer und das menschliche Wohlergehen zu schützen.

Thesis outline

This thesis is a monograph, consisting of three main chapters (chapters 2 to 4) that have been either published, submitted for publication, or are in preparation for submission to peer-reviewed journals, a general introduction (**Chapter 1**) and a general discussion (**Chapter 5**). The general introduction provides background information, context and the general research aims, as well as specific aims of each chapter. In the general discussion chapter, I discuss the findings from each chapter in detail and demonstrate the connections between individual chapters.

Chapter 2 (Manuscript 2) X.C., T.G.E., J.M.J., S.C.J. and F.H. conceived the ideas and developed methods; X.C. collected data; X.C. analysed the data and prepared figures and tables, with substantial contributions from T.G.E., J.M.J., S.C.J. and F.H.; X.C. wrote the first draft, with substantial contributions from T.G.E., J.M.J., S.C.J. and F.H.

Chapter 3 (Manuscript 3) X.C., T.G.E., J.M.J., S.C.J. and F.H. conceived the ideas and developed methods; X.C. collected data; X.C. analysed the data and prepared figures and tables, with substantial contributions from T.G.E., J.M.J., S.C.J. and F.H; X.C. wrote the first draft, with substantial contributions from T.G.E., J.M.J., S.C.J. and F.H.

Chapter 4 (Manuscript 4) X.C., T.G.E., J.M.J., S.C.J. and F.H. conceived the ideas and developed methods; X.C. collected data and prepared figures and tables, with substantial contributions from T.G.E., J.M.J., S.C.J., P.G. and F.H; X.C. led the writing and all authors contributed substantially to the drafts of the manuscript.

List of figures

List of tables

1. General introduction

1.1 Significance of freshwater ecosystems: biodiversity and ecosystem services

Freshwater ecosystems, including rivers, lakes and wetlands, cover only approximately 3% of the surface of the Earth but provide habitats for a disproportionately large amount of species (Dudgeon et al., 2006; Reid et al., 2019). For example, freshwater ecosystems support nearly 10% of all known animal species, approximately a third of all vertebrate species and over 50% of fish species (Balian et al., 2008; Carrete Vega & Wiens, 2012). In addition, freshwater ecosystems provide essential ecosystem services that are important for sustaining life on Earth (Vári et al., 2022). They act as fundamental regulators of the hydrological cycle, buffering floods and maintaining freshwater resources (Kundzewicz et al., 2007). They contribute to the mitigation of the effects of climate change by acting as substantial carbon sinks (Salimi et al., 2021). Moreover, freshwater ecosystems play a pivotal role in the purification of water, effectively removing pollutants, sediment and nutrients and ensuring the availability of clean water for human consumption (Bogardi et al., 2020). Freshwater ecosystems also provide recreation value, including fishing and boating (Lynch et al., 2023).

1.2 Importance and diversity of freshwater megafauna

Among freshwater species, the situations of freshwater megafauna (i.e., animals that spend a critical part of their life cycle in freshwater or brackish ecosystems and have a maximum reported body mass of at least 30 kg; He et al., 2017) are particularly worrisome. These large animals, including sturgeons, catfishes, crocodilians, turtles, river dolphins, hippopotamuses, beavers and giant salamanders were once abundant in many rivers, lakes and wetlands across the world. Currently, 57% of all assessed freshwater megafauna species are considered threatened by the IUCN Red List (IUCN, 2023). From 1970 to 2012, the abundance of monitored freshwater megafauna population had an average decline of 88% globally (He et al., 2019). Baiji (*Lipotes vexillifer*) and Chinese paddlefish (*Psephurus gladius*) became extinct in the last century while the populations of Yangtze sturgeon (*Acipenser dabryanus*) and Chinese sturgeon (*Acipenser sinensis*) are only sustained by human-assisted supplement

(Zhang et al., 2020).

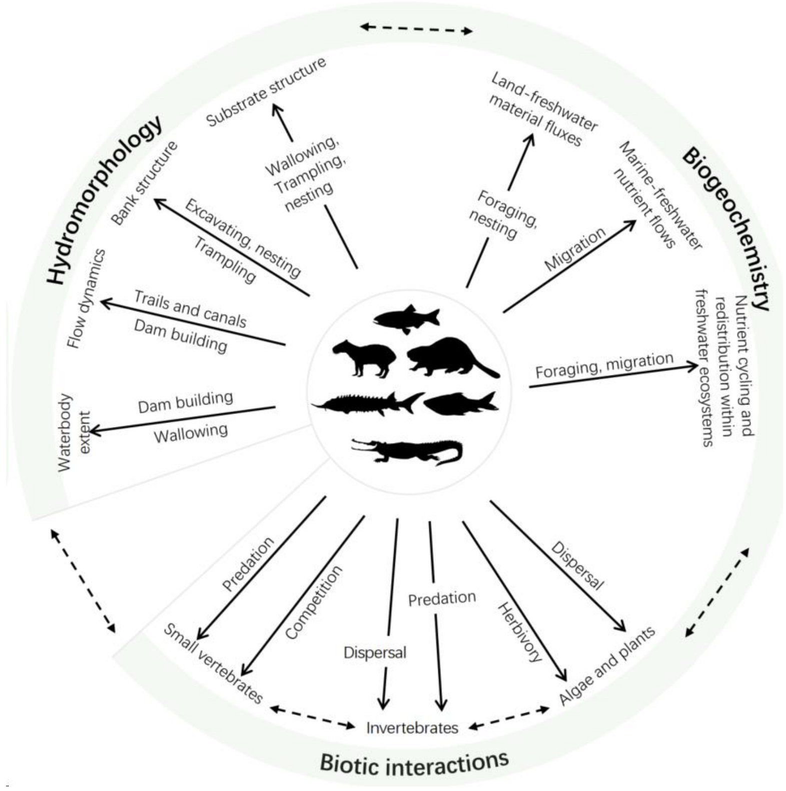

Fig. 1.1 Ecological importance of freshwater megafauna in freshwater ecosystems (adapted from He et al., 2024).

The loss of freshwater megafauna has profound ecological impacts because these large animals support vital ecological functions and nature's contributions to people (Fig. 1.1). Freshwater megafauna play a pivotal role in shaping hydro morphological aspects of freshwater habitats through their direct physical activities (e.g., dam building, trampling and excavating). A prominent example in this regard is beavers. American beavers (*Castor canadensis*) construct dams that elevate water levels and transform surrounding landscapes into expansive open-water areas and wetlands (Larsen et al., 2021). In the Baldwin Peninsula (Alaska, U.S.), the influence of beavers led to a remarkable 14.3% increase in waterbody areas from 2002 to 2019 (Jones et al., 2020). Moreover, beaver dams and associated ponds create backwater channels, effectively reducing downstream peak flows (Brazier et al., 2021; Puttock et al., 2021).

Freshwater megafauna also play a pivotal role in enhancing the flow of biomass and nutrients across ecosystem boundaries. For example, hippopotamuses spend extended periods immersed in water and release faeces and urine into freshwater ecosystems. On average, a single hippopotamus contributes 8.7 kg of faeces daily to the Mara River, resulting in a total daily flux of 36,200 kg of feces, carrying 3,499 kg of carbon, 492 kg of nitrogen and 48 kg of phosphorus from hippopotamuses populations to the river (Subalusky et al., 2015). Furthermore, freshwater megafauna facilitated nutrient exchange between freshwater and terrestrial ecosystems through intricate trophic interactions with both terrestrial animals and plants. For instance, Arrau turtles (*Podocnemis expansa*) rely heavily on fruits and seeds as their primary food source, contributing to the movement of nutrients from terrestrial to freshwater environments (Cunha et al., 2020). Conversely, certain megafauna species, such as tiger catfish (*Pseudoplatystoma fasciatum*) and caimans, become prey for terrestrial predators like jaguars (*Panthera onca*), creating a mechanism for nutrient transfer from water to land (Eriksson et al., 2022). Moreover, anadromous and potamodromous fish species serve as crucial agents in redistributing nutrients across various aquatic ecosystems.

Freshwater megafauna often have a strong influence on local trophic dynamics. Their herbivorous activities wield significant influence over the composition and growth of aquatic plants. For instance, manatees, found in both Africa and South America, exhibit a diverse palate by feeding on over 30 plant species (Guterres-Pazin, 2014; Takoukam Kamla et al., 2021). In addition, many freshwater megafauna such as river dolphins, anacondas, crocodilians and various large piscivorous fish species, are top predators and have strong impacts (Hammerschlag et al., 2019).

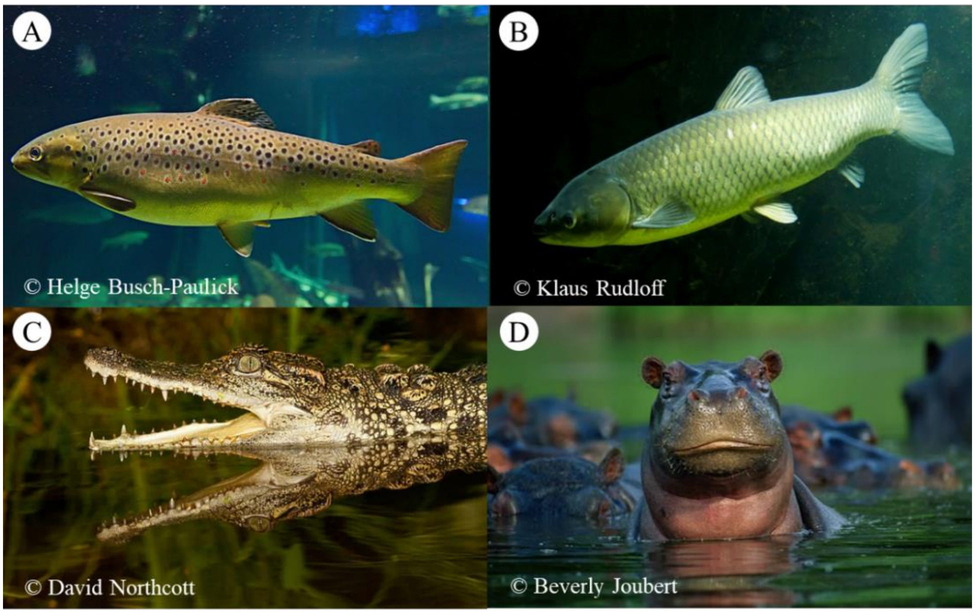

Fig. 1.2 Examples of freshwater megafauna associated with NCP: (A) brown trout (*Salmo trutta*); (B) grass carp (*Ctenopharyngodon idella*); (C) Siamese crocodile (*Crocodylus siamensis*); (D) Hippopotamus (*Hippopotamus amphibius*).

Beyond their ecological importance, freshwater megafauna support important nature's contributions to people, including regulations, materials and non-materials (Fig. 1.2). For example, many species, such as grass carp, silver carp, bighead carp and striped bass (*Morone saxatilis*), are used to control detrimental organisms (Dibble & Kovalenko, 2009; Feyrer et al., 2003; Sass et al., 2014). Moreover, freshwater megafauna provide various material elements. Their eggs, skins and meat serve as luxury items, foods and traditional medicines for local communities (Bronzi et al., 2011; Cheung & Dudgeon, 2006; Tosun, 2013). Due to human fascination with large animals, freshwater megafauna contribute to recreation activities, including fishing, hunting and tourism. For example, the Florida manatee (*Trichechus manatus latirostirs*) supports coastal Florida communities through ecotourism and brought millions of dollars income (Solomon et al., 2004). Similarly, northern pike (*Esox lucius*) is crucial for recreational fishing in Europe and North America (Arlinghaus et al., 2023).

1.3 Anthropogenic threats to freshwater ecosystems including freshwater megafauna

Despite that freshwater ecosystems support high level of biodiversity and provide vital contributions to human well-being, they are subject to multiple and growing threats (Reid et al., 2019). Overexploitation, habitat conversion (e.g., converting wetlands to farmland) and fragmentation, flow modification, chemical pollution (e.g., nutrients and pesticides) and alien species have been regarded as major threats to freshwater ecosystems (Dudgeon et al., 2006). For instance, at least 3,700 large hydropower plants with a capacity of more than 1 MW and 82,800 smaller plants are operating, under construction, or being planned, which have fragmented over 60% of the world's long rivers that are longer than 1000 km (Couto & Olden, 2018; Zarfl et al., 2015; Zhang & Gu, 2023). These modifications disrupt natural flow regimes, causing changes in the transportation of sediment and blocking migration of various species (He et al., 2021; Nilsson et al., 2005; Wu et al., 2019). Additionally, pollution from domestic, industrial and agricultural sources poses a significant threat to freshwater ecosystems (Dudgeon, 2019; Wen et al., 2017). For example, chemical pollutants, including heavy metals (Schuler & Relyea, 2018), plastics (Lebreton et al., 2017) and pharmaceuticals (Burns et al., 2018), can accumulate in freshwater ecosystems, endangering aquatic organisms and human health. Moreover, emerging threats such as climate change, light and noise pollution and freshwater salinization are increasingly documented in various regions (Reid et al., 2019).

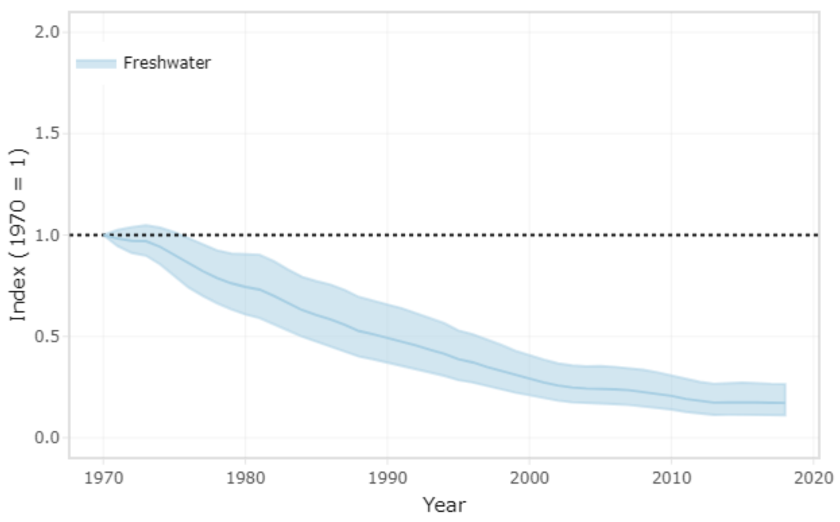

Fig. 1.3 The Living Planet Index (LPI) values for freshwater ecosystems from 1970 to 2018, with 95% confidence intervals shown in shaded areas (data from WWF, 2022).

These persistent and emerging threats have led to severe biodiversity declines in freshwaters. From 1970 to 2016, 6617 monitored populations of 1398 freshwater vertebrate species had an average decline of 83% globally (Fig. 1.3, WWF 2022). According to the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species (hereinafter referred as IUCN Red List; IUCN 2023), 285 freshwater species have been evaluated as "Extinct" or "Extinct in the Wild". Moreover, 7949 freshwater species are considered threatened with extinction (i.e., they have been listed as Critically Endangered, Endangered or Vulnerable; IUCN 2023). The rate of biodiversity loss in freshwater ecosystems is unprecedented and faster than terrestrial or marine realms (Tickner et al., 2020).

Freshwater megafauna are particularly vulnerable to anthropogenic impacts, experiencing an 88% population declined between 1970 and 2012 due to the aforementioned threats (He et al., 2019). Dam construction poses a significant threat to migratory species, disrupting long-distance migrations that are essential for finishing their life cycle. For example, since 1981, the cascade dams on the Yangtze River have drastically reduced the migration distance of Chinses sturgeon (*Acipenser sinensis*) by 1,175km, resulting in gonadal development being delayed 37 days and the effective breeding population size and environmental capacity of the new spawning ground respectively reduced to 24.1% and 6.5% of the original (Huang & Wang, 2018). In some cases, dam construction and increasing salinity have contributed to local extinctions, such as the ship sturgeon (*Acipenser nudiventris*) in the Aral Sea (Gesner et al., 2010; Zholdasova, 1997). Habitat degradation and water pollution are also major concerns for freshwater megafauna, given their large range of habitat requirements and susceptibility to chronic effects and chemical bioaccumulation. High concentrations of mercury and methylmercury have been detected in top predators like brown trout (*Salmo trutta*), posing potential risks to both the species and those consuming them (Arcagni et al., 2018). In Lake Baikal, the Baikal seal (*Pusa sibirica*) experienced mass mortality events due to the bioaccumulation of contaminants in the 1980s (Tsydenova et al., 2004).

Compared to other threats, limited attention has been paid to the impacts of alien species on native freshwater megafauna. Alien species are considered as a major threat to global biodiversity and have posed profound impacts on freshwater ecosystems (Gallardo et al., 2016). Freshwater megafauna species are also not immune to them. For example, introduced wild pigs (*Sus scrofa*) prey on eggs of the false gharials (*Tomistoma schlegelii*) in Sumatra (Shaney et al., 2023).

1.4 Alien species in freshwater ecosystems

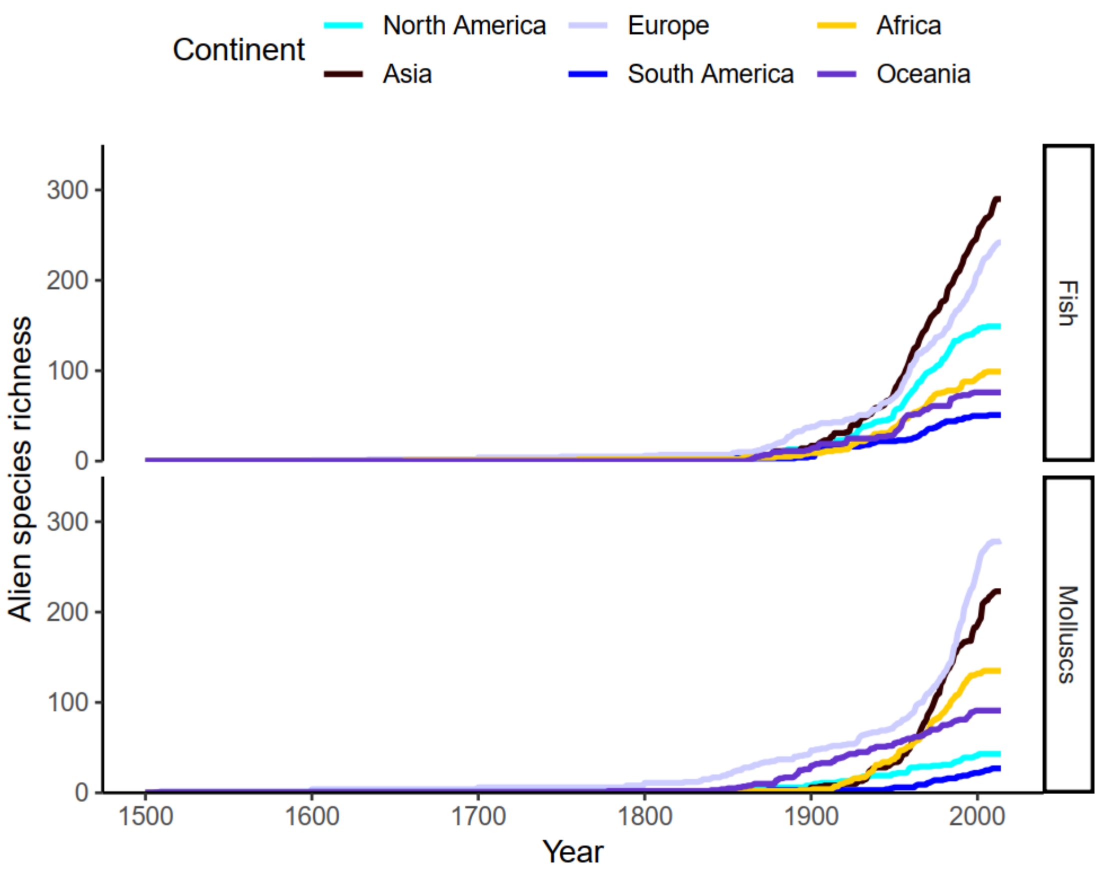

Fig. 1.4 Cumulative established alien species richness across fish and molluscs in six continents. Time series are based on the year of first record of those alien species that later became established in the given continent (data from Seebens et al., 2017).

Alien species, which are defined as species introduced to areas beyond their natural distribution by anthropogenic activities, have been widely documented worldwide (Pyšek et al., 2020). At least 37,000 species have established alien populations outside of their native ranges, while more than 3500 species are considered as invasive (IPBES et al., 2023). Alien species are a major threat to many species groups, including plants, amphibians, reptiles, birds and mammals (Bellard et al., 2016). Alien species have contributed to 33% of all documented animal extinctions and 25% of plant extinctions since 1500 (Blackburn et al., 2019). Over the past two centuries, the number of alien species has steadily increased worldwide, with introduction rates on the rise (Seebens et al., 2017). This growth is particularly obvious in freshwater ecosystems (Fig. 1.4; Seebens et al., 2017).

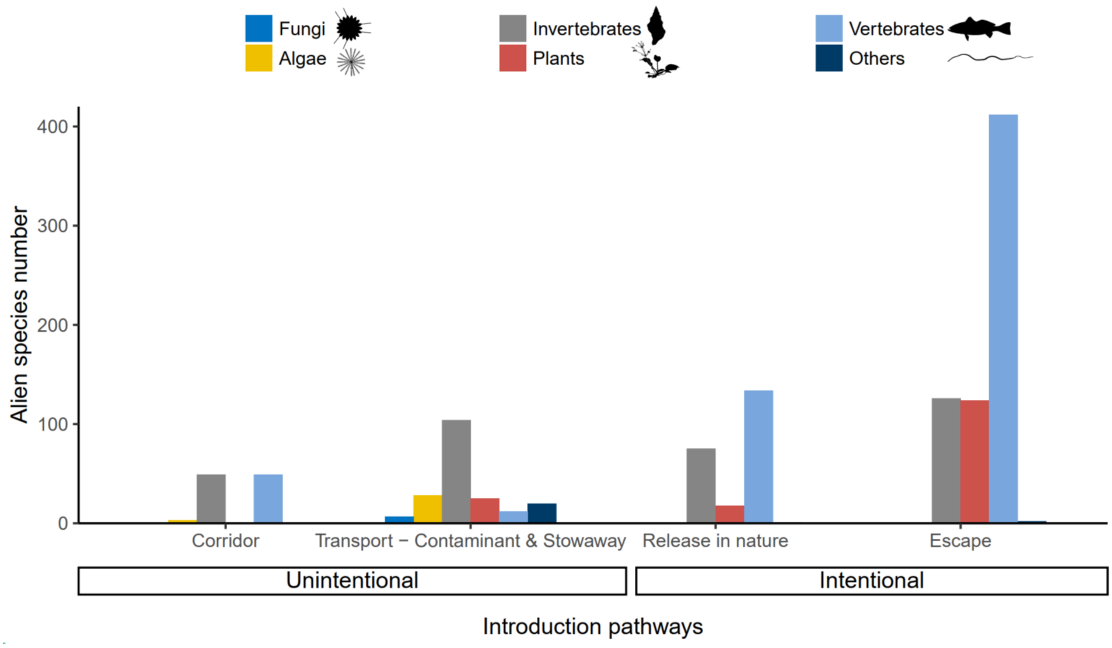

Fig. 1.5 Number of alien species introduced via unintentional and intentional pathways across fungi, algae, invertebrates, plants, vertebrates and other organisms in freshwater ecosystems (data from Saul et al., 2017).

Anthropogenic activities in freshwater ecosystems have significantly contributed to species invasions (Fig. 1.5; Ervin et al., 2006; Saul et al., 2017). For example, dam construction results in the extirpation of species unable to adapt to rapid environmental changes, creating vacant niches exploited by alien species (Liew et al., 2016). Various vectors, including boats, ballast water, aquariums and aquaculture, facilitate introductions of alien species into freshwater ecosystems (Lodge et al., 1998). A study on Lake St. Clair in Michigan, U.S., estimated 170 dispersal events of zebra mussels (*Dreissena polymorpha*) from boats during the summer season (Johnson et al., 2001). Moreover, escaping alien species from aquaculture facilities has become a global challenge as the rapid growth of aquaculture production relies heavily on the introduction of exotic species (Arthur et al., 2010; Ju et al., 2020; Kang et al., 2023). The global pet trade has also become a major contributor to the spread of alien species around the world (Gippet & Bertelsmeier, 2021; Lockwood et al., 2019). For instance, at least 100 freshwater fish species have been introduced into North America through pet trading, with 40 of them having established populations (Lockwood et al., 2019). In addition, recreational fishing is also a key introduction pathway for the introduction of invasive fish (South et al., 2022). For example, rainbow trout (*Oncorhynchus mykiss*) have been introduced to 82 countries for recreational fishing and still spreading (Cambray, 2003).

Freshwater ecosystems, characterized by high connectivity, are particularly vulnerable to the spread of alien species (Francis & Chadwick, 2011). The hydrological connections between different water bodies and water traffics can facilitate the spread of alien species. For example, round gobies (*Neogobius melanostomus*) were introduced to the Great Lakes in the U.S. through ballast water from transoceanic ships from Europe and have rapidly spread through waterways and interconnected river systems across the U.S. (Kornis et al., 2012). In addition, artificial waterways have been widely constructed worldwide. Many of them have connected basins that were naturally isolated. Such connections can help alien species spread across basins. For instance, the Welland canal, connecting lakes Ontario and Erie, may facilitate the dispersal of invasive fish (e.g., common carp; Kim & Mandrak, 2016). Moreover, environmental changes such as impoundment and climate change can facilitate the establishment and spread of alien species in freshwaters. Johnson et al. (2008) estimated alien species are 2.4 to 300 times more likely to occur in impoundments than in natural lakes, with impoundments frequently supporting multiple invaders. Many freshwater alien species possess adaptability to disturbances such as droughts and floods, enabling them to survive in a range of conditions and increasing their chances of establishment (Francis & Chadwick, 2011; Strayer, 2010). For instance, alien ringed crayfish (*Orconectes neglectus*) and signal crayfish (*Pacifastacus leniusculus*) exhibit high tolerance to stream drying compared to the native

Orconectes eupunctus (Larson et al., 2009).

Alien species can pose profound impacts on the recipient freshwater ecosystems through various mechanisms. For example, alien American minks (*Neovison vison*) prey on diverse native species in Europe, such as birds, mammals, amphibians and crustaceans (Bonesi & Palazon, 2007). Hybridisation between alien rainbow trout (*Oncorhynchus mykiss*) and native cutthroat trout (*Oncorhynchus clarkii*) in the Western U.S. threatens the genetic diversity of native cutthroat trout populations (Hitt et al., 2003). Alien species also compete with native freshwater species for resources, such as food and habitat, which has been widely documented (e.g., alien silver carp outcompeted native black crappie; *Pomoxis nigromaculatus and* sauger; *Sander canadensis* in the Upper Mississippi River; Solomon et al., 2016). Additionally, alien species also affect native species via disease transmission or by introducing parasites. For example, the introduction of amphibian chytrid fungus (*Batrachochytrium dendrobatidis*) by the African clawed frog (*Xenopus laevis*) to various regions, causing major amphibian declines in South Africa and the U.S. (Skerratt et al., 2007; Tinsley et al., 2015; Vredenburg et al., 2013). Moreover, some alien species can alter local habitats, in turn, posing impacts on native species. For example, alien American beavers (*Castor canadensis*) modified both terrestrial and freshwater habitats in Tierra del Fuego (Chile) through felling trees and building dams, leading to declines in native species (e.g., *Nothofagus betuloides* and *Nothofagus pumilio*) while promoting the invasion of other alien species such as brown trout, *Salmo trutta* (Anderson et al., 2006, 2009; Arismendi et al., 2020).

However, it is essential to recognize that alien species can also benefit native species through providing food resources and facilitating species dispersal. For example, zebra mussels increased food availability for the amphipod *Gammarus roeselii* through deposition of faces, leading to increased growth rate and body length of *Gammarus roeselii* in Germany (Gergs & Rothhaupt, 2008). Asian hornsnail (*Batillaria attramentaria*) increased the abundance of eelgrass (*Zostera japonica*) in Padilla Bay, U.S., by altering oxygen and nitrogen levels through bioturbation (Wonham et al., 2005). Alien Aldabra giant tortoises (*Aldabrachelys gigantea*) aid in seed dispersal and improve seed germination, contributing to the successful establishment of new ebony seedlings in their introduced regions (Griffiths et al., 2011).

The introduction and establishment of alien species in freshwater ecosystems have exerted profound socio-economic impacts, both positive and negative. On the negative side, invasions by alien species often lead to the displacement of native flora and fauna, disrupting local ecosystems and diminishing biodiversity (Pyšek et al., 2017). These alterations can have cascading effects on fisheries, agriculture and recreational activities, thereby impacting the livelihoods of communities depending on freshwater resources (Haubrock et al., 2021; Shackleton et al., 2019; Silva et al., 2009). For instance, a continued decline in catch of Indian major carps from around 130kg km^{-1} to 40kg km^{-1} due to invasion of alien common carp in the Ganges River, India (Singh et al., 2013). Moreover, the economic costs associated with managing and mitigating the impacts of invasive species, including control measures and ecological restoration, pose substantial burdens on local and regional budgets (Diagne et al., 2020; Hudgins et al., 2023). Conversely, certain alien species have been intentionally introduced for economic purposes, such as aquaculture or commercial fisheries, contributing positively to socio-economic development (Silva et al., 2009). For instance, the introduction of Nile perch, common carp and sturgeons have enhanced local fisheries, providing new opportunities for employment and economic growth (Aloo et al., 2017; Bronzi et al., 2011; Li et al., 2021). Moreover, some alien species, despite their ecological impact, have been used as ornamental plants or aquarium species, creating markets and economic opportunities (Lockwood et al., 2019).

1.5 Advances in assessing the impacts of alien species

In order to effectively manage and allocate limited resources to tackle the challenges posed by alien species, it is crucial to prioritize conservation actions and prevent introductions of species that could potentially pose severe environmental and socio-economic impacts (Roy et al., 2014). However, a major obstacle to achieving this goal is the lack of comparable data to assess impacts posed by alien species.

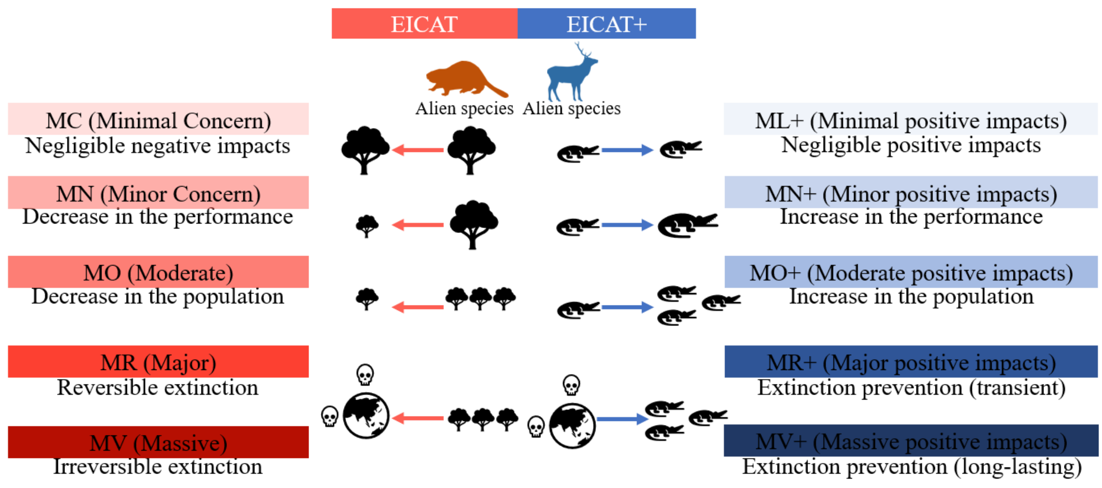

Fig. 1.6 Different impact categories under the EICAT and EICAT+ frameworks and the relationships between them (adapted from Blackburn et al., 2014; Vimercati et al., 2022).

In the last two decades, several protocols have been developed to systematically assess alien species impacts (Bacher et al., 2018; Blackburn et al., 2014; Katsanevakis et al., 2014; Kumschick et al., 2012; Martinez-Cillero et al., 2019; Nentwig et al., 2016; Olenin et al., 2007; Sandvik et al., 2013; Vimercati et al., 2022). For example, the Environmental Impact Classification for Alien Taxa (EICAT) framework provides a standardized approach to quantifying and categorizing the negative environmental impacts of alien species on native species (Blackburn et al., 2014; IUCN, 2020a, 2020b; Volery et al., 2020). The negative impacts of alien species can be assigned to one of the 12 mechanisms (e.g., competition, predation, hybridisation and disease transmission). In addition, it provides a semi-quantitative approach to evaluating the magnitude of impacts on native species. The impact magnitude can be assigned to one of the five categories (i.e., Minimal Concern, Minor, Moderate, Major and Massive) based on its influence on native species (Fig. 1.6). EICAT has been formally adopted by the International Union for Conservation of Nature (IUCN) as an assessment protocol for alien species impacts (IUCN, 2020a, 2020b). It has been successfully applied to various taxa, including birds (Evans et al., 2016), rabbits (Allmert et al., 2021), amphibians (Kumschick et al., 2017), bamboos (Canavan et al., 2019), ungulates (Volery et al., 2021) and gastropods (Kesner & Kumschick, 2018), allowing cross-taxonomic and cross-regional impact comparisons.

It is vital to acknowledge the positive environmental effects associated with alien species to comprehensively understand their influence on recipient ecosystems (Vimercati et al., 2020). To address this, EICAT+ was recently developed to quantify and categorize positive environmental impacts caused by alien species on native species (Vimercati et al., 2022). Similar to EICAT, EICAT+ provide 10 impact mechanism categories and uses a semi-quantitative approach to classify positive environmental impacts into five categories (i.e., Minimal positive impact+, Minor+, Moderate+, Major+ and Massive+). Although EICAT+ has not yet been widely applied to different taxonomic groups, combining EICAT and EICAT+ frameworks allows for a more nuanced understanding of the environmental impacts caused by alien species (Latombe et al., 2022).

In addition to their ecological impacts on native species, alien species can also pose profound impacts on human society. For instance, it is estimated that alien species at least cost US$1.288 trillion (2017 US dollars) during 1970-2017 (Diagne et al., 2021). In freshwaters, global costs incurred by invasive macrofouling bivalves reached US$ 63.7 billion between 1980 and 2020 (Haubrock et al., 2022). However, these monetary evaluations only capture a small part of the socio-economic impacts of alien species. Alien species impacts on human well-being, such as health and risk, are frequently left out of traditional assessments focusing on economic costs (Bacher et al., 2018).

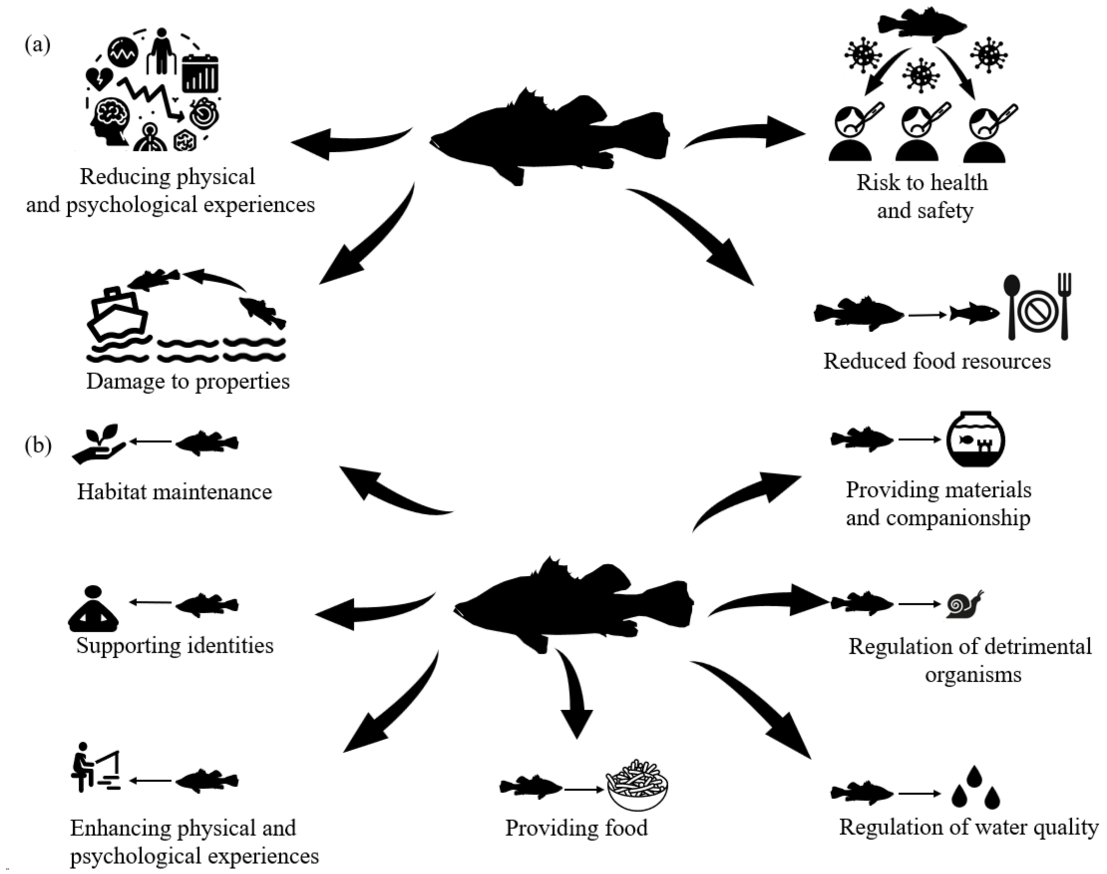

Fig. 1.7 Categories of detrimental (a) and beneficial (b) NCP provided by alien freshwater megafauna.

In order to capture the full socio-economic impacts of an alien species, Socio-Economic Impact Classification for Alien Taxa (SEICAT) was developed, with the same key characteristics of EICAT (Bacher et al., 2018; Blackburn et al., 2014). It translates a broad spectrum of impact types and measures into ranked levels of socio-economic impact and has been applied to diverse taxa, including birds (Evans et al., 2020), marine fish (Galanidi et al., 2018), ants (Gruber et al., 2022) and rabbits (Allmert et al., 2021). However, SEICAT only considers negative socio-economic impacts of alien species. Despite their often-reported detrimental impacts, alien species provide diverse types of benefits to human well-being (Sax et al., 2022). For example, alien freshwater fish such as common carp, bighead carp and brown trout are vital food resources in their introduction regions due to their large size and rapid growth (Fig. 1.7). To date, no standardized protocol has been developed to comprehensively assess beneficial socio-economic impacts associated with alien species. The nature's contributions to people (NCP) framework evolves from ecosystem services concept (Díaz et al., 2018) and could be used to assess both detrimental and beneficial socio-economic impacts associated with alien species.

1.6 Aims and structure of the thesis

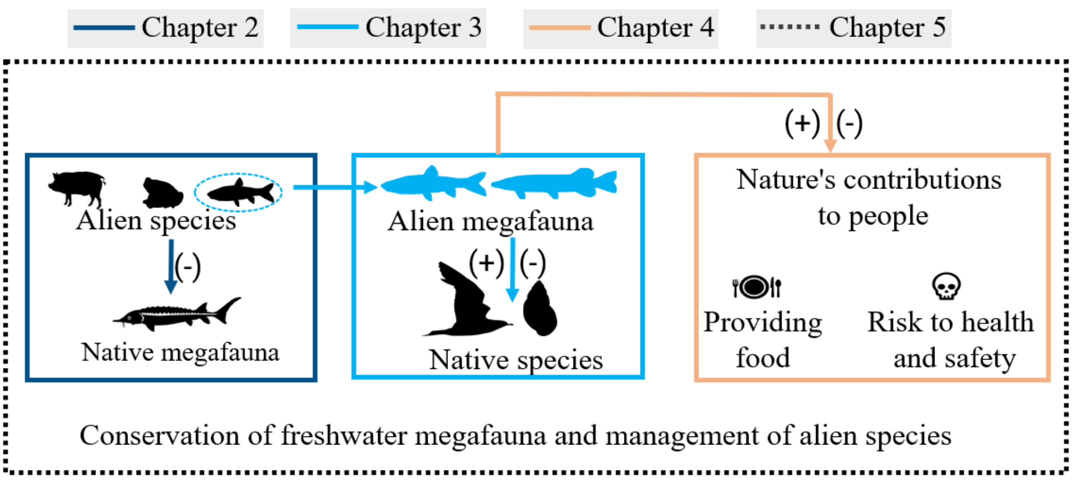

Fig. 1.8 Conceptual overview of this thesis and linkages between each chapter ("+" indicates positive impacts caused by alien species while "-" indicates negative impacts caused by alien species).

This thesis aims to gain a comprehensive understanding of alien species impacts related to freshwater megafauna, including the influence of alien species on native freshwater megafauna and impacts posed by alien freshwater megafauna on native species in the recipient ecosystems. It covers both negative and positive aspects in environmental and socio-economic aspects (Fig. 1.8). Three research objectives are embedded within the thesis: 1) assess negative impacts of alien species on native freshwater megafauna; 2) evaluate both negative and positive impacts of alien freshwater megafauna on native species; 3) investigate beneficial and detrimental nature's contributions to people (NCP) associated with alien freshwater megafauna.

Chapter 2 focuses on the first research objective. I systematically collected reported data on negative impacts posed by alien species on native freshwater megafauna. Following the EICAT framework, I classified the main impact mechanisms and magnitudes of these records. Given that freshwater megafauna have a long life-span and complex life-cycle, I examined the patterns in impact mechanisms and magnitudes associated with different life-cycle stages (i.e., egg, juvenile and adult). I expect these large animals to be more vulnerable to alien-species impacts in their egg and juvenile stages than they are as adults.

Chapter 3 is associated with the second research objective and considers both negative and positive impacts of alien freshwater megafauna on native species. Given the limited data on other groups (i.e., megamammls and megaherpitiles), this chapter focuses on alien megafish. I created a global database of alien megafish, including their introduced regions, introduction times and pathways and environmental impacts in the introduced regions. I evaluated their positive and negative impacts on native species following EICAT and EICAT+ frameworks. In addition, I ranked alien freshwater megafish based on their potential impacts after being introduced to a new basin. Finally, I investigated factors associated with severe impacts of alien freshwater megafish.

In **Chapter 4**, I systematically collected reported data on NCP provided by alien freshwater megafauna, considering both beneficial and detrimental NCP. Following the NCP framework, I investigated the main categories of NCP and magnitudes of each record. Given the high economic value of alien freshwater megafauna, I expect that more data are reported for beneficial NCP than detrimental NCP.

In **Chapter 5**, I summarize key findings from the previous chapters and discuss their implications for the management of biological invasions. I provided recommendations for future research regarding conservation of native freshwater megafauna and management of alien freshwater megafauna. I also emphasise the need of conducting long-term monitoring and balancing environmental and socio-economic impacts of alien species when developing assessment approaches and management strategies.

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2. Do alien species affect native freshwater megafauna?

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2.1 Abstract

Freshwater megafauna species (i.e., animals that can reach a body mass ≥ 30 kg, including fish, reptiles, mammals and amphibians) play important roles in freshwater systems (e.g., by influencing habitat structure, trophic dynamics, or the dispersal of smaller species). As they tend to be large and charismatic, they may also function as flagship umbrella species in future freshwater conservation initiatives. Despite this, as a group they are highly threatened and our knowledge of the nature of these threats is limited. In this study, we aim to improve our understanding of the impacts of alien species on native freshwater megafauna. We undertook the first global assessment of the impacts of alien species on native freshwater megafauna using the Environmental Impact Classification for Alien Taxa (EICAT) framework. We conducted a literature review to identify published and grey literature on impacts, which we quantified and categorised by their severity and type, following the EICAT guidelines. Negative impacts on native freshwater megafauna were caused by 61 alien species from a diverse range of taxonomic groups, including both freshwater and terrestrial alien species and both vertebrates and invertebrates. They adversely affected 44 of 216 native freshwater megafauna species, including amphibians, fish, mammals and reptiles. The Great Lakes Basin had the highest number of affected megafauna species (six of the 14 freshwater megafauna species it supports, mainly fish). Impacts occurred through a broad range of mechanisms (ten of the 12 identified mechanisms under EICAT); predation and competition were the most frequently reported mechanisms. Some impacts were relatively minor, adversely affecting the performance of individuals of native freshwater megafauna species. However, some reported impacts did cause declining populations of native freshwater megafauna species and one impact contributed to the local extinction of the ship sturgeon (*Acipenser nudiventris*) in the Aral Sea. The vulnerability of native freshwater megafauna species to different types of impact varies during different life-cycle stages (egg, juvenile and adult). Our understanding of impacts posed by alien species on native freshwater megafauna is limited because data is unavailable for many regions, particularly the Global South, including hotspots for freshwater megafauna diversity such as the Amazon, Congo, Mekong and Ganges-Brahmaputra basins.

Freshwater megafauna species are often subject to multiple threats, which makes it difficult to determine the significance of alien species impacts relative to other threats such as habitat degradation and overexploitation. In addition, short-term studies are likely to be masking the severity of the impacts identified. We call for more long-term studies that attempt to identify population-level impacts and for studies that identify impacts in data-deficient regions. The EICAT assessments undertaken for this study will be reviewed by the EICAT Authority and subsequently incorporated into the IUCN EICAT database. They may be used to guide future research and conservation actions.

Keywords: biological invasions, competition, EICAT, freshwater biodiversity, invasive alien species

2.2 Introduction

Freshwater ecosystems, including lakes, rivers and wetlands, are among the most diverse ecosystems on Earth (Strayer & Dudgeon, 2010; Wetzel, 2001). Although only covering about 3% of the Earth's surface (Lehner & Döll, 2004), they support approximately one-third of all known vertebrate species and half of all described fish species (Balian et al., 2008; Carrete Vega & Wiens, 2012). They also provide vital contributions to people, for example enabling the transportation of goods, providing opportunities for recreation, supplying fertile soils for agriculture and regulating flood events (Postel & Carpenter, 1997; Vári et al., 2022). Despite this, freshwater ecosystems are among the world's most vulnerable ecosystems; the proportion of species that are threatened or extinct is much higher in freshwaters when compared to terrestrial or marine realms (Costello, 2015). Indeed, over 25% of assessed freshwater species are considered threatened (evaluated as being Vulnerable, Endangered, or Critically Endangered on the International Union for Conservation of Nature's [IUCN] Red List of Threatened Species) and more than 260 freshwater species are extinct (IUCN, 2022). This may be because freshwater ecosystems are subject to multiple stressors that act together to negatively affect freshwater species (Reid et al., 2019).

Freshwater megafauna species (i.e., animals that can reach a body mass ≥ 30 kg) include, for example, river dolphins, hippopotamuses, crocodilians, large turtles, sturgeons and giant salamanders. They often have important ecological roles as ecosystem engineers or keystone species (Hammerschlag et al., 2019; Moore, 2006). For example, hippopotamuses (*Hippopotamus amphibius*) alters floodplain habitats and river morphology and transfers large amounts of nutrients from grasslands to freshwater ecosystems, influencing the diversity of invertebrate and fish species in the ecosystems it occupies (Stears et al., 2018; Subalusky et al., 2015). Freshwater megafauna including river dolphins and piscivore megafish are top predators and have a profound influence on local trophic dynamics (Hammerschlag et al., 2019), while megafish species are often highly mobile and facilitate dispersal of smaller species (Correa et al., 2015; Lopes-Lima et al., 2017). Furthermore, many freshwater megafauna species are considered to be charismatic and as such may play important roles in future conservation initiatives (e.g., as flagship umbrella species; He et al., 2021a; Kalinkat et al., 2017). Despite this, they tend to be long-lived with slow life-history traits (e.g., long lifespan and late maturity), which makes them vulnerable to human impacts (He et al., 2021b; WWF, 2020) because individuals lost from a population are not replaced at a rate fast enough to prevent declines in that population (sensu Webb, 2002). For example, the incubation period for eggs of Australian freshwater crocodiles (*Crocodylus johnsoni*) is typically 75–85 days (which gives predators, including alien wild boar [*Sus scrofa*], an adequate opportunity to consume their egg; Webb et al., 1983). Freshwater megafauna also often require a variety of habitats to complete their life cycle (He, Langhans, et al., 2021) and impacts on any one of these habitats may adversely affect their ability to reproduce (Schlosser, 1991). Hence, freshwater megafauna are threatened by a diverse range of activities. For example, harvesting of their meat, skin and eggs has led to a collapse of local populations of sturgeons, beavers, turtles and giant salamanders (He & Jähnig, 2019; Ripple et al., 2019). Recreational fishing has contributed to the decline of the Siberian taimen (*Hucho taimen*; Jensen et al., 2009). Dams and levees have reduced the connectivity of rivers that freshwater megafauna inhabit, which has restricted their access to spawning and nesting sites (He et al., 2021c). As a consequence, between 1970 and 2012, global monitored populations of freshwater megafauna declined by 88% (He et al., 2019).

Alien species (i.e., species that have been introduced deliberately or unintentionally by human activities to areas outside of their natural distribution) are a critical threat to biodiversity (Pyšek et al., 2020). They are one of the causes of 33% of all animal species extinctions and 25% of all plant species extinctions since 1500 CE (Blackburn et al., 2019). The number of alien species has grown continuously across the world over the last 2 centuries and rates of their introduction continue to rise (Seebens et al., 2017). The connectivity of freshwater ecosystems fosters the spread of alien species, which is furthered by human activities such as aquaculture and shipping (Francis & Chadwick, 2011; Moorhouse & Macdonald, 2015). In addition, many freshwater alien species are adapted to disturbances (e.g., drought and flood) and can survive in a range of conditions, which increases their chance of survival and establishment in regions into which they are introduced (Francis & Chadwick, 2011; Strayer, 2010). The introduction of alien species can have catastrophic impacts on local freshwater ecosystems, including the freshwater megafauna species they support. For example, the introduction of the Nile perch (*Lates niloticus*) to Lake Victoria caused the extinction of approximately 200 species of fish through predation and competition (Goldschmidt et al., 1993) and led to population declines of several native freshwater megafauna species, including the marbled lungfish (*Protopterus aethiopicus*), African catfish (*Clarias gariepin*) and Sudan catfish (*Bagrus docmak*; Goudswaard & Whitte, 1997). Despite these observed impacts, the influence of alien species on freshwater megafauna has received limited attention in comparison to impacts associated with other types of threat, such as overexploitation and dam construction (He et al., 2017).

Understanding the impacts of alien species on biodiversity is crucial for the development of efficient and effective management strategies to protect them from extinction (Jeschke et al., 2014; Kumschick et al., 2015). The Environmental Impact Classification for Alien Taxa (EICAT) protocol provides a systematic approach for categorising the impacts of alien species (Blackburn et al., 2014) and has been adopted by the IUCN to assess the environmental impacts of alien species (IUCN, 2020a, 2020b). It has been used to assess the impacts of several groups of alien species in terrestrial ecosystems, including birds (Evans et al., 2016, 2021), mammals (Allmert et al., 2021; Hagen & Kumschick, 2018; Volery et al., 2021), gastropods (Kesner & Kumschick, 2018) and plants (Canavan et al., 2019; Jansen & Kumschick, 2022). However, with the exception of amphibians (Kumschick et al., 2017), EICAT has not been used to carry out a global-scale assessment of the effects of alien species in freshwater ecosystems. As alien species are widely distributed across freshwater ecosystems and can have significant adverse impacts (Francis & Chadwick, 2011; Moorhouse & Macdonald, 2015; Strayer, 2010), such an assessment may provide important information that informs future research to identify and mitigate impacts, to the benefit of imperilled native freshwater megafauna species.

In this study, we use EICAT for the first time to undertake a global assessment of the environmental impacts of alien species on native freshwater megafauna. We aim to answer the following three questions: (1) Which freshwater megafauna species have been affected by alien species and where do these impacts occur? (2) In what way and how severely, are freshwater megafauna species affected by alien species? (3) Do the types of impacts sustained by freshwater megafauna vary across different stages of their life cycle? Freshwater megafauna species reach a very large final body size and we therefore expect them to be more vulnerable to the impacts of many alien species in their egg and juvenile stage than they are as adults.

2.3 Materials and Methods

2.3.1 Literature review

An updated version of the published list of freshwater megafauna taxa was collected from He et al. (2018), comprising 134 fishes, 47 reptiles, 33 mammals and two amphibians. Their conservation status was collected from the IUCN Red List of Threatened Species (hereafter IUCN Red List; IUCN, 2022). We conducted a literature review to search for evidence documenting the impacts of alien species on each of these native freshwater megafauna species. Following Evans et al. (2016), we used terms describing alien species in combination with the scientific and common names of each freshwater megafauna species to search for literature on the Web of Science and Google Scholar. For example, the search string for the Nile crocodile was: (“invasive” OR “alien” OR “non-indigenous” OR “non-native” OR “introduced” OR “exotic”) AND (“Nile crocodile” OR “Crocodylus niloticus”). We screened the titles and abstracts of articles to identify those that were relevant and reviewed the reference list published in each selected relevant article to identify additional references. We included articles describing impacts in the wild, or impacts identified through experiments. Articles written in either English or Chinese were considered. We also reviewed information on each freshwater megafauna species published on the IUCN Red List, CABI's Invasive Species Compendium (http://www.cabi.org/isc/), the Global Invasive Species Database of the Invasive Species Specialist Group (http://www.iucngisd.org/gisd/) and USGS's Nonindigenous Aquatic Species (https://nas.er.usgs.gov/).

Impact records were divided into three groups. The first included direct observations of impacts in the wild or established through laboratory experiments, which may be used for EICAT assessments (group 1). The second contained references that could not be included in the EICAT assessment for various reasons (group 2). For example, these references provided no direct observation of impacts (e.g., they are review articles) or no evidence of a negative impact (e.g., potential impacts were inferred). Some articles documented positive impacts whilst others focused on stocked native species rather than individuals in the wild. These references were also not included in our analysis. The third group contained references that were excluded because we could not assess the complete article due to access restrictions (group 3). The following data were extracted from studies in group 1: names of alien species and affected native freshwater megafauna species; description of observed impact; location of impact; and life-cycle stage of affected freshwater megafauna species (egg, juvenile, or adult).

2.3.2 Distribution mapping

We obtained the native ranges of each freshwater megafauna species (He et al., 2018) and used level-3 HydroBASINS as spatial units to map their distributions (Lehner & Grill, 2013). HydroBASINS delineates catchments at a global scale based on their topographic position and hydrological connections and provides hierarchical sub-basins with 12 levels. Level-3

HydroBASINS mainly corresponds to large river basins such as the Amazon, Congo, Ganges-Brahmaputra, Mekong, Mississippi, Nile and Yangtze basins. We assigned each recorded impact on a native freshwater megafauna species to one or more level-3 HydroBASINS at this scale. We also categorised each alien species by the continent of its origin and by the continent where it caused impacts (i.e., Africa, Asia, Europe, North America, Oceania and South America). If an alien species was native to more than one continent and/or caused impacts on more than one continent, we assigned it to the category multiple continents.

2.3.3 EICAT assessment

We assessed the impacts of alien species on native freshwater megafauna following the EICAT guidelines (IUCN, 2020a, 2020b; Volery et al., 2020). We assigned each impact record by its type to one of 12 impact mechanisms: competition; predation; hybridisation; transmission of disease; parasitism; poisoning/toxicity; bio-fouling or other direct physical disturbance; grazing/herbivory/browsing; chemical impact on ecosystem; physical impact on ecosystem; structural impact on ecosystem; and indirect impact through interaction with other species. We also assigned each impact record by its severity to one of five impact severity categories: minimal concern (MC) if no discernible impact was identified; minor (MN) if the alien species reduced the performance of individuals of a native freshwater megafauna species; moderate (MO) if the alien species caused a decline in the population of a native freshwater megafauna species; major (MR) if the alien species caused the local extinction of a native freshwater megafauna species (but this could be reversed if alien species were removed); and massive (MV) if the alien species caused the global extinction of a native freshwater megafauna species or the local extirpation of a native freshwater megafauna species that is not naturally reversible (i.e., the locally extirpated freshwater megafauna could not recolonise the area even if the alien species were removed). When interactions between alien species and native freshwater megafauna were observed but the available data were insufficient to assess the magnitude of any impacts, these records were classified as being data deficient (DD) under EICAT. We categorised impacts on each freshwater megafauna species by their affected life-cycle stage (i.e., egg, juvenile and adult). We assigned impacts on viviparous megafauna (e.g., hippos, beavers) by either juvenile or adult stage as they give birth to living young. Freshwater megafauna species affected by hybridisation were classified as adults. In some cases, life-cycle stages were inferred based on the body length and body mass of the affected freshwater megafauna taxa. We assigned a confidence level of low, medium, or high to each impact record to indicate the probability of our EICAT assessment being accurate (IUCN, 2020a, 2020b). For example, confidence levels may be affected by data quality, the spatial and temporal scale of the observed data and the presence of confounding factors that make it difficult to determine the cause of an impact. All EICAT assessments were reviewed by at least two co-authors to minimise subjectivity.

When calculating the number and percentage of each impact mechanism and severity category, we only included unique records. For example, if two or more records documented the same species interaction (i.e., between one alien species and one native freshwater species) with the same impact mechanism in the same level-3 HydroBASINS, only one record was counted. We examined the distribution of impacts across impact severity and life-cycle stage using contingency table tests (unconditional exact tests) with the FunChisq package (Zhong & Song, 2019) in R (R Core Team, 2021). For impact severity, due to small sample sizes in some categories of interest, we grouped EICAT categories as follows: MC and MN impacts = less severe impacts; MO, MR, or MV impacts = harmful impacts. The FunChisq package generated an estimate for each contingency table, which is a number between 0 and 1, where 1 represents a complete mathematical dependency of the two variables and 0 represents complete independence.

2.4 Results

2.4.1 Spatial distribution

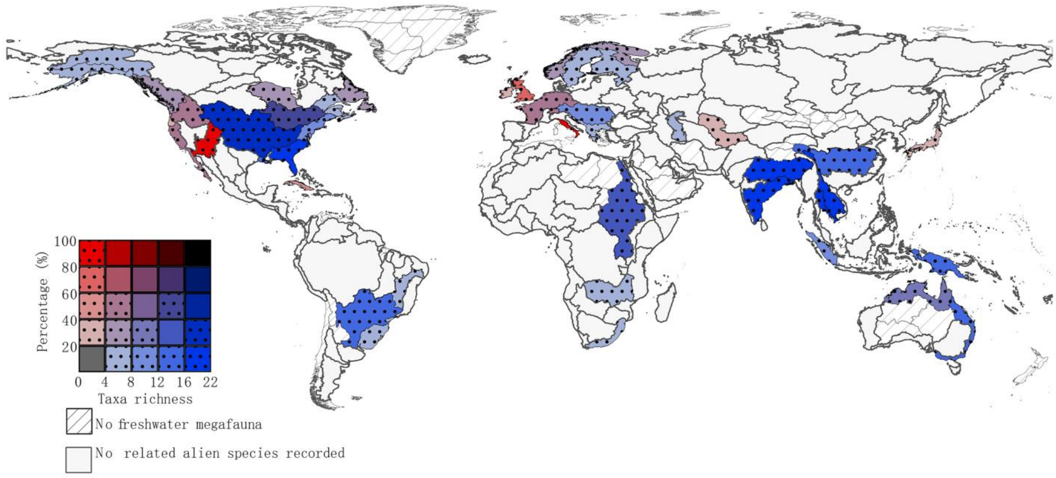

Fig. 2.1 Taxa richness of native freshwater megafauna and percentage of impacted native freshwater megafauna in each HydroBASINS level-3 catchment. Alien species that posed impacts on native freshwater megafauna were recorded from catchments shown with black dots.

Negative impacts on native freshwater megafauna were reported in 45 level-3 HydroBASINS (Fig. 2.1) and affected 44 species (28 fishes, 11 reptiles, four mammals and one amphibian; Table S2.1). A quarter of these species were threatened (listed as Vulnerable, Endangered, or Critically Endangered on the IUCN Red List). The Great Lakes Basin had the highest number of affected freshwater megafauna (six species), followed by the Mississippi Basin (five) and the western European coastal region (four). Some freshwater megafauna-rich basins, such as the Mekong and Ganges-Brahmaputra basins, had few affected freshwater megafauna species and no reported impacts were identified in others, including the Amazon, Orinoco and Congo basins.

Twenty-three alien species (i.e., 38% of the 61 alien species that negatively affected native freshwater megafauna) were native to North America. Of these, 12 were introduced to other areas in North America that were outside of their native ranges (e.g., smallmouth bass, *Micropterus dolomieu*; alewife, *Alosa pseudoharengus*). The other 11 species were introduced to other continents (Fig. S2.1). Over a quarter of all identified alien species (16 species) were native to more than one continent; eight species were introduced to more than one continent. None of the identified alien species that affected freshwater megafauna were native to Oceania.

2.4.2 Taxonomic distribution

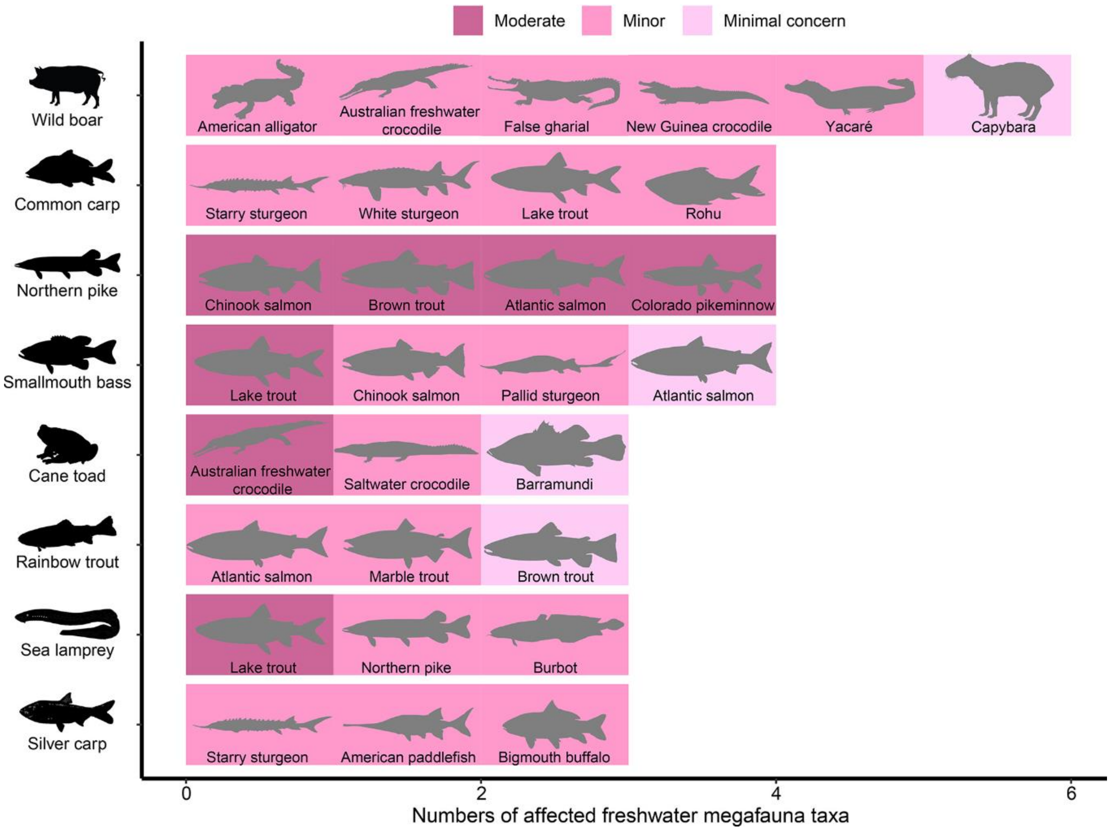

Fig. 2.2 Alien species that affected at least three native freshwater megafauna taxa categorised by the severity of impacts caused.

Among the 61 alien species that posed a negative impact on native freshwater megafauna, 36 (59%) were fish. Negative impact reports were found for other taxonomic groups, including mammals (five reports), crustaceans and plants (four each), reptiles (three) and amphibians, molluscs and worms (two each). Eight alien species caused negative impacts on three or more native freshwater megafauna species (Fig. 2.2). Three of these alien species were also freshwater megafauna species (common carp, *Cyprinus carpio*; northern pike, *Esox lucius*; and silver carp, *Hypophthalmichthys molitrix*). The alien species affecting the highest number of native megafauna species (six) was a terrestrial mammal, the wild boar.

2.4.3 Impact mechanisms and severity

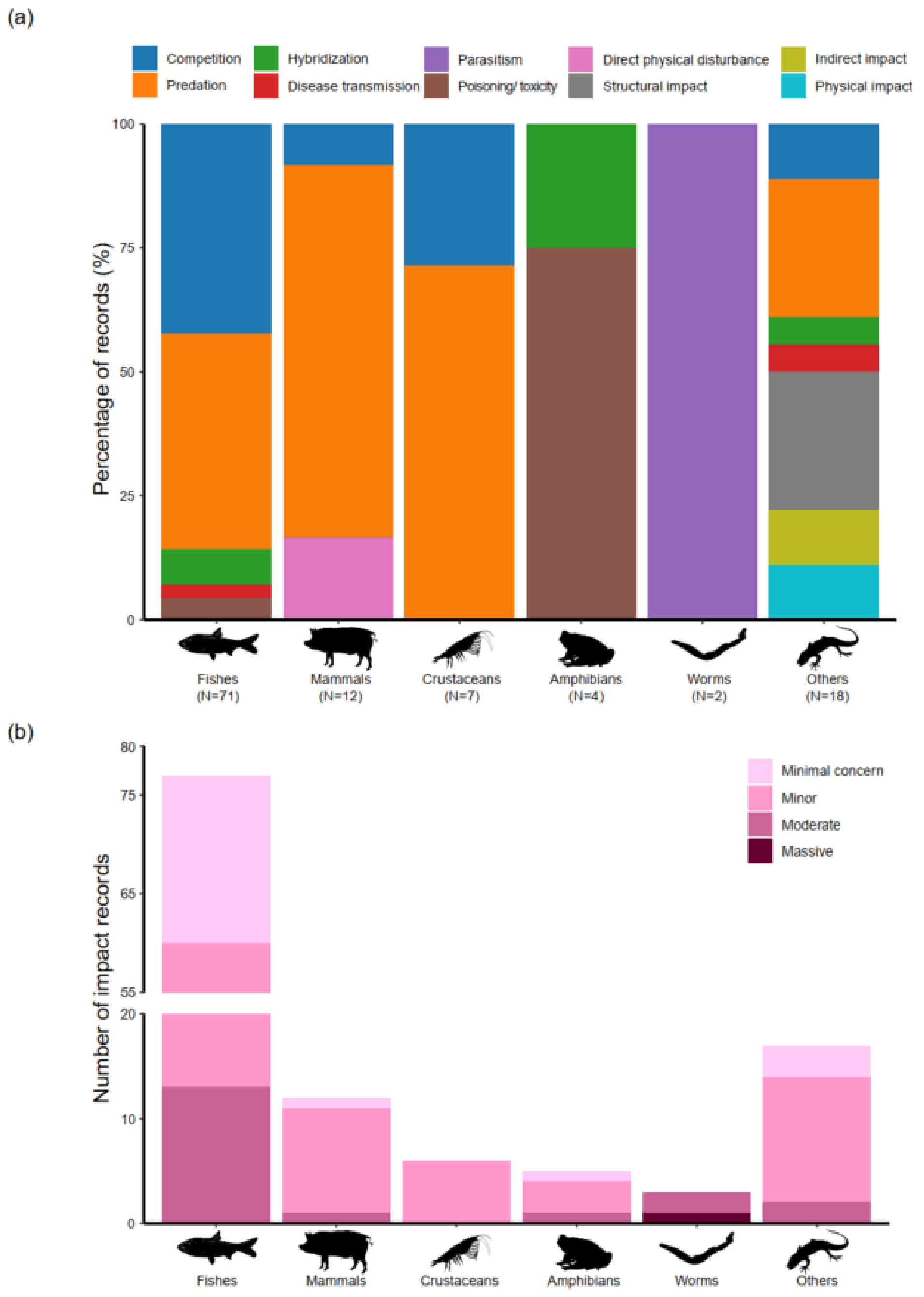

Fig. 2.3 (a) Percentage of alien species as categorised by the mechanism of their impacts on native freshwater megafauna and (b) number of impact records of alien species group, categorised by impact severity.

In total, 257 impact records with sufficient information to identify the severity and mechanism of impact were extracted from 209 reports. Competition and predation were the most widely reported impact mechanisms (Fig. S2.2), being associated with 44% and 31% of all impact records, respectively. Groups of alien species tended to affect native freshwater megafauna through different types of impact mechanisms (Fig. 2.3a). Predation was the most common impact caused by alien mammals (75%), crustaceans (72%) and fish (44%), whilst poisoning/toxicity dominated for alien amphibians (75%) due to the extensive impacts of the cane toad (*Rhinella marina*) in Australia where poisoning/toxicity was the most frequently reported impact mechanism. Parasitism was the most common impact caused by alien worms.

We identified 58 records of interactions between alien species and native freshwater megafauna where the impact mechanism or magnitude could not be identified due to inadequate information. This resulted in 15 alien species being categorised as DD under EICAT (e.g., water hyacinth, *Pontederia crassipes*). These impact records involved 21 native freshwater megafauna species. Five of these species, including hippopotamus and beluga (*Huso huso*), were completely DD under EICAT (i.e., the severity and mechanism of impact on these freshwater megafauna species could not be established).

Among those records with sufficient information to evaluate the impact magnitude, 83% were MC or MN (Fig. 2.3b). A further 16% were MO, causing declining populations of 14 native freshwater megafauna species. MR impacts were identified (i.e., reversible local population extinctions), but one MV impact was identified (i.e., gill fluke contributing to the irreversible local extinction of ship sturgeon [*Acipenser nudiventris*] in the Aral Sea). Northern pike had harmful impacts on the highest number of native freshwater megafauna species (four). We found no significant differences in the severity of impacts that were sustained by different taxonomic groups of native freshwater megafauna species (Table S2.2) or associated with different impact mechanisms (Table S2.3).

2.4.4 Life-cycle stage

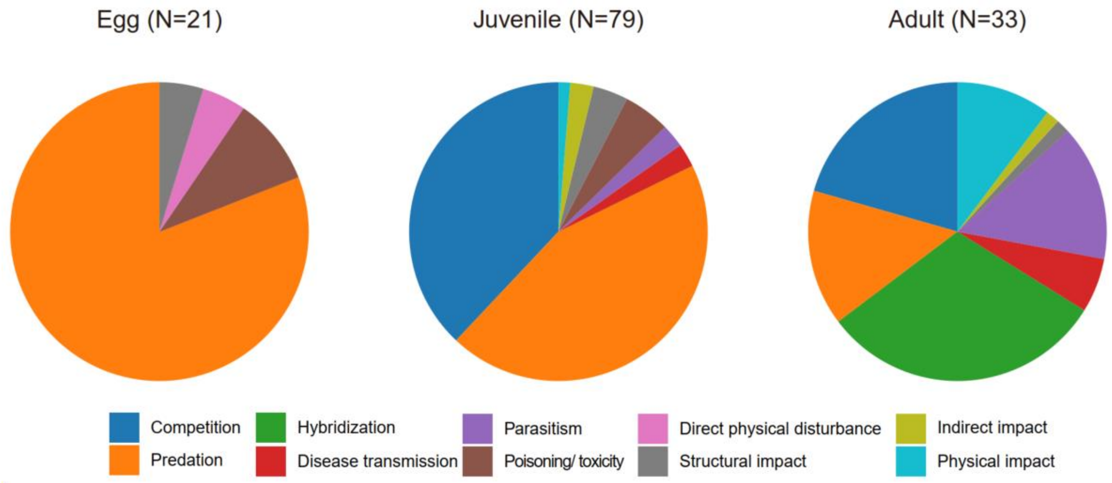

Fig. 2.4 Percentage of native species impact records as categorised by impact mechanisms and life-cycle stages.

Impacts were caused through four mechanisms during the egg stage and through eight during the juvenile and adult stages (Fig. 2.4). Impacts were caused through two mechanisms (i.e., predation and structural impact on ecosystem) during all three life-cycle stages. Impacts caused by direct physical disturbance only occurred during the egg stage. Predation impacts accounted for 81% of all records for the egg stage; 30% for the juvenile stage and 15% for the adult stage. A decline in the proportion of all records that were associated with competition was observed from the juvenile stage (38%) to adult stage (24%). Impact mechanisms and severity were nonrandomly distributed across life-cycle stage (Tables 2.1 and 2.2). In particular, there were more records describing competition between alien species and juvenile freshwater megafauna than would be expected by chance and fewer records of predation on adult freshwater megafauna than would be expected by chance. In addition, there were fewer records of damaging impacts during the egg stage and more during the adult stage than would be expected by chance.

Table 2.1 Contingency table (chi-squared test) showing the actual and expected number of impacts associated with each impact mechanism for juvenile and adult stages [a, b].

	Competition	Predation	Hybridisation	Poisoning/toxicity	Others	Total
Juvenile	30	35	0	4	10	79
	27.29	*30.16*	*5.75*	4.31	11.49	
	(0.27)	(0.78)	(5.75)	(0.02)	(0.20)	
Adult	8	7	8	2	6	31
	10.71	*11.84*	*2.25*	*1.69*	*4.51*	
	(0.69)	(1.98)	(14.64)	(0.06)	(0.50)	
Total	38	42	8	6	16	110

[a] $\chi^2 = 24.86$, df=4, P <0.01, estimates = 0.23.

[b] Expected values are displayed in italics. Individual χ^2 values are displayed in parentheses. Due to small sample sizes, "Transmission of diseases to native species", "Direct physical disturbance", "Structural impact on ecosystem" and "Indirect impacts through interactions with other species" were combined as "Others".

Table 2.2 Contingency table (chi-squared test) showing the actual and expected number of less severe and harmful impacts for each life-cycle stage [a, b].

	Egg	Juvenile	Adult	Total
Less severe impacts (Minimal Concern and Minor)	21	63	22	106
	17.39	*61.28*	*27.33*	
	(0.75)	(0.05)	(1.04)	
Harmful impacts (Moderate, Major and Massive)	0	11	11	22
	3.61	*12.72*	*5.67*	
	(3.61)	(0.23)	(5.01)	
Total	21	74	33	128

[a] $\chi 2 = 7.31$, df=2, P = 0.02, estimates = 0.19.

[b] Expected values are displayed in italics. Individual χ^2 values are displayed in parentheses.

2.5 Discussion

Alien species are found in most major river basins worldwide and their impacts on native freshwater megafauna species have been recorded across many regions of the world. However, we observed major data gaps in many regions. As economic development influences the availability of impact data on alien species, fewer data tend to be available in developing countries (Bellard & Jeschke, 2016; Evans et al., 2018; Evans & Blackburn, 2020; Pyšek et al., 2008). It is therefore possible that the impacts of alien species on freshwater megafauna are going unnoticed in the Global South. We also acknowledge that as we carried out our literature review using search terms in English, we might not have found all available information published in other languages (Nuñez & Amano, 2021).

Most impacts sustained by native freshwater megafauna are caused by alien fish. This is likely to be because most of the native freshwater megafauna species sustained impacts are also fish species. Nevertheless, native freshwater megafauna species are also affected by alien species from other taxonomic groups, including species that are predominantly terrestrial. Indeed, alien species with impacts on three or more native freshwater megafauna species include amphibians (cane toad) and mammals (wild boar). Other alien species with impacts include flatworms (gill fluke), crustaceans (rusty crayfish, *Faxonius rusticus*), crocodilians (spectacled caiman, *Caiman crocodilus*), comb jellies (sea walnut, *Mnemiopsis leidyi*) and flowering shrubs (Siam weed, *Chromolaena odorata*). This diverse range of alien species is one of the reasons for native freshwater megafauna being affected by 10 different impact mechanisms.

Alien species causing impacts on native freshwater megafauna tend to be relatively large. As the most frequently recorded impact mechanisms are predation and competition (i.e., accounting for 75% of all identified records), this may be because their size enables them to prey on and compete with, other megafauna species (Cucherousset et al., 2012; Eby et al., 2006). In Cuba, the spectacled caiman competes with two native crocodile species (American crocodile, *Crocodylus acutus* and Cuban crocodile, *Crocodylus rhombifer*) and preys on juvenile Cuban crocodiles (Targarona et al., 2010). Hybridisation with alien species also affects native freshwater megafauna and some of these alien species are also large, being freshwater megafauna themselves. For example, the introduction of the brown trout (*Salmo trutta*) to Slovenia led to a decline in the population of the native marble trout (*Salmo marmoratus*) due to genetic introgression (Fumagalli et al., 2002). Hybridisation between the alien Chinese giant salamander (*Andrias davidianus*) and the native Japanese giant salamander (*Andrias japonicus*) has also been widely observed in Japan (Fukumoto et al., 2015).

Nevertheless, some small alien species can affect native freshwater megafauna, but generally through different impact mechanisms. For example, native species are susceptible to the impacts of small alien parasites with which they have no coevolutionary history (sensu Saul & Jeschke, 2015). The introduction of the stellate sturgeon (*Acipenser stellatus*) to the Aral Sea also resulted in the unknown, accidental introduction of gill flukes (as a parasite of the stellate sturgeon). Gill flukes were observed in native ship sturgeons, reaching a density of 100–300 or sometimes even up to 600 individuals per ship sturgeon. About 150–200 mL of fish blood would be consumed by 300–400 gill fluke individuals per day (Bauer et al., 2002). Combined with overexploitation, dam construction and increased salinity, this caused the local extinction of ship sturgeon in the Aral Sea (Gesner et al., 2010; Zholdasova, 1997).

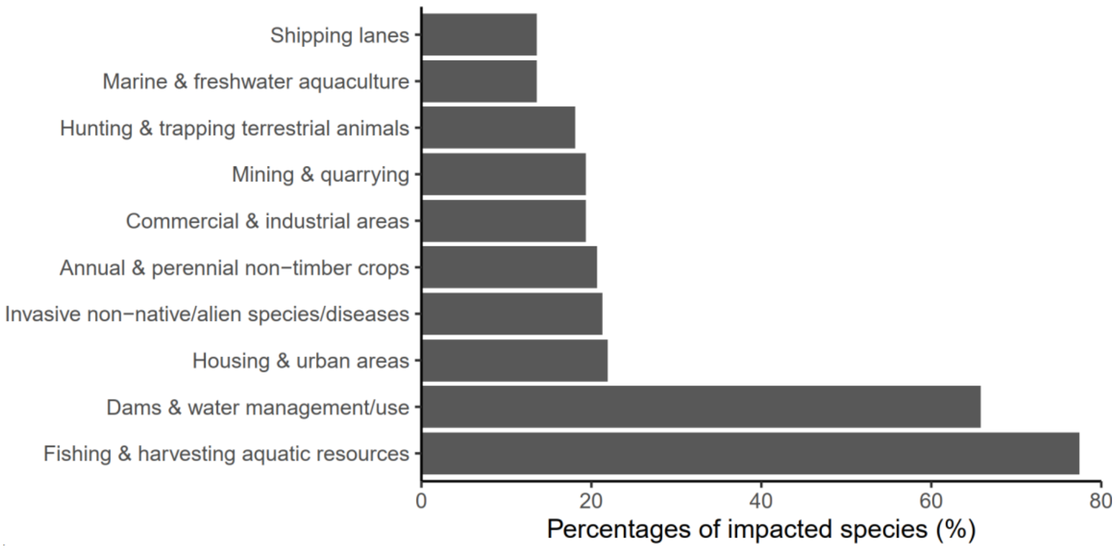

Fig. 2.5 The 10 main threats to global freshwater megafauna according to IUCN Red List

assessments (n = 155 freshwater megafauna species that have detailed information on threat categories in their assessment reports; IUCN, 2022).

Indeed, freshwater megafauna species are subject to a broad range of threats (Fig. 2.5) and we found several examples of alien species impacts combining with some of these threats. For example, predation by the sea lamprey has caused a decline in the population of the lake trout (*Salvelinus namaycush*) in the Great Lakes, but overfishing has also contributed to this decline (Smith & Tibbles, 1980). It is difficult to determine the significance of alien species impacts in these cases and some threats, such as overexploitation and habitat loss and degradation, may have stronger negative impacts on freshwater megafauna than alien species (He et al., 2017). Threats such as dam construction and climate change (Albert et al., 2021; Reid et al., 2019; Xi et al., 2021) may facilitate the establishment and spread of alien species (Johnson et al., 2008; Rahel & Olden, 2008). Extreme weather events associated with climate change may increase the chance that alien species in captive environments escape to the wild. For example, approximately 10,000 tonnes of five alien sturgeon species escaped from aquaculture farms into the Yangtze River due to an extreme flooding event (Gao et al., 2017). These alien sturgeon species may be competing with the native Chinese sturgeon (Acipenser sinensis), which is critically endangered (Ju et al., 2019).

Impacts on native freshwater megafauna tend to be relatively weak, with only a few studies reporting impacts causing declining populations. However, the true severity of many impacts may be underestimated due to a lack of long-term monitoring (Pergl et al., 2020). Many studies on predation determined that an alien species preyed on a native freshwater megafauna species (i.e., an MN impact) but did not extend this research to determine whether this predation caused a declining population of the native species (i.e., an MO impact). This may be because documenting population-level changes in natural habitats requires considerably more time and effort than studying individual-level responses. However, where long-term monitoring data does exist, reductions in native freshwater megafauna populations have been documented. From 1987 to 1995, the impacts of the northern pike were studied after its introduction to Lake Skjeltjønna, Norway, revealing a decline in the native brown trout population across all age groups due to pike predation (Hesthagen et al., 2015). Monitoring of the population dynamics of Australian freshwater crocodiles from 1978 to 2013 revealed that the cane toad invasion reduced their population by approximately 70% on the Daly River, Australia (an MO impact; Fukuda et al., 2016). A related study that only considered the diet contents of dead Australian freshwater crocodiles identified impacts to the individual level (an MN impact; Doody et al., 2009).

Impact severity may have also been underestimated because many studies we identified were carried out under laboratory conditions. Given their large body size, long lifespan and large habitat requirements, it is challenging to observe impacts on freshwater megafauna throughout their entire life cycle under laboratory conditions. Indeed, many experiments were solely concerned with impacts on individual native species rather than populations. Furthermore, under EICAT, impacts identified through experiments can be classified as no more severe than MN (Volery et al., 2020). Whether the MN impacts identified in these studies actually have more severe consequences for native freshwater megafauna in the wild remains unknown.

We identified a tendency for impacts to be more damaging during the adult stage and less damaging during the egg stage (i.e., no population-level impacts were identified at the egg stage). We feel that this may be due to a lack of long-term studies undertaken on impacts during the egg stage and we do not place much emphasis on this result. Indeed, this seems plausible, as the large size of both juvenile and adult freshwater megafauna means that they are less susceptible to predation than they are during the egg stage. For example, juvenile lake sturgeons (*Acipenser fulvescens*) show a strong anti-predator response when exposed to the alien rusty crayfish, but nonetheless, their eggs are vulnerable to predation (Crossman et al., 2018). Red fire ants (*Solenopsis invicta*) introduced from South America to Florida prey on the eggs of American alligators (*Alligator mississippiensis*), causing reduced hatching success (Allen et al., 1997; Reagan et al., 2000), but negative impacts caused by red fire ants on juvenile or adult American alligators have not been recorded. Thus, the maximum recorded EICAT impact sustained by a native freshwater megafauna species may vary over its life span.

Taking into account life-cycle stage when undertaking EICAT assessments may provide important insights that inform measures to protect native freshwater megafauna species. For example, the predation risk posed by largemouth bass (*Micropterus salmoides*) on green sturgeon (*Acipenser medirostris*) decreases as the size of the sturgeon increases and is negligible once the sturgeon is 20 cm long (Baird et al., 2020).

During our assessments, we noticed that some impacts did not fit within any of the established EICAT mechanisms. For example, alewife contain thiaminase which can cause thiamine deficiency in the eggs of native fish that feed on it. This has increased mortality in Atlantic salmon and lake trout fry (Fitzsimons et al., 1995; Ketola et al., 2000; Ladago et al., 2020). There is no suitable mechanism for this impact, which we eventually assigned to poisoning/toxicity even though the mechanism does not accurately reflect the impact. It is worth noting that the interactions between alien species and other threats also represent emerging stressors to freshwater megafauna, which might not be captured by the current EICAT framework. For example, consumption of alien Mozambique tilapias (*Oreochromis mossambicus*) contaminated with toxins associated with severe pollution caused the death of over 100 gharials (*Gavialis gangeticus*) in the Chambal and Yamuna rivers in India (Stevenson, 2015). Although we assigned this impact to the poisoning/toxicity mechanism, it does not really fit, as the tilapias do not normally contain toxins. To account for this, we suggest that the indirect impacts through interaction with other species mechanism could be amended to also include interactions with other factors (i.e., indirect impacts through interactions with other species or other factors).

Our study highlights the vulnerability of native freshwater megafauna to the impacts of alien species, which have caused population declines of 14 freshwater megafauna species and contributed to the local extinction of one species (the ship sturgeon in the Aral Sea). We show that native freshwater megafauna species are vulnerable to impacts from a broad range of alien species and through many different impact mechanisms. Indeed, we observed clear differences in main impact mechanisms associated with the different life-cycle stages of freshwater megafauna (egg, juvenile and adult). On the one hand, we observed that documented impacts of alien species on native freshwater megafauna tend to be relatively weak. On the other hand, the more severe (population-level) impacts sustained by native freshwater megafauna may be going unnoticed because of the short-term nature of many impact studies and also because of a lack of research being undertaken in the Global South, including megafauna-rich basins such as the Amazon, Congo, Mekong and Ganges-Brahmaputra. We call for long-term monitoring studies to more accurately assess the severity of the impacts sustained by native freshwater megafauna species and for studies in data-deficient regions where the impacts of alien species on freshwater megafauna species are likely to be going unnoticed. Finally, we found several alien freshwater megafauna species (e.g., Asian carps, northern pike, brown trout) to have negative impacts on native freshwater megafauna. To the best of our knowledge, a synthesis of the impacts of alien freshwater megafauna within freshwater ecosystems is missing and yet they are likely to have adverse impacts because introduced large freshwater animals can profoundly influence local trophic dynamics (Cucherousset et al., 2012; Eby et al., 2006). Indeed, given that freshwater megafauna are often ecosystem engineers or top predators and that many freshwater megafauna species have been introduced to regions outside of their native ranges, future research focusing on the impacts of alien freshwater megafauna is warranted.

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3. Global introductions and environmental impacts of freshwater megafish

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3.1 Abstract

Freshwater megafish species, such as sturgeons, salmonids, carps and catfishes, have a maximum reported weight ≥ 30 kg. Due to their charisma and economic value, they have been widely introduced to freshwater ecosystems outside of their native ranges. Here, we provide a comprehensive overview of the introduction of freshwater megafish and an assessment of their environmental impacts. Almost half of the 134 extant freshwater megafish species have been introduced to new freshwater ecosystems and almost 70% of the introduced species have established self-sustaining alien populations. They have been introduced to 172 level-3 HydroBASINS worldwide (59% of all basins globally). The U.S. and western Europe are hotspots of freshwater megafish introductions. Using the Environmental Impact Classification for Alien Taxa (EICAT and EICAT+) frameworks, we assessed the severity and type of negative and positive impacts posed by alien megafish on native species. They caused negative impacts through nine different mechanisms. Predation was the most frequently reported impact mechanism associated with 1190 negative impact records identified, followed by herbivory and competition. More than half of the alien megafish species with sufficient data to evaluate the severity of their impacts caused declining populations of native species, or worse, extirpations of native species populations. The positive environmental impacts of alien megafish were far less frequently documented (31 records). They included, for example, the provision of trophic resources. There is a clear tradeoff between the economic benefits associated with the megafish introduction, many of which are deliberate and the severe adverse impacts they have on native biodiversity. Our study highlights the urgent need for enhanced biosecurity protocols to reduce future introductions and release to natural waterbodies. Data on impacts is scarce in many regions, but particularly the Global South, where more research is required to inform management actions to protect biodiversity.

Keywords: alien species; biological invasions; EICAT; EICAT+; impact assessment; invasive species; IUCN; megafauna; non-native fish

3.2 Introduction

Species that have been intentionally or unintentionally introduced by human activities to regions outside of their native ranges are termed alien species (Essl et al., 2018). Since the 19th century, the number of established alien species has increased rapidly worldwide, with more than one-third of all recorded alien species having been successfully established between 1970 and 2014 (Pyšek et al., 2020; Seebens et al., 2017). Alien species profoundly influence recipient ecosystems in many ways (e.g., by modifying habitats, preying on or competing with native species and altering food webs). These impacts affect the long-term survival of native species, increasing their risk of extinction (David et al., 2017; Ehrenfeld, 2010; Gallardo et al., 2016). Indeed, alien species are one of the main drivers of global biodiversity loss (Essl et al., 2020; Jaureguiberry et al., 2022; IPBES et al., 2023), having contributed to approximately one-third of all animal extinctions and a quarter of all plant extinctions since 1500 (Blackburn et al., 2019).

Alien species are now widespread in freshwater ecosystems, where they are considered to threaten approximately 4000 native freshwater species (IUCN, 2022). Fishes are one of the most widely introduced groups – pathways for their introduction include deliberate stocking for aquaculture and recreational fishing, the deliberate release of individuals kept as pets or for ornamental purposes and species inadvertently released within the ballast water of container ships (Rahel, 2007; Strayer, 2010). Globally, more than 550 alien freshwater fish species have established populations outside of their native basins (Bernery et al., 2022). The natural hydrological connectivity of freshwaters and artificial waterways facilitates their spread within introduced regions (Francis & Chadwick, 2011; Moorhouse & Macdonald, 2015).

Freshwater megafish have a maximum reported body mass ≥ 30 kg and spend a critical part of their life cycle in freshwater or brackish ecosystems (He et al., 2017). Many megafish species have been intentionally introduced to all continents except Antarctica (Bernery et al., 2022). Common carp (*Cyprinus carpio*), brown trout (*Salmo trutta*), African catfish (*Clarias gariepinus*), grass carp (*Ctenopharyngodon idella*) and silver carp (*Hypophthalmichthys* *molitrix*) are among the most widely established alien megafish species (Bernery et al., 2022). Their widespread introduction is mainly attributed to their charisma and economic value (Jarić et al., 2020). For example, arapaima (*Arapaima gigas*) is a commonly traded ornamental fish in Europe, North America and Asia (Magalhães et al., 2017; Marková et al., 2020), whilst various sturgeons (*Acipenser* spp.) are farmed for caviar (Brevé et al., 2022; Kang et al., 2023). Other megafish species have been introduced as biological control agents, for example, to suppress the excessive growth of algae (silver carp and bighead carp; *Hypophthalmichthys nobilis*) (Pal et al., 2020) and aquatic vegetation (grass carp) (Dibble & Kovalenko, 2009).

Alien freshwater megafish are known to severely affect native biodiversity. For example, predation by Nile perch (*Lates niloticus*) introduced to Lake Victoria (East Africa) led to the extirpation of numerous haplochromine cichlid species (Witte et al., 1992), whilst competition from lake trout (*Salvelinus namaycush*) introduced to Bow Lake (Canada) resulted in the extirpation of bull trout (*Salvelinus confluentus*) (Donald & Alger, 1993). However, despite their widespread distribution as alien species and the severity of some of their reported impacts on native biodiversity, as far as we are aware, a global investigation of the introduction of megafish and an assessment of their impacts as alien species has yet to be conducted.

In this study, we aimed to address four research questions: (1) Which freshwater megafish species have been introduced outside of their native ranges and which have established alien populations? (2) How do alien freshwater megafish interact with native species and to what extent do they affect native species, either positively or negatively? (3) Which freshwater megafish species have the potential to pose severe impacts on native species if introduced to a new basin? (4) What factors are associated with severe impacts of alien freshwater megafish?

3.3 Materials and Methods

3.3.1 Literature review

A list of freshwater megafish species was compiled based on the 30 kg threshold used to define freshwater megafauna species (Carrizo et al., 2017; He et al., 2017, 2018). The list includes 134 fish species that spend an essential part of their life cycle in freshwater or brackish ecosystems. To address our first research question, we conducted a literature search to identify information on freshwater megafish introductions. For each species, we identified records of introductions as aliens by reviewing published IUCN Red List assessments for freshwater megafish species and searching other databases, including CABI's Invasive Species Compendium (www.cabi.org/isc), the Global Invasive Species Database (GISD) of the Invasive Species Specialist Group (ISSG) (www.iucngisd.org/gisd), USGS's Nonindigenous Aquatic Species (www.nas.er.usgs.gov), FishBase (www.fishbase.org) and the Global Biodiversity Information Facility (GBIF) (www.gibf.org). We then searched online databases (Web of Science and Google Scholar) for information on introductions and impacts, combining search terms for alien species with each species' scientific and common name(s). For example, the search term for the Wels catfish was: ("invasive" OR "alien" OR "non-indigenous" OR "non-native" OR "introduced" OR "exotic") AND ("Wels catfish" OR "*Silurus glanis*"). Titles and abstracts of articles identified were screened for relevance; relevant articles were reviewed for introduction and impact data. We reviewed the references in these articles to identify any additional articles.

For each record, we collated data on the taxonomy of the introduced megafish, introduction location, introduction pathway, time of first observation, establishment status (established, not established, or unknown) and impact on native species. We used HydroBASINS as a spatial template to map the distribution of each alien freshwater megafish. The HydroBASINS dataset depicts subbasin boundaries based on topographic location and hydrological connections and provides 12 levels of hierarchically nested sub-basins at the global scale (Lehner & Grill, 2013). We used level-3 HydroBASINS, which often represent watersheds of large rivers, such as the Amazon, Congo, Ganges-Brahmaputra, Mekong, Mississippi, Nile and Yangtze, as spatial units. The spatial resolution of introduced locations varied among different sources. We compared the introduced locations of each freshwater megafish species with their native ranges (He et al., 2018) and assigned each record to a level-3 HydroBASIN. We excluded records in which information on introduced locations was insufficient to determine the level-3 HydroBASIN (e.g., only the names of introduced countries were described). We adapted the approach proposed by Harrower (2018), grouping introduction pathways of alien megafish into six categories (Table S3.1): commercial fishery (e.g., aquaculture, fishery in the wild), aquarium (e.g., pet and ornament), biological control, recreational fishing, research and waterways (e.g., introduced via canals).

3.3.2 EICAT and EICAT+ assessments

The IUCN Environmental Impact Classification for Alien Taxa (EICAT) and the EICAT+ framework have been developed to assess the negative and positive environmental impacts of alien species on native species, respectively (Blackburn et al., 2014; IUCN, 2020a, 2020b; Vimercati et al., 2022). To address our second research question, we used EICAT and EICAT+ to assess the environmental impacts of alien freshwater megafish in their introduced basins. We categorised impact records by their type into one of 12 EICAT impact mechanisms: competition, predation, hybridisation, transmission of disease (hereafter disease transmission), parasitism, poisoning/toxicity, bio-fouling or other direct physical disturbance (hereafter direct physical disturbance), grazing/herbivory/browsing (hereafter herbivory), chemical impact on ecosystem, physical impact on ecosystem, structural impact on ecosystem and indirect impact through interaction with other species (hereafter interaction with other species). We then quantified the severity of each impact record by assigning them to one of five EICAT impact categories: Minimal Concern (MC) if the impacts of alien freshwater megafish were negligible; Minor (MN) if they reduced the performance of individuals of at least one native species; Moderate (MO) if they led to declines in populations of native species; Major (MR) if they caused local extinctions of at least one native species, but this could be reversed if the alien species was removed; or Massive (MV) if they resulted in the global extinction of a native species, or the local extinction of a native species which could not be reversed even the alien species were removed. For some records, information was only sufficient to determine either the impact mechanism or impact category; records with undetermined impact mechanisms or categories were classified as Data Deficient (DD). Using the EICAT guidance documentation, each assessment was assigned a confidence level (low, medium, or high) to indicate the probability of the assessment being correct (IUCN, 2020a, 2020b; Volery et al., 2020). Confidence levels were allocated by considering factors such as the quality of the impact data and the presence of confounding effects.

In a similar manner to the EICAT assessments, we allocated each positive impact record to one of 10 EICAT+ impact mechanisms: provision of trophic resources, overcompensation, hybridisation, disease reduction, dispersal facilitation, epibiosis or other direct provisions of habitat, chemical impact on ecosystem, physical impact on ecosystem, structural impact on ecosystem, indirect impacts through interaction with other taxa. EICAT+ includes sub-mechanisms; impacts were assigned to them where relevant. The magnitude of an impact was quantified using one of five EICAT+ impact categories: Minimal positive impact (ML+) if the alien freshwater megafish had a positive influence on native species, but this did not increase the individual performance of native species; Minor positive impact (MN+) if it enhanced the individual performance of native species; Moderate positive impact (MO+) if it led to an increased population size of native species; Major positive impact (MR+) if it facilitated a temporary increase in species occupancy (or prevented temporary declines) through local or subpopulation reestablishment (or extinction prevention); Massive positive impact (MV+) if it led to long-term increases in species occupancy (or stopped long-term losses) through local or subpopulation reestablishment (or extinction prevention). Data Deficient (DD) records and confidence levels were assigned as for EICAT. All assessments were completed by the first author; 20% were randomly selected and reviewed by coauthors. Any inconsistent assessments were revisited to establish assessor consensus. In addition, all MO, MR and MV assessments were reviewed by coauthors.

3.3.3 Ranking alien freshwater megafish by the severity of their environmental impacts

Assessments using the EICAT and EICAT+ frameworks tend to assess the environmental impacts of an alien species based on its most severe reported impact. However, this may not provide a complete understanding of the potential impacts associated with a species (Volery et al., 2021). For example, the most severe impact of two alien species may be Moderate (MO) under EICAT, but one may have caused population declines of several native species at several locations, whilst the other may have only caused the population decline of one native species at a specific location. In such cases, it is reasonable to assume that the former alien species poses a higher risk to native species if introduced to a new basin. To answer our third research question, we followed Volery et al. (2021) to consider variations in the severity of the reported impacts of an alien freshwater megafish in order to estimate its potential threat when introduced to new freshwater ecosystems.

We estimated the potential risk of each species causing their most severe impact after introduction to a new basin to address our third research question. We calculated Bayesian binomial 95% confidence intervals and highest probability density means using *binom.bayes* function in the "binom" package (Dorai-Raj, 2014) in R (R Core Team, 2021) according to the frequency of alien freshwater megafish causing their most severe impact. The first and second shape parameters were set as 1 (i.e., a flat beta prior distribution). We used two approaches to calculate the frequency of the most severe impact for each species. First, we used the frequency of the most severe impact records regardless of the basins where these records were documented. Second, we used the frequency of basins within which the most severe impact records were reported to reduce potential bias associated with sampling effort (Volery et al., 2021), as the most severe impact of a species in a well-investigated basin could be reported in several studies. The range in confidence intervals was directly associated with the number of observations, meaning that species with limited observations (few impact records or few introduced basins with impact records) had wide confidence intervals. We only ranked alien freshwater megafish based on their negative environmental impacts because we did not have enough EICAT+ impact records to repeat this process for positive impacts.

3.3.4 Identifying factors associated with severe impacts

To address our fourth research question (whether documented severe impacts were associated with certain factors), we examined the relationships between impact severity and several variables applicable to each alien species, including impact mechanism, taxonomy, alien distribution (presence in number of basins) and number of impact records. Due to low numbers of impact records in certain impact severity categories, we divided impact records into two groups: 'harmful' impacts (MO, MR and MV) and 'less harmful' impacts (MC and MN).

Following Volery et al. (2021), we categorised four impact mechanisms as direct impacts (predation, herbivory, hybridisation and direct physical disturbance) and five as indirect (competition, disease transmission, physical impact on ecosystem, structural impact on ecosystem and interaction with other species). As predation, herbivory and physical disturbance are more likely to cause direct mortality of native species, we expected direct impacts would cause more harmful impacts. To test this hypothesis, we ran a generalised linear mixed-effects model (GLMM) using the "lme4" package (Bates et al., 2015). Impact severity (harmful/less harmful) was used as the response variable and we assumed that it followed a binomial distribution. Impact mechanism (direct/indirect) was used as the fixed predictor, with the continent of observation included as a random factor to control for spatial autocorrelation. In addition, we performed unconditional exact tests with the "FunChisq" package (Zhong & Song, 2019) to compare the distribution of impact severity across impact mechanisms and across families of alien freshwater megafish.

We expected to find that harmful impacts would be more frequently reported for widely distributed alien species (those present in many basins) and those that were more intensively researched (those with more impact records). To test this hypothesis, we calculated the number of level-3 HydroBASINS with established populations for each species and the number of impact records for each species and each basin. We then ran a binomial general linear model (GLM) with impact severity (harmful/less harmful) as the response variable and the numbers of level-3 HydroBASINS and impact records as the explanatory variables. We also used linear regression to test whether the number of impact records for a species increased with increasing distribution (measured as the number of level-3 HydroBASINS in which the species had established populations). Furthermore, we used a GLMM to test whether the number of impact records increased with the number of established megafish species in each level-3 HydroBASIN, with continents included as a random effect.

3.4 Results

3.4.1 Global introductions of alien freshwater megafish

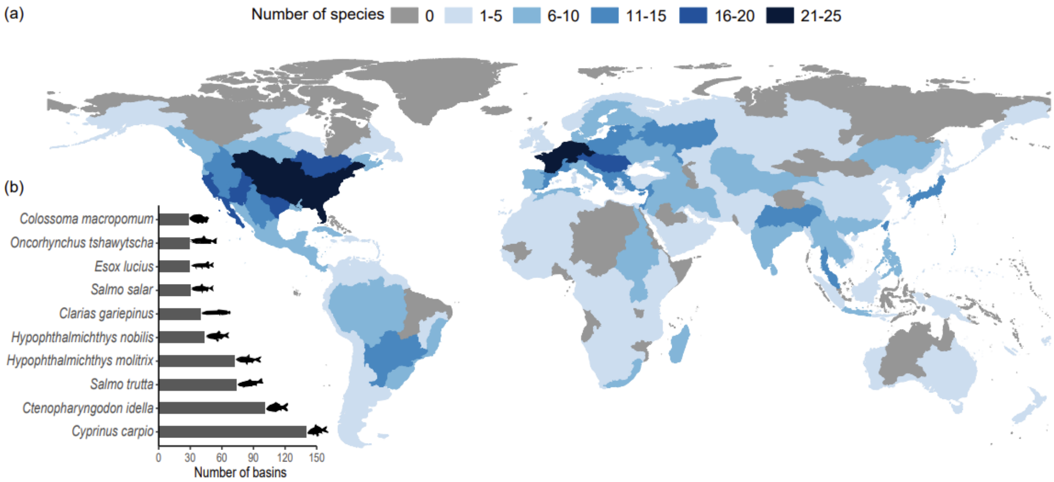

Fig. 3.1 (a) Numbers of alien freshwater megafish species introduced to each level-3 HydroBASIN and (b) the 10 most widely introduced alien megafish species.

Freshwater megafish species have been introduced to every continent except Antarctica, affecting 172 level-3 HydroBASINS (59% of all basins globally, hereafter termed basins; Fig. 3.1a). Regions with the highest number of introduced alien megafish species include the Mississippi Basin and the Florida Peninsula (n = 25), the east coast of the U.S. (24) and the west coast of Europe (22). Almost half of extant freshwater megafish species (46%) have been introduced (62 species from 15 orders and 26 families). The common carp has the highest number of introduced basins (140; 81% of all introduced basins) (Fig. 3.1b). In addition, Asian carp species, such as grass carp, silver carp and bighead carp, have been extensively introduced (101, 72 and 43 basins, respectively). Several salmonid species, including brown trout, Atlantic salmon (*Salmo salar*) and Chinook salmon (*Oncorhynchus tshawytscha*), have also been widely introduced (> 20 basins each).

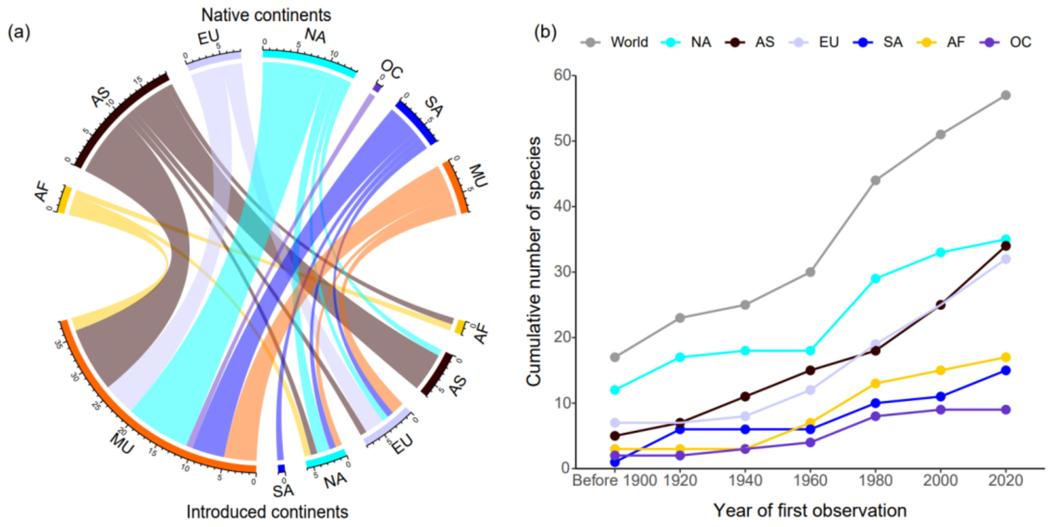

Fig. 3.2 (a) The number of megafish species transferred from native continents to introduced continents. The width of the bands represents the number of species transferred from native continents to introduced continents. **AF**, Africa; **AS**, Asia; **EU**, Europe; **NA**, North America; **OC**, Oceania; **SA**, South America; **MU**, multiple continents. (b) Cumulative numbers of introduced alien megafish species in each continent and globally (calculated using data on the year of the first observation of an introduced megafish species in a continent).

Almost one-third (31%) of introduced freshwater megafish species are native to Asia (19 species); 23% are native to North America (14 species; Fig. 3.2a). Freshwater megafish have been widely introduced both to new continents and to other basins within their native continents. Indeed, 21% of all introductions are to basins within the continent that the megafish species is native to. More than half of the identified alien megafish species (38) were introduced to multiple continents.

Introductions of freshwater megafish species occurred prior to the 20th century (Fig. 3.2b). For example, the common carp was introduced to the Rhine (Europe) during the 12th century and the brown trout to South Africa, Australia, New Zealand, Sri Lanka and the U.S. during the 19th century. However, the numbers of alien megafish species increased substantially after 1960, particularly in North America, Asia and Europe. Globally, no signal of a slowdown in megafish introductions was observed (Fig. 3.2b).

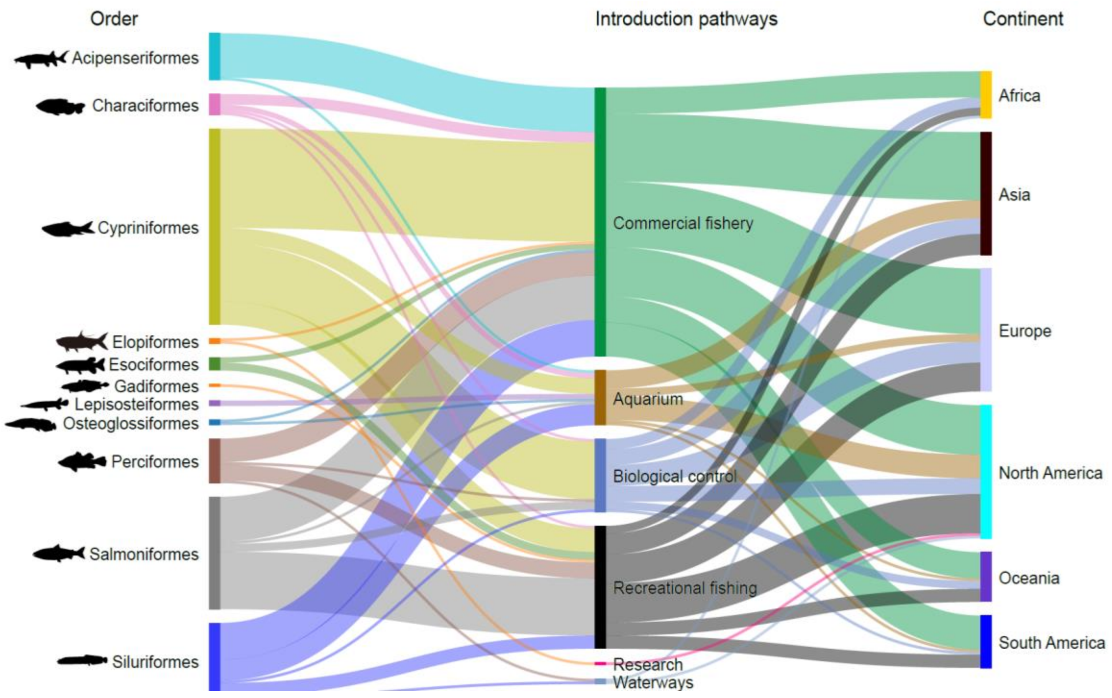

Fig. 3.3 Introduction pathways of alien freshwater megafish, categorised by order and continent. The width of the lines represents the number of species. Acipenseriformes: sturgeons; Characiformes: characins; Cypriniformes: carps and minnows; Elopiformes: tarpons; Esociformes: pikes; Gadiformes: cods; Lepisosteiformes: gars; Osteoglossiformes: bony tongues; Perciformes: perches; Salmoniformes: salmonids; Siluriformes: catfish.

Most introductions were intentional (Fig. 3.3); commercial fishery was the most common introduction pathway (38 species), followed by recreational fishing (23 species) and aquarium (13 species). Only two species (African catfish and striped bass, *Morone saxatilis*) were introduced inadvertently, both through artificial waterways (e.g., the African catfish entered East Africa and South Africa via a water tunnel when the Orange River and Great Fish River were connected). One species (Tarpon, *Megalops atlanticus*) was introduced during research on cold tolerance carried out at the Victor Brauning Reservoir, Texas (U.S.).

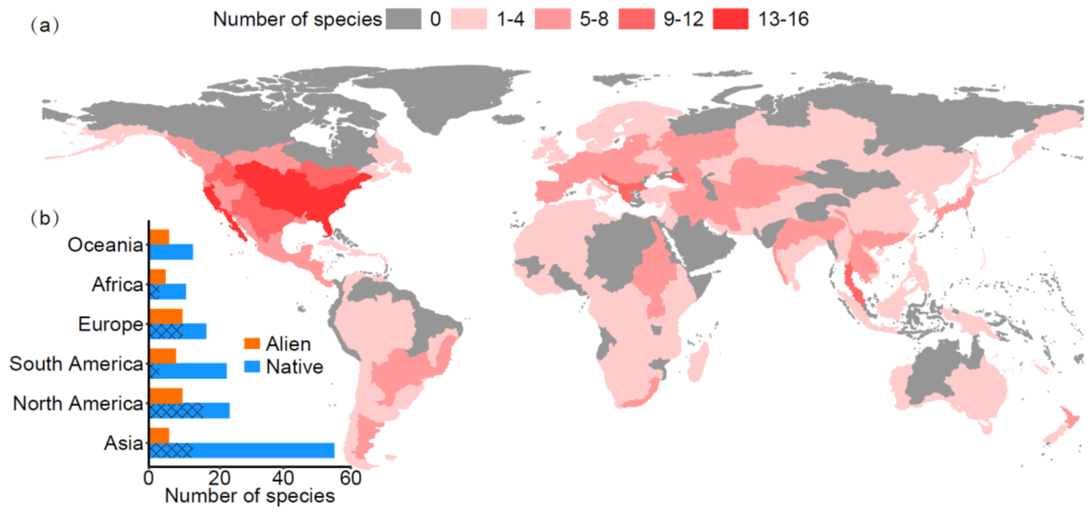

Fig. 3.4 (a) Numbers of alien megafish species established in each level-3 HydroBASIN and (b) numbers of native (blue) and established alien megafish species in each continent. Established alien megafish includes species introduced from another continent (orange) or from another basin within the same continent (blue with black diamond pattern) to a basin that is not occupied naturally by the species.

Almost 70% of introduced species (43) have successfully established alien populations (Fig. 3.4a). The U.S. is a diversity hotspot for established alien megafish species; regions with high species numbers include the Florida peninsula (16), east coast (15), Mississippi Basin (14) and west coast, including Baja California Peninsula (13). On most continents, established alien megafish species originated from both across-continent and within-continent introductions. However, all established alien megafish in Oceania were introduced from other continents (Fig. 3.4b).

3.4.2 Negative impacts of alien freshwater megafish

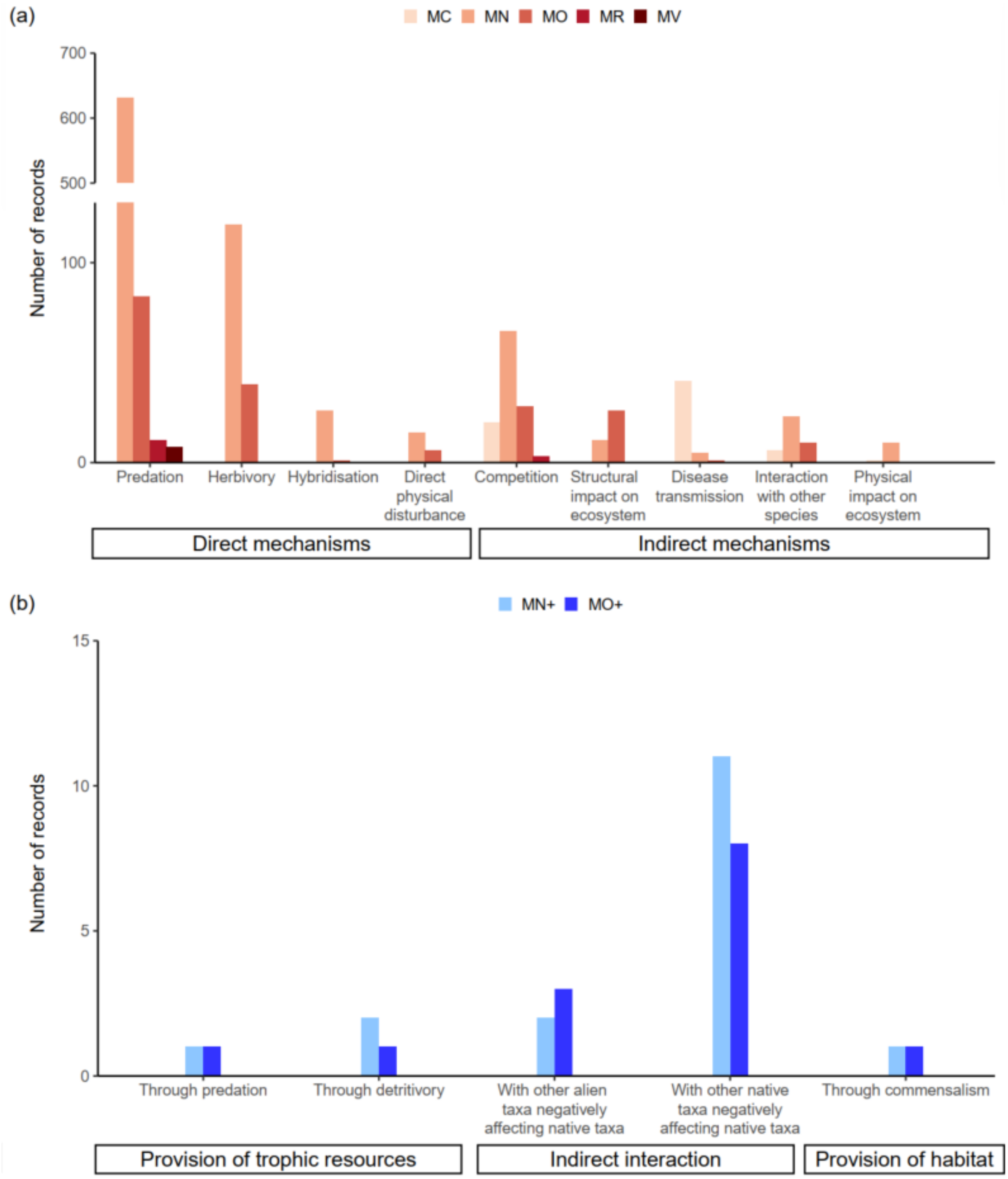

Fig. 3.5 Distribution of observed impact mechanisms and magnitudes of alien freshwater megafish, classified using (a) EICAT (negative impacts) and (b) EICAT+ (positive impacts) frameworks. Negative impact mechanisms were grouped as direct or indirect. No positive Minimal (ML+), Major (MR+) or Massive (MV+) impacts were detected for alien megafish species.

Alien freshwater megafish cause adverse environmental impacts through a broad range of impact mechanisms (nine; Fig. 3.5a). Predation was the most frequently reported impact mechanism (62% of 1190 impact records), followed by herbivory (13%) and competition (10%). Approximately 65% of alien megafish species caused negative impacts through more than one mechanism. Impact mechanisms were not randomly distributed across families ($\chi 2$ = 720.40, df = 35, P < 0.01; Table S3.2). In particular, there were more predation impacts than expected for most families except Cyprinidae (carps and minnows) and Salmonidae (salmonids). In addition, there were more competition impacts than expected for Salmonidae and fewer than expected for Ictaluridae (North American catfishes).

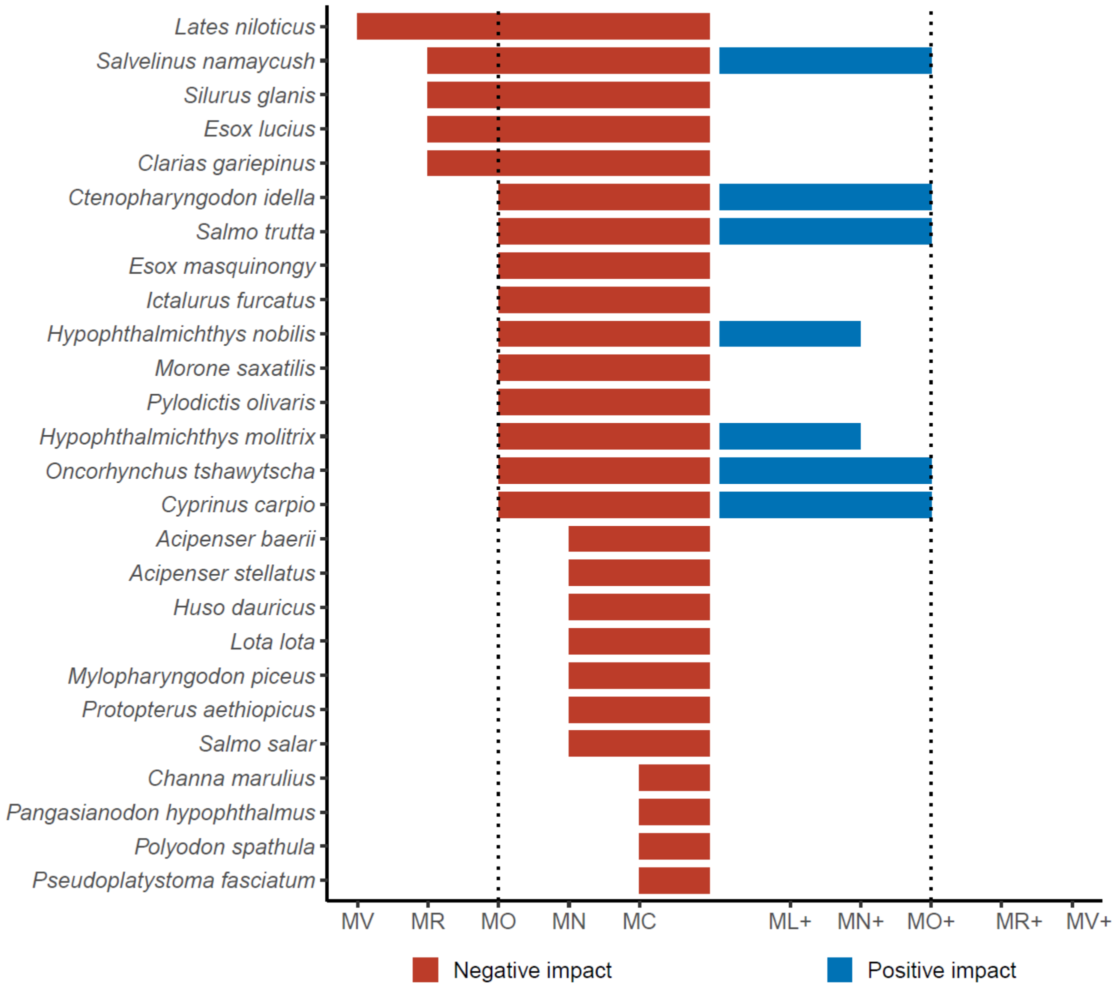

Fig. 3.6 The highest impact magnitude of an alien megafish species identified using EICAT and EICAT+. Dashed lines represent MO or MO+ impact magnitude.

Nearly 58% (15) of the 26 species with sufficient information to evaluate their impact severity had harmful (MO, MR or MV) impacts on native species (Fig. 3.6). The Nile perch had the most severe impact (MV), causing the extinction of numerous native fish species in Lake Victoria through predation and competition. The Wels catfish (*Silurus glanis*), lake trout, northern pike (*Esox lucius*) and African catfish had MR impacts, causing local extinctions of at least one native species through predation (11 records) and competition (3 records). A further ten alien megafish species had MO impacts, causing declining populations of native species through a diverse range of impact mechanisms (competition, predation, hybridisation, disease transmission, direct physical disturbance, herbivory, structural impact on ecosystem and interaction with other species).

Most records were associated with direct impact mechanisms (direct = 939; indirect = 251; Fig. 3.5a). However, indirect mechanisms were more likely to be harmful (estimate 0.80 [SE 0.18], $P < 0.01$, Table S3.3). Impact severity was not randomly distributed across impact mechanisms. In particular, more harmful impacts than expected were associated with competition, direct physical disturbance, herbivory, structural impact on ecosystem and interaction with other species ($\chi^2 = 119.74$, df = 8, $P < 0.01$; Table S3.4). Across families of alien freshwater megafish, Cyprinidae (carps and minnows), Salmonidae (salmonids), Esocidae (pikes) and Latidae (lates perches) caused more harmful impacts than would be expected ($\chi^2 = 87.27$, df = 7, $P < 0.01$; Table S3.5).

The Nile perch was the species with the highest potential risk after introduction because it was the only species with an MV impact (Table 3.1). For species with MR and MO impacts, the two approaches adopted to rank species by their potential impact severity produced different results (Table 3.1). When basin information was considered, species with fewer introduced basins but more observation records per basin were likely to have a higher ranking (i.e., with more severe potential impacts). Among the species with MR impacts, Wels catfish and northern pike switched positions depending on the ranking method adopted. For species with MO impacts, those introduced within the U.S., such as striped bass, flathead catfish (*Pylodictis olivaris*) and blue catfish (*Ictalurus furcatus*), were more highly ranked when basin information was considered.

Table 3.1 Top 15 alien freshwater megafish with the most detrimental impacts on native species. Species were first ranked into five categories (Minimal Concern, Minor, Moderate, Major and Massive) based on their highest impact magnitude. Then, they were further ranked according to the frequency of the highest impact magnitude (HIM) reported in all identified records and different basins.

Scientific name	Common name	HIM	Ranking based solely on the frequency of HIM				Ranking based on frequency of HIM and basins			
			Rank	Frequency of HIM	Impact risk	CI range	Rank	Frequency of HIM	Impact risk	CI range
Lates niloticus	Nile perch	Massive	1	8/83	0.106	0.127	1	1/1	0.667	0.776
Salvelinus namaycush	Lake trout	Major	2	3/64	0.061	0.106	2	1/3	0.400	0.728
Esox lucius	Northern pike	Major	3	4/81	0.060	0.097	4	3/10	0.333	0.495
Silurus glanis	Wels catfish	Major	4	2/62	0.047	0.005	3	2/6	0.375	0.604
Clarias gariepinus	African catfish	Major	5	1/57	0.034	0.079	5	1/6	0.25	0.514
Ctenopharyngodon idella	Grass carp	Moderate	6	56/176	0.309	0.135	6	11/18	0.600	0.413
Esox masquinongy	Muskellunge	Moderate	7	2/8	0.300	0.514	8-9	1/2	0.500	0.812
Oncorhynchus tshawytscha	Chinook salmon	Moderate	8	7/25	0.296	0.333	14	1/7	0.222	0.465
Hypophthalmichthys nobilis	Bighead carp	Moderate	9	5/22	0.250	0.330	10	2/6	0.375	0.604
Hypophthalmichthys molitrix	Silver carp	Moderate	10	7/36	0.211	0.250	13	3/11	0.308	0.465
Salmo trutta	Brown trout	Moderate	11	21/120	0.180	0.135	7	11/21	0.522	0.400
Cyprinus carpio	Common carp	Moderate	12	23/143	0.166	0.120	15	5/32	0.176	0.244
Morone saxatilis	Striped bass	Moderate	13	5/39	0.146	0.206	11-12	1/4	0.333	0.644
Pylodictis olivaris	Flathead catfish	Moderate	14	7/97	0.081	0.119	11-12	1/4	0.333	0.644

Scientific name	Common name	HIM	Ranking based solely on the frequency of HIM				Ranking based on frequency of HIM and basins			
			Rank	Frequency of HIM	Impact risk	CI range	Rank	Frequency of HIM	Impact risk	CI range
Ictalurus furcatus	Blue catfish	Moderate	15	1/123	0.016	0.038	8-9	1/2	0.500	0.812

3.4.3 Positive impacts of alien freshwater megafish

Few records of positive impacts were identified (n = 31; Fig. 3.5b); they were caused by seven species (Fig. 3.6). The most frequently reported impact mechanism was indirect impacts through interactions with other taxa (77% of all records; e.g., an increase in algal biomass and density occurred after grass carp eliminated submerged vegetation), followed by provision of trophic resources (16%; e.g., common carp as prey for great crested grebe, *Podiceps cristatus*) and habitats (7%; e.g., common carp uprooting macrophytes increased the availability of carbon resources from substrates to benthic invertebrates such as chironomids and oligochaetes). With all three impact mechanisms, we identified records of increases in the performance of individuals (MN+) and increases in the size of populations (MO+). Alien megafish were found to suppress the negative impacts of some native taxa on other native taxa. For example, alien brown trout, grass carp and lake trout preyed on native taxa and generated trophic cascading effects, leading to increased abundances of zooplankton, phytoplankton and insects. Additionally, introduced alien megafish were a source of food for native species, causing growth in their populations. An additional 30 records suggested that alien freshwater megafish provided food resources for native species, but the impacts on the native species were not quantified, so these records were classified as DD.

3.4.4 Bias in reported impacts

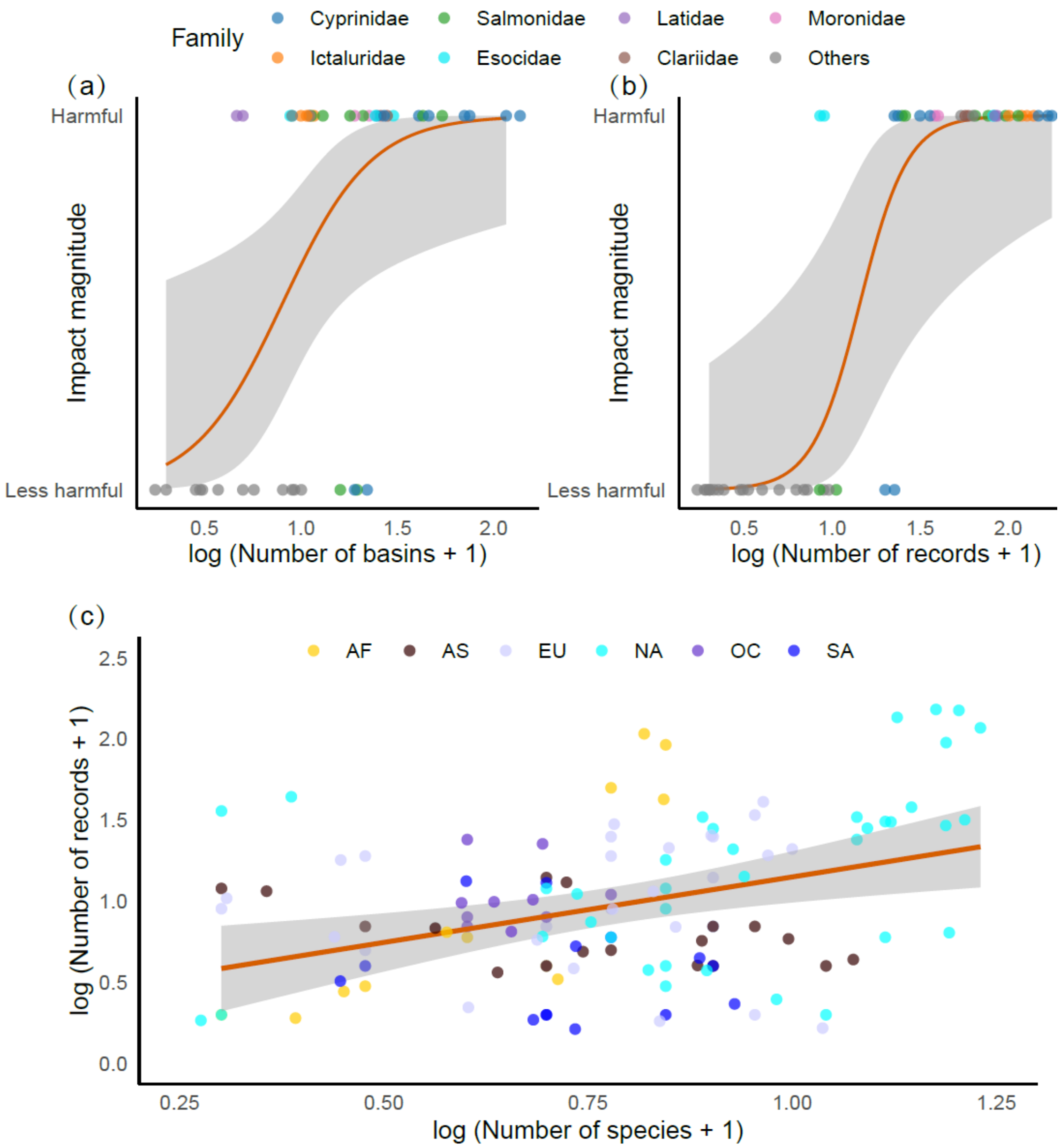

Fig. 3.7 Relationship between the highest impact magnitude and (a) the number of basins in which each alien megafish species has established populations, (b) the number of identified impact records for each alien megafish species, (c) the number of established alien megafish species and the number of impact records in individual level-3 HydroBASINS. The shade indicates the 95% confidence level. **AF**, Africa; **AS**, Asia; **EU**, Europe; **NA**, North America; **OC**, Oceania; **SA**, South America.

The impacts of widely introduced species (i.e., species introduced to many basins) have been more extensively studied compared to species introduced to fewer basins (estimate 1.38 [SE 0.17], $P < 0.01$; Fig. S3.1). Alien megafish in families of Ictaluridae (North American catfishes), Esocidae (pikes) and Latidae (lates perches) received more research attention than other species. Moreover, harmful impacts were more likely to be documented for species that were widely introduced (estimate 4.34 [SE 1.93], $P < 0.01$; Fig. 3.7a) and well-studied (estimate 7.31 [SE 3.19], $P < 0.01$; Fig. 3.7b).

Basins with greater numbers of established alien freshwater megafish species had greater numbers of impact reports (estimate 0.74 [SE 0.26], $P < 0.01$; Fig. 3.7c). Most basins in Europe, North America and Oceania were well studied (with more records), except for a few basins in eastern Europe and Central America. Although a few regions in Africa (e.g., the Nile and the south coast of South Africa), Asia (e.g., Hokkaido) and South America (e.g., eastern Patagonia) had relatively high numbers of reported impact records, most basins within these continents with established alien megafish had few or no impact records with sufficient data to undertake EICAT assessments.

3.5 Discussion

3.5.1 Global introductions of alien freshwater megafish

Almost half of extant freshwater megafish species have been introduced to freshwater environments outside of their native range. These introductions affect 172 basins (59% of the world's basins) that are distributed across all continents except Antarctica – alien megafish are a global phenomenon. Furthermore, there is no evidence to suggest that the rate of megafish introductions is slowing globally. As increasing numbers of freshwater megafish species are being farmed for aquaculture or kept in aquaria as pets (Maceda-Veiga et al., 2016; Magalhães et al., 2017; Valladão et al., 2018), additional megafish species may be introduced to more basins in the future.

Our study demonstrates that these introductions are highly likely to result in established populations of alien freshwater megafish. Indeed, the intrinsic traits of freshwater megafish, which include a long lifespan, high fecundity and strong dispersal ability (He et al., 2021), facilitate their establishment and spread when introduced to new freshwater environments. Releases of small numbers of individuals (e.g., from personal aquaria) may be sufficient for establishment because released individuals can survive in suitable habitats for a long time until they have the opportunity to reproduce. Furthermore, females of many megafish species such as, African catfish, common carp, silver carp and Wels catfish, can produce hundreds of thousands of eggs (He et al., 2021), enabling rapid population growth. After the establishment of these populations, the high dispersal ability of megafish species facilitates their spread through the new environments they have been introduced to. For example, grass carp have travelled over 100 river km in three months in their ongoing invasion of North American freshwater ecosystems (Chapman et al., 2013; Embke et al., 2016; Hessler et al., 2023). Muskellunge (*Esox masquinongy*) spread 500 km within 20 years after their introduction to Lac Frontière (Canada) in the 1970s (Zelman et al., 2023).

Our results indicate that these introductions mainly occur because many freshwater megafish species are valuable commodities. For example, the common carp, African catfish and several sturgeon species have been widely introduced for commercial aquaculture (Bernery et al., 2022; Gozlan et al., 2010; Kang et al., 2023). Although these megafish species are often contained within enclosed environments to prevent their release into natural waterbodies, escape events sometimes occur due to poor management or extreme climate events (Casimiro et al., 2018; Ju et al., 2020). For example, due to a severe flood, over 9000 tonnes of alien megafishes, including Siberian sturgeon (*Acipenser baerii*), Russian sturgeon, Amur sturgeon (*Acipenser schrenckii*), Kaluga (*Huso dauricus*) and American paddlefish (*Polyodon spathula*), escaped from an aquaculture facility into a tributary of the Yangtze River in China (Gao et al., 2017; Ju et al., 2020)

Some megafish species are deliberately released outside of their native range. For example, several salmonid species and the Wels catfish have been knowingly introduced to freshwater lakes for recreational fishing (Cucherousset et al., 2018; Jones & Closs, 2017). Other species, such as the alligator gar (*Atractosteus spatula*) and arapaima, have been released from personal aquaria into new freshwater ecosystems after reaching a large size, as the owners could no longer keep them in standard aquarium settings (Magalhães et al., 2017; Marková et al., 2020; Padilla & Williams, 2004). Species such as grass carp (Pípalová, 2006), black carp (Poulton et al., 2021), silver carp (Lieberman, 1996) and bighead carp (Datta & Jana, 1998), have been widely released into new freshwater environments to be used for biological control (e.g., to reduce the abundance of algae and macrophytes). These intentional introductions often involve large numbers of alien megafish individuals or eggs, creating high propagule pressure, which increases the chance of successful establishment (Drake & Lodge, 2006; Simberloff, 2009). For example, millions of Chinook salmon eggs were deliberately released into New Zealand's rivers between 1901 and 1907 for recreational fishing (McDowall, 1994).

3.5.2 Environmental impacts of alien megafish

Our results indicate that freshwater megafish species tend to have harmful impacts on native biodiversity if they are introduced to new environments. Due to their large body size, these harmful impacts are often the result of predation on smaller freshwater species. Indeed, many freshwater megafish species such as blue catfish, flathead catfish, African catfish and Wels catfish, are top predators with a wide prey spectrum enabling them to affect many different taxonomic groups of native species (Bruton, 1979; Carol et al., 2009; Cucherousset et al., 2012;

Hammerschlag et al., 2019; Martino et al., 2011; Vagnon et al., 2022; Winemiller et al., 2015). For example, Wels catfish prey on birds, fish, reptiles, mammals, amphibians and insects (Carol et al., 2009; Cucherousset et al., 2012; Martino et al., 2011; Vagnon et al., 2022).

Alien freshwater megafish also cause harmful impacts through several other mechanisms, including herbivory (e.g., grass carp herbivory caused a decline in the abundance of native aquatic plants in South Africa and the U.S.; Hanlon et al., 2000; Weyl & Martin, 2016), competition (e.g., the joint effects of predation and competition by northern pike contributed to the extirpation of Arctic char (*Salvelinus alpinus*) in a subarctic lake in Sweden; Byström et al., 2007) and hybridisation (e.g., between Siberian sturgeon with endangered sterlets [*Acipenser ruthenus*] in the Danube River which poses a serious threat to the survival of this isolated sturgeon species; Ludwig et al., 2009).

The broad range of impact mechanisms associated with alien freshwater megafish species means they can adversely affect a diverse range of native species from different taxonomic orders. Indeed, their indirect impacts affect both terrestrial and freshwater species. For example, predation by introduced lake trout caused a severe decline in native Yellowstone cutthroat trout (*Oncorhynchus clarkii bouvieri*) in Yellowstone National Park (U.S.), which led to a reduced food supply for other native species, including grizzly bears (*Ursus arctos*), black bears (*Ursus americanus*), bald eagles (*Haliaeetus leucocephalus*) and ospreys (*Pandion haliaetus*; Koel et al., 2019). Herbivory by common carp in Hennepin and Hopper Lakes (U.S.) modified the structure of aquatic vegetation, leading to a decline in the abundance of waterfowl (Bajer et al., 2009). Herbivory by grass carp led to a severe decline in the abundance of submerged aquatic plants in Lake Pamvotis (Greece), resulting in a loss of habitat (refugia) for the Epirus minnow (*Pelasgus epiroticus*), which caused its severe population decline (Leonardos et al., 2005).

Our results suggest that these indirect impacts tend to be more severe than direct impacts. Volery et al (2021) similarly found that the indirect impacts of ungulates tended to be more severe than their direct impacts. However, this trend may arise because the less harmful impacts associated with indirect impacts are overlooked because they are difficult to detect and demonstrate (Volery et al., 2021). Indeed, direct interactions between alien species and native species (e.g., predation and herbivory) are easier to detect and demonstrate compared to indirect mechanisms – including the impacts that are not harmful. Furthermore, many records of direct predation solely rely on assessments of the stomach contents of alien freshwater megafish without evaluating population-level impacts. Thus, these impacts are only categorised as MN. Therefore, less harmful impacts caused by direct predation impacts may be overrepresented in our dataset and more harmful impacts may be underrepresented.

The limited data on the positive impacts of alien freshwater megafish reflects a general trend for invasion biology, with most research focusing on negative impacts (Vimercati et al., 2020). Indeed, it is likely that the positive impacts of alien freshwater megafish are underrepresented. For example, most freshwater megafish have high fecundity (He et al., 2021); their eggs and juveniles are a source of food for native predators. However, only a few studies identified this positive impact. Examples include juvenile common carps as prey for great crested grebes (*Podiceps cristatus*) and grey herons (*Ardea cinerea*) in Poland and Spain (Kloskowski et al., 2021; Maceda-Veiga et al., 2017) and spawning salmonid species providing food for many native species (Collins et al., 2016). Other positive impacts of alien freshwater megafish include suppressed predation of native species. For example, predation by the introduced bighead carp and silver carp in the Illinois River reduced the abundance of large cladocerans and copepods, reducing predation pressure on rotifers (Sass et al., 2014). In addition, some alien megafish species modify habitat structure, which benefits certain native species. For example, the foraging activity of common carp uproots macrophytes and increases the availability of detritus and carbon resources to benthic invertebrates such as chironomids and oligochaetes (Miller & Crowl, 2006).

3.5.3 Uncertainties in assessments and future investigations

Our results support those of other recent studies concluding that we lack data on the environmental impacts of alien species in the Global South (Evans & Blackburn, 2020; Volery et al., 2021). For example, the alligator gar is a large predatory fish widely introduced to multiple regions, including China (Xie et al., 2023), India (Manna et al., 2021) and Iran (Esmaeili et al., 2017), but we could not find any impact data for this species. Indeed, many megafish species have been introduced to Africa, Asia and South America, where they are likely to have severe, widespread impacts on native biodiversity that are going unreported and unmanaged. Nevertheless, we only searched for literature written in English and may therefore have missed impact records written in other languages, including those describing impacts occurring in the Global South (Nuñez & Amano, 2021).

Long-term studies are often required to understand the severity of the impacts posed by alien species (Measey et al., 2020; Strayer et al., 2006). For example, long-term monitoring of Nile perch (Witte et al., 2007), lake trout (Koel et al., 2019), Wels catfish (Castaldelli et al., 2013) and brown trout (Morita, 2018) identified harmful (MO and MV) impacts on native species associated with declining populations over long time periods. However, these long-term studies are resource-intensive (Measey et al., 2020) and we only found a small number during our literature search. This means population-level impacts of alien megafish species are likely to be underreported. For example, several studies indicated that alien megafish serve as hosts for parasites but did not quantify the impact of this parasitism on native species at the population level (Garrido-Olvera et al., 2017; Otachi et al., 2014; Waicheim et al., 2014).

3.6 Summary and outlook

Our study represents the first comprehensive assessment of megafish introductions and their environmental impacts at a global scale. Negative environmental impacts posed by alien freshwater megafish have been observed in all continents except for Antarctica, causing population decline or even extirpation of native species mainly through predation, herbivory and competition. Meanwhile, positive impacts on native species through indirect interactions and provision of trophic resources and habitats have also been documented, highlighting the complex ecological dynamics associated with alien megafish introductions. There is a clear tradeoff between the economic benefits associated with introductions of freshwater megafish, many of which are deliberate and the severe adverse impacts they have on native biodiversity. Given the severe threat to biodiversity posed by alien megafish, their management should be integrated into international and national policy (Bernery et al., 2022; Ju et al., 2020). Mandatory risk assessments to evaluate their potential impacts should be required prior to any proposed introductions. Strict biosecurity requirements and management plans for megafish aquaculture operations and pet trade should be implemented to reduce the chances of escapes or releases to natural waterbodies (Ju et al., 2020; Magalhães et al., 2017). Further, targeted communication of the impacts caused by alien freshwater megafish can be used as a tool to deter deliberate introductions (e.g., by owners of aquaria). We call for more long-term monitoring, which is needed to better understand how alien freshwater megafish affect the population dynamics of native species (Chen et al., 2023; Pergl et al., 2020) and greater attention to the impacts that alien freshwater megafish may have on biodiversity in the Global South.

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4. Beneficial and detrimental contributions of alien freshwater megafauna to people: A global assessment

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4.1 Abstract

Freshwater megafauna have been intentionally introduced globally due to their charisma and economic value. Despite their well-documented interactions with human communities, a comprehensive assessment of their socio-economic impacts has yet to be conducted at a global scale. In this study, we systematically collected evidence regarding the interactions between alien freshwater megafauna and humans. We adapted the framework of nature's contributions to people (NCP) and developed a semi-quantitative approach to assess their beneficial and detrimental socio-economic impacts. We identified 584 records that documented NCP associated with 59 species. In total, 430 records reported various beneficial NCP categories provided by alien freshwater megafauna, including habitat maintenance, regulation of water quality, regulation of detrimental organisms, provision of food, materials and companionship, enhanced physical and psychological experiences and supporting identities. Provision of food is the most frequently reported category (58%), followed by enhanced physical and psychological experiences (20%) and materials and companionship (12%). Most beneficial NCP records were linked to megafish species, especially Cypriniformes, Salmoniformes and Siluriformes. Geographically, Asia, Europe and North America covered most of the beneficial NCP records. Meanwhile, we identified much fewer records showing detrimental NCP associated with alien freshwater megafauna (154), with risk to health and safety being the most frequently reported category (68%). Our study demonstrates the frequent and complex interactions between humans and alien freshwater megafauna. We highlight the gaps in monitoring introductions and assessing impacts of alien species in the Global South, where many freshwater megafauna have been increasingly introduced due to their economic values. When introductions of freshwater megafauna species are proposed, strict biosecurity requirements, mandatory risk assessments and management plans should be implemented to safeguard native freshwater biodiversity and associated ecosystem functions and services.

Keywords: alien species; aquaculture; ecosystem services; impact assessment; nature’s contributions to people; pet trade; socio-economic impacts

4.2 Introduction

Globalization and ongoing environmental change (e.g., habitat conversion and climate change) have facilitated introduction of alien species, with more than 37,000 species having established populations outside of their native ranges and over 5,000 species being considered invasive (IPBES, 2023). Alien species have caused profound ecological and socio-economic impacts in the introduced regions (Pejchar & Mooney, 2009a, 2009b; Pyšek et al., 2020). They are a major driver of biodiversity loss and listed as a contributing factor to over 55% of documented vertebrate extinctions since 1500, according to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (IUCN, 2023). Habitat alterations and biodiversity declines caused by alien species also affect ecosystem functions and services, which can lead to severe socio-economic impacts (Katsanevakis et al., 2014; Kumar & Singh, 2020; Pyšek & Richardson, 2010). Indeed, alien species can influence human well-being through various mechanisms, such as damaging properties, altering availability of natural resources and modifying social and cultural relations (Bacher et al., 2018). The estimated costs related to alien species from 1970 to 2017 are over USD 1.28 trillion without a sign of a decrease in annual costs (Diagne et al., 2021).

Freshwater ecosystems are particularly vulnerable to alien species due to their strong links with human societies (Francis & Chadwick, 2011; Moorhouse & Macdonald, 2015). Many alien species have been introduced to freshwater ecosystems intentionally (e.g., aquaculture, ornaments) or accidentally (e.g., ballast water), triggering profound socio-economic impacts in the introduced regions (Havel et al., 2015; Hulme, 2021; Moorhouse & Macdonald, 2015). For example, water hyacinth (*Eichhornia crassipes*), which is native to South America but has been widely introduced to North America, Africa, Asia, Europe and Oceania, can degrade water quality, disrupt irrigation systems and impede access to water bodies for fishing and transport (Villamagna & Murphy, 2010). Introduced zebra mussels (*Dreissena polymorpha*) in the Great Lakes have blocked waterways and caused damage to boats and equipment, resulting in economic costs of over USD 19.3 billion (Karatayev & Burlakova, 2022). Introductions and establishments of alien species below the water surface are often challenging to detect at an early stage, which may lead to a missed window of management opportunity (Haubrock et al., 2022; Moorhouse & Macdonald, 2015). In addition, hydrological connections between waterbodies facilitate the spread of alien species (Kao et al., 2021; Seebens et al., 2021). Water traffic can further boost the expansion of alien species (Schwindt et al., 2020), in some cases, even across basins via artificial waterways. For instance, African catfish (*Clarias gariepinus*) colonized the Great Fish River in South Africa via the Orange – Fish tunnel, an artificial waterway that connects the Orange River and Great Fish River (Cambray, 2003).

Freshwater megafauna (i.e., freshwater animals with a maximum reported body mass ≥ 30 kg, including beavers, hippopotamuses, sturgeons, large carps and catfishes, crocodilians, turtles and giant salamanders; He et al., 2017) have been widely introduced outside of their native ranges. For example, common carp (*Cyprinus carpio*), brown trout (*Salmo trutta*), African catfish, grass carp (*Ctenopharyngodon idella*) and silver carp (*Hypophthalmichthys molitrix*) are among the most widely established alien freshwater fish species worldwide (Bernery et al., 2022). Introductions of freshwater megafauna are typically intentional (e.g., for aquaculture, biological control, recreational fishing, or pet trade) due to their high economic values and charisma. Therefore, alien freshwater megafauna often provide benefits to people in the introduced regions. For example, the profit margin from introduced carps in Bangladesh has reached almost USD 12,000 per hectare (Alam et al., 2019). However, these large animals can fundamentally alter habitat structure and ecosystem processes in the introduced regions, leading to reduced human well-being and increased economic costs to manage them. For example, at least USD 1-2 million per year would be required to control population growth of alien hippopotamuses (*Hippopotamus amphibius*) in Colombia (Subalusky et al., 2023; Taylor, 2023).

Despite the wide intentional introductions of freshwater megafauna in various continents and well documented interactions between human and alien freshwater megafauna, a systematic assessment of their socio-economic impacts has yet to be conducted. Here, we systematically collected evidence from published literature regarding interactions between alien freshwater megafauna and humans at a global scale. We adapted the concept of nature's contributions to people (NCP, Díaz et al., 2018) to assess their socio-economic impacts with a semi-quantitative approach, covering both beneficial and detrimental aspects. Finally, we highlight the importance of combining assessments of environmental and socio-economic impacts to facilitate effective strategies to manage species introductions in freshwater ecosystems.

4.3 Materials and Methods

4.3.1 Collecting data on introductions of alien freshwater megafauna

The native ranges of freshwater megafauna (including 134 fishes, 47 reptiles, 33 mammals and two amphibians) were obtained from He et al. (2018). We conducted a literature review to search for publications documenting the introduction of freshwater megafauna outside of their native ranges. Following Evans et al. (2016), we used terms describing alien species in combination with common names and scientific names of each freshwater megafauna species to search for related literature on the Web of Science and Google Scholar. For instance, the search term used for the silver carp was: ("invasive" OR "alien" OR "non-indigenous" OR "non-native" OR "introduced" OR "exotic") AND ("silver carp" OR "*Hypophthalmichthys molitrix*"). We screened the titles and abstracts of the yielded articles to exclude that those were not relevant. For each introduction record in relevant studies, we extracted data on the geographic locations of the introduced region. In addition, we searched for occurrence records of each freshwater megafauna taxon on online databases, including the Global Biodiversity Information Facility (www.gbif.org), USGS's Nonindigenous Aquatic Species (www.nas.er.usgs.gov), IUCN's Global Invasive Species Databases (www.iucngisd.org/gisd), CABI's Invasive Species Compendium (www.cabi.org/isc/) and FishBase (www.fishbase.org). We then compared the occurrence records with their native ranges to identify cases of megafauna introduction. For each country, we calculated the number of alien freshwater megafauna species that occurred outside of their native ranges.

4.3.2 Assessing nature’s contributions to people (NCP) associated with alien freshwater megafauna

To assess nature's contributions to people (NCP) associated with alien freshwater megafauna, we employed a framework acknowledging the multifaceted impacts, both positive and negative, on human well-being. The conceptualization of NCP recognizes the diverse constituents of human well-being influenced by biodiversity, such as regulation of water quality, energy and learning and inspiration (Díaz et al., 2018). Our framework is an adaptation of the comprehensive model proposed by Díaz et al. (2018), extending beyond the 18 beneficial NCP categories to incorporate detrimental aspects caused by alien freshwater megafauna. Detrimental NCP categories considered include reduced food resources, damage to properties, reduced physical and psychological experiences and risks to human health and safety (Table 4.1).

Given the challenges in measuring the complete influence of alien species on human well-being, particularly in the absence of sufficient data or recognition of their impacts, we introduced the concept of potential magnitude. This aspect indicates that beneficial or detrimental NCP associated with alien megafauna were inferred, but without direct documented evidence (Table 4.2).

The focus on the magnitude of affected populations/individual people is crucial for evaluating the magnitude of impacts on human well-being. Categorizing alien species based on the magnitude of affected populations/individual people (Table 4.2) enables a comparative method of their impacts across different spatial scales and diverse societal backgrounds. The semi-quantitative aspect of our framework involves six categories that sequentially describe impact levels. For instances where NCP associated with alien megafauna have been investigated, but the impacts are minimal and negligible, we classified them as low impact (+ -). In cases where beneficial or detrimental NCP affect individual people but not entire communities in the introduced region, we classified them as medium impact (+ -). A high impact (+ -) classification was assigned when beneficial or detrimental NCP associated with alien megafauna are widespread and impact at least one community of people in the introduced region. Only direct evidence of impacts posed by alien freshwater megafauna was used for the assessment. Review articles were generally excluded, unless they presented a synthesis leading to a novel and previously unreported conclusion. Each assessment was assigned a confidence level indicating the likelihood that it accurately reflected the true impact category or magnitude.

Table 4.1 Categories of beneficial NCP provided by alien freshwater megafauna. The classification of beneficial NCP was adapted from Díaz et al., 2018.

NCP direction	Categories of NCP	Examples
	Habitat maintenance	Ponds created by introduced American beaver (*Castor canadensis*) in Chile provided freshwater habitats and drinking water for livestock (Araos et al., 2020).
	Regulation of water quality	Silver carp (*Hypophthalmichthys molitrix*) control algae abundance and regulate water quality in the U.S. (Perdikaris et al., 2010).
	Regulation of detrimental organisms	Black carp (*Mylopharyngodon piceus*) control harmful snail populations in the U.S. (Buck et al., 2014).
Beneficial	Provision of food	African catfish (*Clarias gariepinus*) are used for aquaculture in Malaysia (Dauda et al., 2018).
	Materials and companionship	Siamese crocodile (*Crocodylus siamensis*) are farmed for their skin or traded as pets in China (Zhang et al., 2021).
	Enhanced physical and psychological experiences	Chinook salmon (*Oncorhynchus tshawytscha*) are used for recreational fishing in Australia (Hunt et al., 2017).
	Supporting identities	American beavers (*Castor canadensis*) are regarded as symbolic species, even adopting them as mascots in in Tierra del Fuego (Zhu et al., 2018).
	Reduced food resources	Silver carp have caused declining populations of native carps (e.g., *labeo dero*) in India, which are food source for local communities (Kaushal, 2007).
	Damage to properties	Silver carp and bighead carp (*Hypophthalmichthys nobilis*) jump out of the water when disturbed by water traffic in the Great Lakes (U.S.), causing damage to boats (Buck et al., 2014).
	Reduced physical and	Asian carps (*Hypophthalmichthys* spp.) damage the public image of the Great Lakes and reduce the sense of

NCP direction	Categories of NCP	Examples
	psychological experiences	well-being and pride of human residents (Lauber et al., 2020).
Detrimental	Risk to health and safety	Introduced hippopotamuses in Columbia have attacked local people and caused serious injury (Castelblanco-Martínez et al., 2021).

Table 4.2 The type and magnitude of NCP associated with alien freshwater megafauna.

Type of NCP	Magnitude	Description	Example
Beneficial	Potential+	Beneficial NCP associated with alien megafauna was inferred, but no direct evidence was documented.	A field experiment was conducted to test the effectiveness of grass carp (*Ctenopharyngodon idella*) in controlling aquatic plants in India. However, it is unclear whether grass carp have been utilized by local people to control aquatic plants in India (Sinhababu et al., 2013).
	Low+	Beneficial NCP associated with alien megafauna was investigated, but only minimal beneficial impact was observed.	Beavers were introduced to Tierra del Fuego for the trade of their fur, but sustained trade was not established (Jusim et al., 2020).
	Medium+	Alien megafauna provided beneficial NCP to individual people in the introduced region.	Alligator gar (*Atractosteus spatula*) have been imported and sold as ornamental fish in Indonesia (Jerikho et al., 2023).
	High+	Alien megafauna provided beneficial NCP to one or more communities of people in the introduced region.	Nile perch (*Lates niloticus*) introduced to Lake Victoria has been a major economic resource for fishers in East Africa (Aloo et al., 2017).
Detrimental	Potential-	Detrimental NCP associated with alien megafauna was inferred, but no direct evidence was documented.	Chinook salmon introduced to Chile contain high levels of organic pollutants, but no adverse impact on human health has been reported (Montory et al., 2020).
	Low-	Detrimental NCP associated with alien megafauna was investigated, but only	No data.

Type of NCP	Magnitude	Description	Example
		minimal detrimental impact was observed.	
	Medium-	Alien megafauna posed detrimental NCP to individual people in the introduced region.	When disturbed, silver carp jump out the water causing serious injury to individual people in the Mississippi River Basin (Vetter et al., 2019).
	High-	Alien megafauna posed detrimental NCP to one or more communities of people in the introduced region.	All medium-sized Arctic charr (*Salvelinus alpinus*) in Lake Grundlsee, Austria, were infected with tapeworms from introduced northern pike (*Esox lucius*) in just two years, leading to the closure of the fishery (Schaufler et al., 2014).

4.4 Results

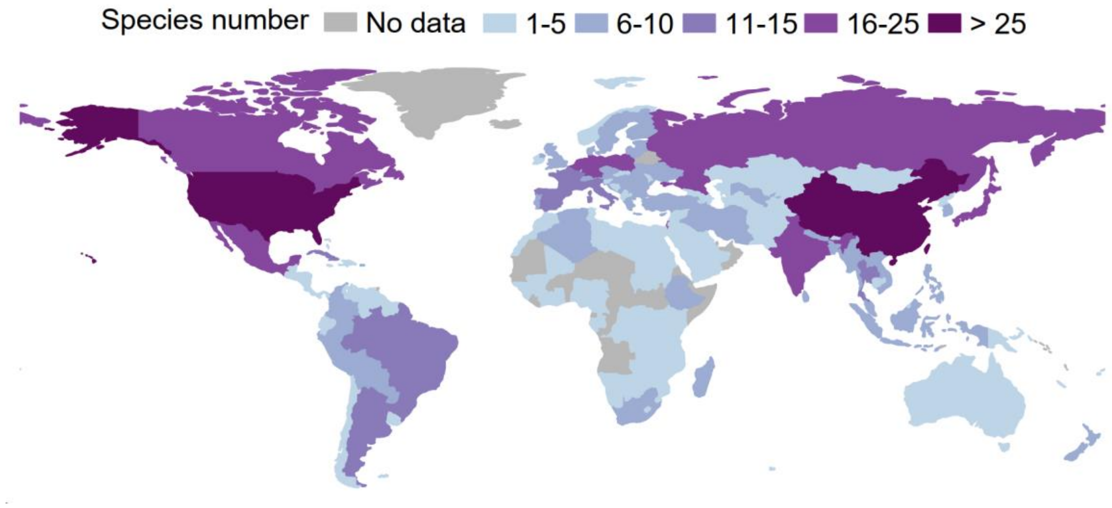

Fig. 4.1 Number of alien freshwater megafauna species introduced to each country.

In total, 93 freshwater megafauna species (43% of extant freshwater megafauna species) have been introduced outside of their native ranges. They have been introduced to every continent except Antarctica, covering 142 countries and regions (Fig. 4.1). The U.S. has the highest number of introduced alien freshwater megafauna species (n = 52), followed by China (28), Canada (23), Russia (19), Belgium (18) and Germany (17). We found comparatively few freshwater megafauna species introductions in Africa and Oceania.

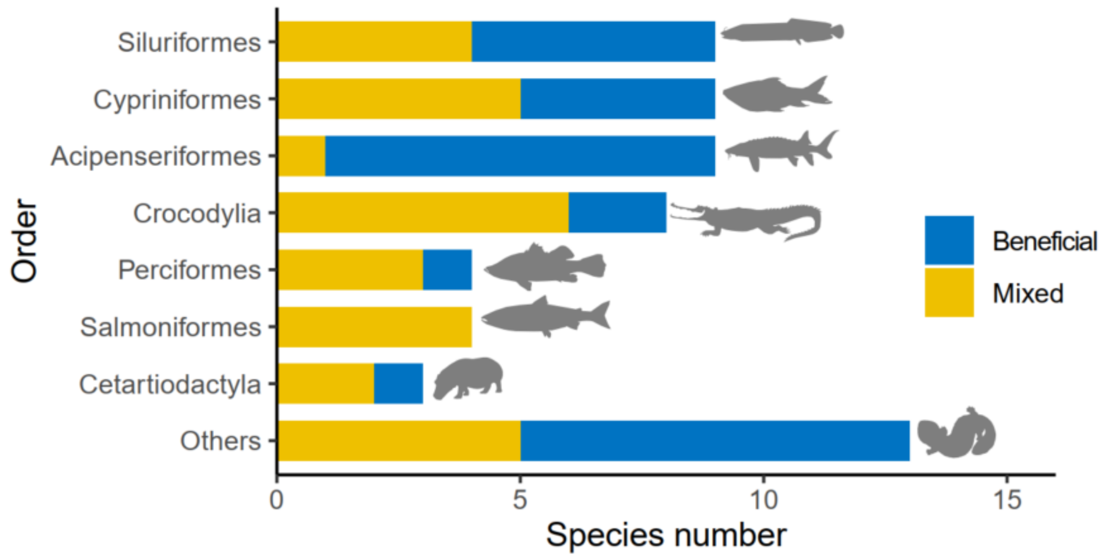

Fig. 4.2 Species number of each order of alien freshwater megafauna categorised by NCP type (either beneficial only or mixed, i.e., beneficial and detrimental records). Others include Caudata, Characiformes, Esociformes, Lepisosteiformes, Osteoglossiformes, Rajiformes, Rodentia, Squamata and Testudines.

In total, we identified 584 records documenting NCP associated with 59 alien freshwater megafauna species, including fish, reptiles, mammals and amphibians (Fig. 4.2). All these alien species were intentionally introduced and associated with at least one beneficial NCP category. In addition, both NCP were documented for 45% of the identified alien freshwater megafauna species.

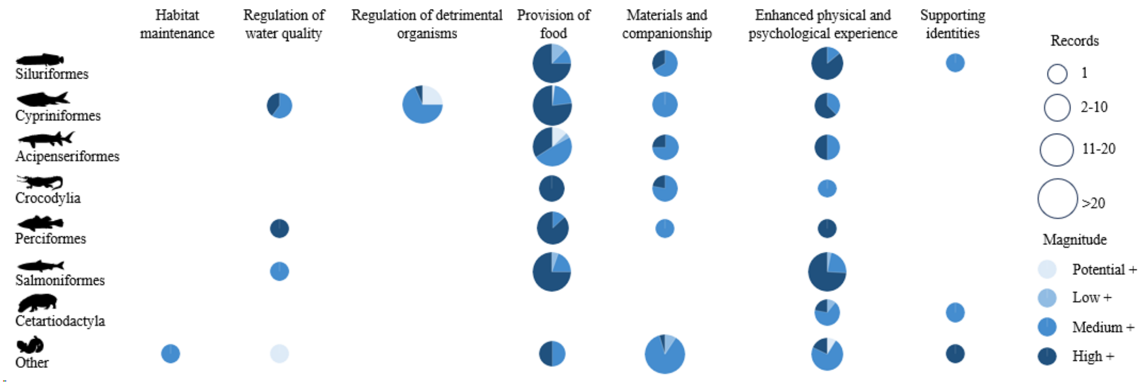

Fig. 4.3 Beneficial NCP records provided by different orders of alien freshwater megafauna.

A broad range of beneficial NCP categories were associated with alien freshwater megafauna, including habitat maintenance, regulation of water quality, regulation of detrimental organisms, provision of food, materials and companionship, enhanced physical and psychological experiences and supporting identities (Table 4.1). Provision of food was the most frequently reported beneficial NCP category (58% of 430 records), followed by enhanced physical and psychological experience (20%) and materials and companionship (12%). Most identified beneficial NCP records were associated with fish species (Fig. 4.3), with Cypriniformes (carps and minnows), Salmoniformes (salmonids) and Siluriformes (catfishes) accounting for 36%, 16% and 14% of all beneficial NCP records, respectively. Nearly half (47% of 59 species) of these species contributed to beneficial NCP through more than one category. Furthermore, 66% of these species were associated with NCP of high magnitude, indicating their substantial contributions to the economies and cultural practices of local human communities in the introduced regions.

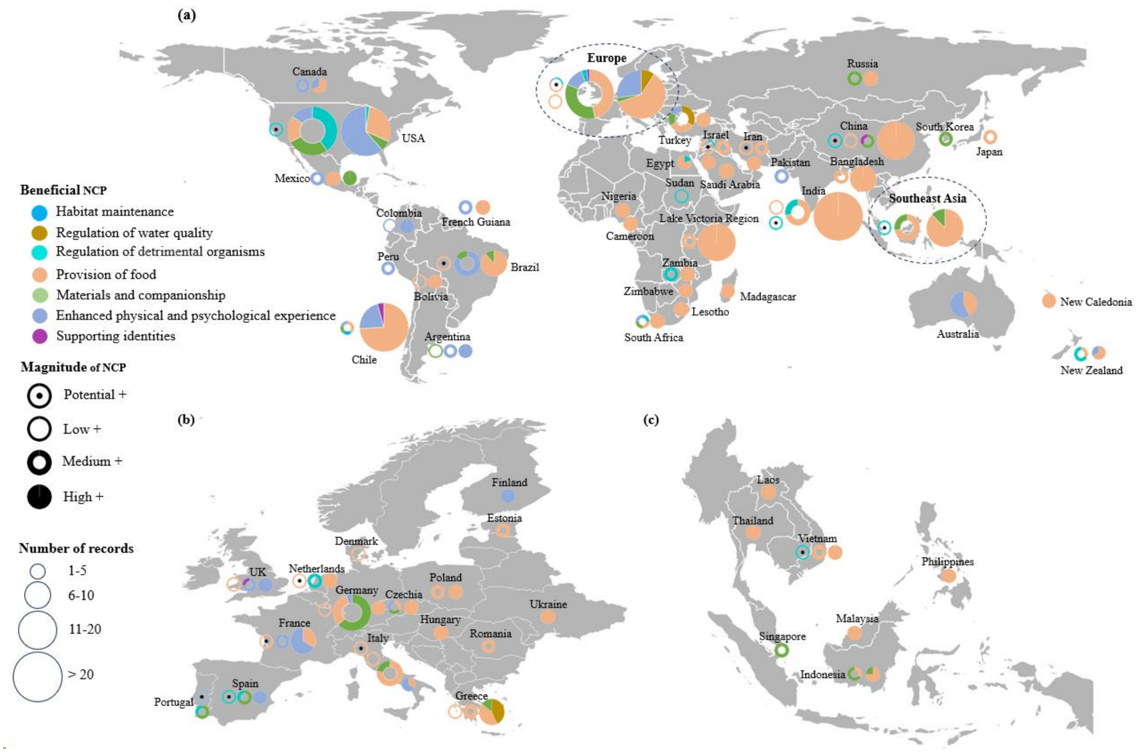

Fig. 4.4 Global distribution of beneficial NCP records provided by alien freshwater megafauna.

Most beneficial NCP records were from Asia (29%), Europe (23%) and North America (21%); whereas Africa (9%) and Oceania (3%) had fewer records (Fig. 4.4). Provision of food was the main benefit in Asia (80%), Africa (80%) and Europe (55%). In North America, enhanced physical and psychological experiences was the main benefit (43%), followed by provision of food (25%). Some benefits were infrequently reported, such as habitat maintenance (1 record, Chile) and supporting identities (3 records, Chile, U.K. and China).

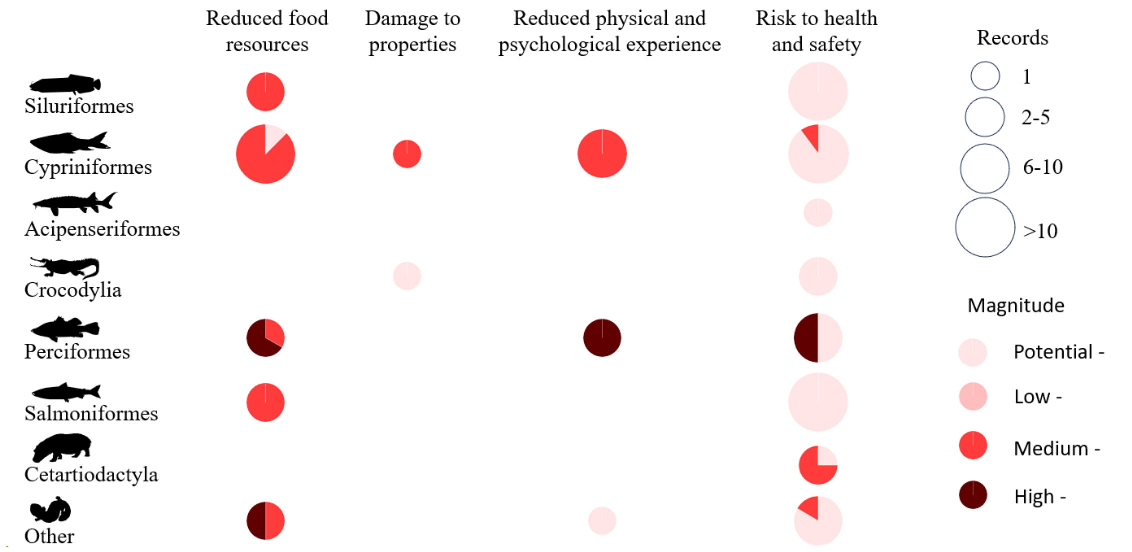

Fig. 4.5 Detrimental NCP records associated with different orders of alien freshwater megafauna.

Fewer records were identified for detrimental NCP (154); they were from four categories and were associated with 25 species (Fig. 4.5). The most frequently reported categories were risk to health and safety (68% of 154 records), reduced food resources (24%), reduced physical and psychological experiences (7%) and damage to properties (0.6%). Similar to beneficial NCP, Cypriniformes (53%), Salmoniformes (16%) and Siluriformes (12%) were associated with most detrimental NCP records. Only three records documented detrimental NCP of high magnitude, which were all associated with risk to health and safety. More than half (60%) of the records described potential detrimental NCP, suggesting a paucity of direct evidence and that detrimental NCP may be more widespread than has been reported.

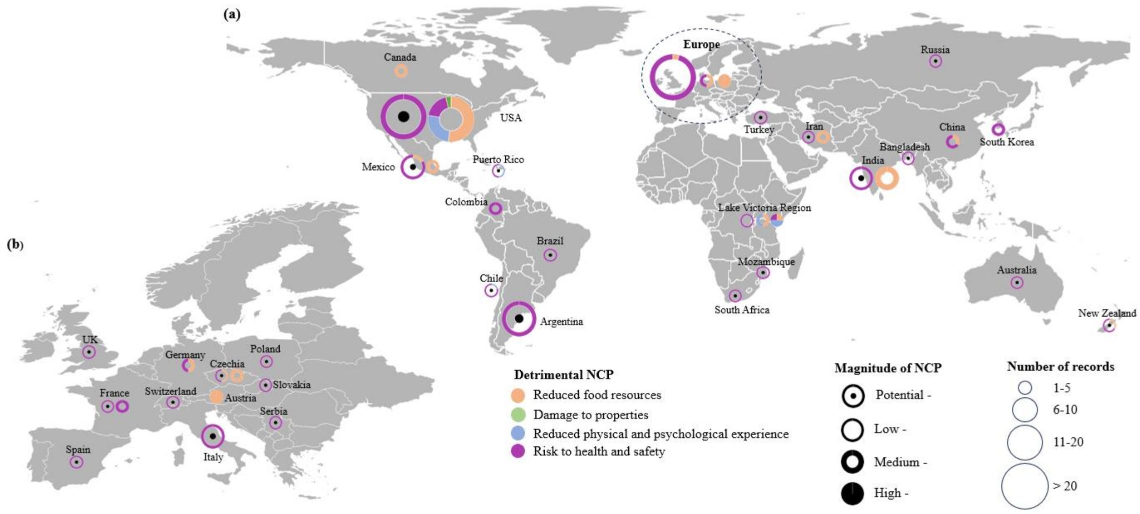

Fig. 4.6 Global distribution of detrimental NCP records associated with alien freshwater megafauna.

Most detrimental NCP records were from North America (nearly 40%, Fig. 4.6), Europe (19%) and Asia (17%). Risk to health and safety accounted for over 50% of detrimental NCP records across all continents. North America was the only continent where all four categories of detrimental NCP were reported.

4.5 Discussion

4.5.1 From farms to faith: diverse beneficial NCP associated with alien freshwater megafauna

Our study shows a broad range of beneficial NCP associated with alien freshwater megafauna globally, including habitat maintenance, regulation of water quality, regulation of detrimental organisms, provision of food, materials and companionship, enhanced physical and psychological experiences and supporting identities. Over 60% of introduced freshwater megafauna species have provided at least one of these NCP. This emphasizes the substantial, diverse contributions of alien freshwater megafauna species to local economies and cultures and explains why they have been widely and intentionally introduced.

Provision of food is the most widely documented beneficial NCP. Megafauna species such as carps, catfishes, salmonids and sturgeons have been widely introduced for aquaculture across the world (FAO, 2023). For example, the African catfish has been introduced to over 30 countries to establish commercial fisheries, including China (Gu et al., 2018), Thailand (Wachirachaikarn et al., 2009), India (Singh & Lakra, 2011) and Malaysia (Dauda et al., 2018). In some regions, the livelihoods of local people are highly reliant on income generated by farming alien freshwater megafauna. In 2018, the annual export value of salmonids in Chile, including Atlantic salmon (*Salmo salar*), brown trout and Chinook salmon (*Oncorhynchus tshawytscha*) was US$5.2 billion (Cid-Aguayo et al., 2021). Salmonids were the second-largest commodity by export value, supporting 38,000 people with direct employment and 15,000 with indirect employment (Cid-Aguayo et al., 2021; Pascual et al., 2009). Beyond providing food resources, alien freshwater megafauna also contributed valuable materials. Species like Siamese crocodile (*Crocodylus siamensis*), Nile crocodile (*Crocodylus niloticus*) and spectacled caiman (*Caiman crocodilus*) were introduced for farming their skins in East Asia (Chen et al., 2018; Huang et al., 2018; Zhang et al., 2021; Zheng et al., 2017).

Alien freshwater megafauna can enhance human-nature connections in the introduced regions. The charisma and rarity of many freshwater megafauna (e.g., turtles, crocodilians and fishes) make them sought-after as pets (Dickey et al., 2023; Esposito et al., 2022; Roberto et al., 2021). Driven by the lucrative pet trade, some regions become dedicated hubs for the breeding of certain alien freshwater megafauna species. For example, the ocellate river stingrays (*Potamotrygon motoro*), native to South America, are strategically farmed in Indonesia to meet the growing demands in the pet market, particularly in Europe, the U.S. and Asia (Jerikho et al., 2023).

The large size, distinctive features and sometimes aggressive behaviour make them excellent candidates for recreational fishing and ecotourism. Flathead catfish (*Pylodictis olivaris*) and blue catfish (*Ictalurus furcatus*) have been regarded as trophy fish in various Atlantic Slope drainages in the U.S. (Fabrizio et al., 2021; Montague & Shoup, 2021). The development of megafauna-based recreational activity could have far-reaching impacts on local communities. The Wels catfish (*Silurus glanis*) promotes socio-economic development through sports angling, generating revenue from tourist services and influencing land prices in the Ebro River Basin, Spain (Rodrı´guez-Labajos, 2014). In Colombia, alien hippopotamuses have become tourist attractions and create commercial opportunities such as boat tours (Subalusky et al., 2023; Taylor, 2023). Moreover, some alien freshwater megafauna hold cultural significance. For example, inhabitants in Tierra del Fuego consider alien American beavers (*Castor canadensis*) as symbolic species, even adopting them as mascots (Schüttler et al., 2011).

Alien freshwater megafauna also provide beneficial NCP through regulation of water quality and detrimental organisms. For instance, silver carps were introduced to many regions to control the growth of phytoplankton (Leventer & Teltsch, 1990; Perdikaris et al., 2010; Smith, 1985). Similarly, other freshwater megafauna species, including grass carp, bighead carp, black carp (*Mylopharyngodon piceus*), Chinook salmon and striped bass (*Morone saxatilis*), are intentionally introduced for the purpose of controlling detrimental organisms (Churchill et al., 2002; Ledford & Kelly, 2006; Whitledge et al., 2022). Hanlon et al (2000) reported that the stocking of grass carp at between 25 to 30 fish per hectare can efficiently regulate the growth of aquatic vegetation. Moreover, black carp can effectively remove targeted snails, the central hosts of many parasites, thereby reducing health risks for humans and native fish (Ledford & Kelly, 2006; Poulton et al., 2019; Venable et al., 2000).

4.5.2 Detrimental NCP associated with alien freshwater megafauna

Although fewer records have documented detrimental NCP associated with alien freshwater megafauna, their influence on the livelihoods of local people is not negligible. They can profoundly modify local ecosystems, causing declines in native species populations and adversely affecting local people who rely on these species as food resources. For example, the introduction of Nile perch (*Lates niloticus*) to Lake Victoria has concentrated the fishery among wealthier individuals equipped with boats and larger, more expensive nets (Riedmiller, 1994). This shift has marginalized traditional fishermen who depended on native species (e.g., haplochromines and tilapias), eventually leading to chronic malnutrition in 40.2% of children and 5.7% of mothers in fisher communities (Aloo et al., 2017; Geheb et al., 2008).

Alien freshwater megafauna also pose threats to human safety, health, property and physical and psychological experiences. Territorial and aggressive species, like hippopotamuses, pose immediate threats to fishermen and individuals working in or close to freshwaters (Subalusky et al., 2021). Even captive freshwater megafauna, such as freshwater stingray, have caused injuries in Germany and France (Brisset et al., 2006). Beyond direct threats to human safety, indirect consequences on human health have also been documented. The introduction of Nile perch changed the fishery structure and social interactions in the fisher communities. Fishermen have increased their mobility to follow the movement pattern of alien Nile perch and stay away from their partners for long time, during which some of them have sexual activity (Aloo et al., 2017; Mojola, 2011). Moreover, local female fishmongers often need to form sexual relationships with fishermen in exchange for rights to buy their fish catch after the declines in native fish catches (Kwena et al., 2012). These changes have contributed to the high prevalence of HIV in shore regions of Lake Victoria in Uganda and Kenya (Aloo et al., 2017; Ondondo et al., 2014; Opio et al., 2013). In addition to increased health risks of people, alien freshwater megafauna can damage human property and potentially reduce participation of local people in recreational activities such as fishing, boating and bird watching (Buck et al., 2014). It is estimated that bighead and silver carps could lead to a substantial decline in recreational activities, causing a potential loss of over 400,000 fishing trips and nearly $139 million in economic value if they establish populations in the Great Lakes and outcompete native fish species (Lauber et al., 2020).

4.5.3 Balancing assessments of NCP associated with alien freshwater megafauna

While alien freshwater megafauna contribute significantly to beneficial NCP, it is crucial to acknowledge their negative impacts on native species (Vitule & Pelicice, 2023). For example, the introduction of Siberian sturgeon (*Acipenser baerii*) for provision of food resulted in their escape into the Danube River, where hybridisation with native sterlets (*Acipenser ruthenus*) poses a serious threat to the survival of the latter (Ludwig et al., 2009). The introduction of northern pike (*Esox lucius*) for sport fishing led to the local extinction of the three-spined stickleback (*Gasterosteus aculeatus*) in Prator Lake, Alaska (McMahon & Bennett, 1996; Patankar et al., 2006).

However, determining the net effect of alien freshwater megafauna in a social-ecological system is not always straightforward. Emblematic cases, such as the introduction of Nile perch in Lake Victoria, show the complexity. While supporting millions of people dependent on this species, it caused irreversible extinction of multiple native species, disrupted the local ecosystem, impacted food security of local people who relied on native species as food and contributed to elevated HIV infection levels in local communities (Aloo et al., 2017; Witte et al., 1992).

Uncertainties in assessing negative impacts of alien species due to factors like study scale, time lags and the absence of long-term monitoring might underestimate their negative impacts and detrimental NCP. For instance, alligator gar (*Atractosteus spatula*) are introduced for pet trading in various regions, including China (Han, 2022), India (Manna et al., 2021) and Iran (Esmaeili et al., 2017). Despite its widespread introduction, there is a lack of impact data for this species. Similarly, ocellate river stingrays, introduced for the pet trade in Indonesia, have established self-sustainable populations, posing potential threats to native species and the safety of local people through envenomation (Jerikho et al., 2023). Despite these potential risks, data deficiency prevents our understanding of their negative impacts on native species and local people communities. Thus, while recognizing the beneficial contributions of alien freshwater megafauna, it is important to propose their introduction with caution, considering potential ecological impacts and implementing robust monitoring strategies (Reed et al., 2023; Sax et al., 2023; Vitule & Pelicice, 2023).

4.5.4 Data limitations and biases

While our study provides a comprehensive overview of the NCP associated with alien freshwater megafauna, we acknowledge the inherent limitations and biases within the available data. We observed a bias towards beneficial NCP in the published literature, with detrimental NCP receiving much less attention (430 records vs. 154 records). Such bias might overemphasize the positive contributions of these large alien species to human societies. Beneficial NCP, such as provision of food, trading as pets and supporting recreational activities, can be easily observed and measured. Conversely, assessments of many detrimental NCP often require more research efforts. Indeed, over half of the identified records on detrimental NCP fall into the potential categories (Potential -). For instance, the levels of heavy metals in 18% of examined Wels catfish that were sampled from the Po River (Italy) between 2007 and 2009 exceeded maximum levels of 0.5 ppm set by European regulations in muscle tissues (Squadrone et al., 2013). However, effects on the health of local people have not been investigated. The lack of detailed data to determine the magnitude of such impacts highlights the need for more follow-up investigations. Thus, due to incomplete research and unreliable bias, which might misguide introduction of alien freshwater megafauna and provide inadequate evidence for decision-makers and politicians who may rather focus on short-term benefits, potentially misleading the public.

Geographically, a broader range of NCP have been documented in North America and Europe, while most records in Africa and Asia are related to provision of food. In these continents, NCP provided by alien freshwater megafauna other than provision of food could be underestimated due to the limited number of studies focusing on socio-economic impacts of alien species. Moreover, our study only included data from literature published in English, which could have limited our ability to detect relevant data published in other languages, particularly in countries that have restricted resources for publishing research results in international journals (Martin et al., 2012).

4.6 Conclusion

In summary, nearly half of alien freshwater megafauna species have been intentionally introduced outside of their native ranges, with beneficial NCP documented for 59 species in 430 records. Provision of food is the most frequently and widely reported beneficial NCP category. Fish species, including Cypriniformes (carps and minnows), Salmoniformes (salmonids) and Siluriformes (catfishes), accounted for over half of the identified beneficial NCP records. In contrast, detrimental NCP associated with alien freshwater megafauna received much less attention in terms of numbers of identified records (154) and related species (25). The majority of NCP records were documented in the Global North, indicating geographical biases in research efforts. Bias towards beneficial NCP in the identified literature may underestimate the negative socio-economic impacts of these large alien species, particularly in Asia and Africa where most records are related to provision of food. More studies are needed to comprehensively understand the impacts on native species and local people, which could facilitate the development of efficient management strategies. When the introductions of freshwater megafauna species are proposed, strict biosecurity requirements, mandatory risk assessments and management plans should be implemented to safeguard native freshwater biodiversity and associated ecosystem functions and services.

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5. General discussion

Anthropogenic activities have led to the widespread introduction and establishment of alien species outside of their native ranges (Ervin et al., 2006; IPBES et al., 2023; Saul et al., 2017). These alien species represent a pressing threat to global biodiversity and have far-reaching influences on local human communities(Bellard et al., 2016; Diagne et al., 2021). This thesis thesis focuses on the impacts of alien species related to freshwater megafauna, including both environmental and socio-economic aspects. The findings provide a scientific foundation for the conservation of native freshwater megafauna and improve our understanding of the introduction, management and impact assessment of alien species.

5.1 Key research findings

In this thesis, I systematically assessed alien species impacts related to freshwater megafauna species, covering both negative and positive aspects of environmental and socio-economic dimensions. In **Chapter 2**, I demonstrated the impacts of alien species on native freshwater megafauna using the EICAT framework. Despite their large body size, freshwater megafauna have been affected by a diverse group of alien species from freshwater and terrestrial ecosystems, including both vertebrates and invertebrates. Impacts occurred through a broad range of mechanisms, leading to declines in individual performance, population abundance, or even local extinction of native freshwater megafauna. I observed a clear difference in the susceptibility of freshwater megafauna to alien species between life-cycle stages (i.e., egg, juvenile and adult).

Meanwhile, freshwater megafauna have been widely introduced outside of their native ranges and have become alien species in many regions. In **Chapter 3**, I took a different angle and focused on alien freshwater megafauna, with megafish as an example because they are the most widely introduced group. I identified the global diversity hotspots of alien freshwater megafish and revealed the main introduction pathways. I assessed negative and positive environmental impacts of alien freshwater megafish on native species following the EICAT and EICAT+ frameworks and ranked their potential to cause severe impacts after introducing a new basin. Negative environmental impacts of alien megafish have been widely documented, with over half of the documented alien megafish species causing population declines of native species. Conversely, positive environmental impacts are infrequently documented.

Alien freshwater megafauna not only pose environmental impacts on native species, but also affect human communities in the introduced regions. In **Chapter 4**, I assessed the socio-economic impacts of alien freshwater megafauna using the framework of nature's contributions to people (NCP). I found that 60% of the introduced species, including fish, reptiles, mammals and amphibians, have records suggesting their socio-economic impacts. Moreover, all of these alien species with records are intentionally introduced and provide at least one type of beneficial NCP, including habitat maintenance, regulation of water quality, regulation of detrimental organisms, food, materials and companionship, physical and psychological experiences and supporting identities. Food is the most frequently documented beneficial NCP. Compared to beneficial NCP, much fewer records were identified for detrimental NCP, with risk to health and safety being the most common category.

5.2 Vulnerability of native freshwater megafauna to alien species

Native freshwater megafauna species are subject to various impacts caused by alien species, including competition, predation, hybridisation, transmission of diseases to native species, parasitism, poisoning/ toxicity, direct physical disturbance, physical impact on ecosystem, structural impact on ecosystem and indirect impacts through interactions with other species. Predation and competition are predominant impact mechanisms, accounting for 75% of all identified records. In addition, some alien species affecting native megafauna are themselves classified as freshwater megafauna. For instance, alien northern pike (*Esox lucius*) have caused declines in populations of native megafauna species such as Chinook salmon (*Oncorhynchus tshawytscha*), Colorado pikeminnow (*Ptychocheilus lucius*) and Atlantic salmon (*Salmo salar*) through predation (Hesthagen et al., 2015; Sepulveda et al., 2015; Zelasko et al., 2016). Hybridisation with alien species also poses threats to native megafauna. For example, hybridisation between the alien Chinese giant salamander (*Andrias davidianus*) and native Japanese giant salamander (*Andrias japonicus*) is a major threat to the latter species in Kyoto rivers, resulting in the production of sterile offspring (Fukumoto et al., 2015). In addition to predation and hybridisation, alien species also interact with native freshwater megafauna through direct physical disturbance and parasitism. For example, introduced wild boars (*Sus sccofa*) often damage eggs and nests of crocodilians in the Atlantic forests (Hegel et al., 2019). Introduced parasites such as worms *Nitzschia sturionis* and *Gyrodactylus salaris*, have been observed in native Atlantic salmon in the River Vefsna (Norway), leading to population decline (Johnsen & Jensen, 1988; Strauss et al., 2012).

Besides these direct interactions, alien species also affect native freshwater megafauna through indirect impact mechanisms, including structural impact on ecosystem, indirect impacts through interaction with others species, poisoning/toxicity and transmission of diseases to native species. For instance, the invasive daces act as a reservoir for parasites *Pomphorhynchus tereticollis*, which reduced fitness of native brown trout (*Salmo trutta*) in Ireland (Tierney et al., 2020). The population of Australian freshwater crocodiles (*Crocodylus johnstoni*) in the Daly River decreased by approximately 70% from 1978 to 2013 due to increased mortality after eating invasive cane toads (*Rhinella marina*), which contain powerful toxins and can kill animals that consume them (Fukuda et al., 2016).

The examination of impact mechanisms also showed a clear variation in magnitude across different life-cycle stages of native freshwater megafauna. Impacts tend to be more severe during the adult stage than in the egg stage. For instance, the population of native marble (*Salmo marmoratus*) dramatically declined due to hybridisation with alien brown trout in Slovenia (Fumagalli et al., 2002). Although severity in the egg stage tends to be less harmful, my thesis might underestimate actual severity in the egg stage due to the limited scope of long-term monitoring efforts during the egg stage (Pergl et al., 2020). For example, although predation by red fire ants (*Solenopsis invicta*) on the eggs of American alligators (*Alligator mississippiensis*) has been observed in Florida (Allen et al., 1997), their influence on the dynamics of the American alligators population, crucial for understanding the impact magnitude, remain unclear due to limited data. Predation is the more frequent impact mechanisms in egg and juvenile stages compared to the adult stage as adult freshwater megafauna are often too large to be consumed by alien species. For instance, wild boars prey on the eggs of American alligators (Elsey et al., 2012), New Guinea crocodiles (*Crocodylus novaeguineae*; Hall & Johnson, 1987) and Yacare caimans (*Caiman yacare*; Larriera & Piña, 2000), yet there are no records documenting predation on juvenile and adult species by wild boars.

5.3 Amplifying impacts with concurrent threats

The impact of alien species on native freshwater megafauna often occurs alongside other threats described in **Chapter 2**. For example, the introduction of stellate sturgeons (*Acipenser stellatus*) also transferred gill flukes (*Nitzschia sturionis*) to the Aral Sea. The joint impacts of alien gill flukes and other threats (i.e., overexploitation, dam construction and increased salinity) led to the local extinction of ship sturgeons (*Acipenser nudiventris*) in the Aral Sea (Gesner et al., 2010; Zholdasova, 1997). Similarly, predation by introduced sea lampreys (*Petromyzon marinus*), compounded by overfishing, contributed to the population decline of lake trout (*Salvelinus namaycush*) in the Great Lakes (Smith & Tibbles, 1980). Moreover, climate change may facilitate the establishment and spread of alien species. For instance, the El Niño rains in 2015/2016 in the Lower and Middle Paranapanema River basin caused the escape of approximately 1.14 million fish, including alien Nile tilapia (*Oreochromis niloticus*), common carp (*Cyprinus carpio*) and redbreast tilapia (*Coptodon rendalli*), constituting 97% of all fish, which pose potential negative impacts on native freshwater megafauna including Arapaima (*Arapaima gigas*), Tambaqui (*Colossoma macropomum*) and redtail catfish (*Phractocephalus hemioliopterus*; Casimiro et al., 2018). Additionally, water pollution can contaminate alien species and affect native megafauna predators. For example, in the Chambal and Yamuna rivers in India, where the consumption of alien Mozambique tilapias (*Oreochromis mossambicus*) with severe pollution led to the demise of over 100 gharials (*Gavialis gangeticus*; Stevenson, 2015). Thus, it is important to comprehend the synergistic impact of alien species and other threats to develop effective conservation measures. On the other hand, evaluating the significance of alien species impacts within these multifaceted scenarios presents a considerable challenge, especially compared to threats like overexploitation and habitat loss, which may exert stronger negative influences on freshwater megafauna (He et al., 2017).

5.4 Implications for conservation of native freshwater megafauna

This thesis identified that alien-species impacts on native freshwater megafauna are often related to a certain life-cycle stage. For instance, the predation risk posed by largemouth bass (*Micropterus salmoides*) on green sturgeon (*Acipenser medirostris*) decreases as the size of sturgeons increases, becoming negligible once it reaches 20cm (Baird et al., 2020). Therefore, early detection of alien species and a comprehensive understanding of their impact mechanisms on native megafauna is important to mitigate their impacts. For comprehensive planning, conservation efforts should integrate strategies addressing multiple threats, including alien species, overexploitation, habitat loss, water pollution, dam construction and climate change. For example, approximately 10 thousand tonnes of five alien sturgeon species escaped from aquaculture farms into the Yangtze River during extreme flooding (Gao et al., 2017). These sturgeons may compete and hybridise with the critically endangered native Chinese sturgeon (*Acipenser sinensis*), whose population has already declined due to habitat loss, dam construction and water pollution (Hu et al., 2009; Wei et al., 1997). Long-term monitoring is essential to provide accurate insights into the interactions between alien species and native freshwater megafauna. Many studies show alien species affecting native megafauna at the individual level but lack long-term data on population dynamics. For instance, eggs of native white sturgeon (*Acipenser transmontanus*) were observed in the guts of alien common carp in Columbia River, U.S. (Miller & Beckman, 1996). However, it lacks long-term monitoring data showing population dynamics when its eggs are under predation pressure by common carp.

5.5 Global introductions and pathways of alien freshwater megafauna

Almost half of the extant freshwater megafauna species have been introduced outside of their native ranges, covering 142 countries and regions (**Chapter 4**). The wide introduction and establishment of alien freshwater megafauna in numerous countries can be attributed to their intrinsic characteristics and potential contribution to human societies. Many freshwater megafauna species possess traits such as rapid growth, high reproductive capacity and tolerance for diverse environmental conditions, enabling them to exploit and thrive in new environments, which makes them excellent candidates for aquaculture. For instance, African catfish can reach maturity within eight months (Kurbanov et al., 2017), with an ability to produce a large number of eggs (e.g., 150,000 to 300,000 eggs for a 6-kg female; Bruton, 1986; Gisbert et al., 2022). Common carp is known for its high fecundity, with large females producing up to 1.5 million eggs. Additionally, when introduced to South Africa, it displayed accelerated growth and earlier maturation (within two years) compared to individuals in its native range (Winker et al., 2011). Some species, like brown trout, show diverse adaptations in novel environments (Sharma et al., 2021).

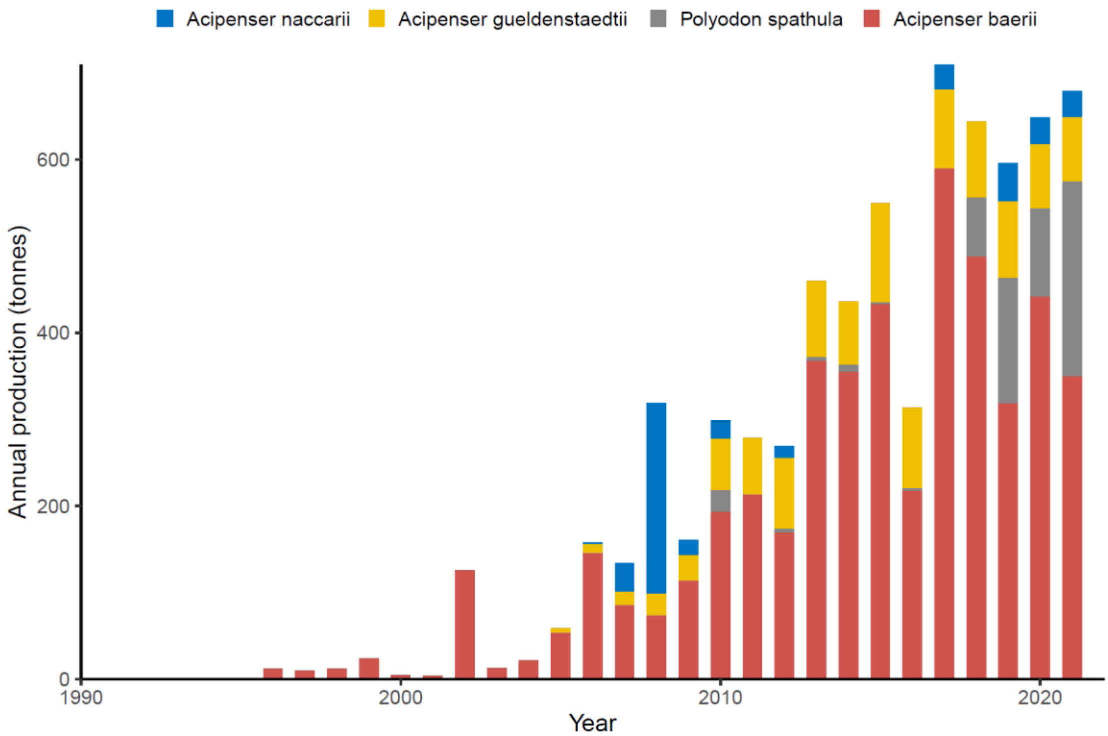

Fig. 5.1 Global annual production of four main sturgeon species through aquaculture and capture in their introduction countries and regions (data from FAO, 2023).

Intentional introduced for various purposes, including commercial farming, recreational fishing, aquarium trade, materials and biological control, contributed to their wide introduction and establishment (**Chapter 3 and Chapter 4**). For instance, in the Rhine-Meuse delta, since 1990, alien sturgeon species, including Russian sturgeon (*Acipenser gueldenstaedtii*), Siberian sturgeon (*Acipenser baerii*), Sterlet (*Acipenser ruthenus*), Adriatic sturgeon (*Acipenser naccarii*), Stellate sturgeon, white sturgeon and beluga (*Huso huso*) have been introduced for commercial fishery (Fig. 5.1) and some of them have escaped to wild environments, presenting ecological concerns (Brevé et al., 2022). Similarly, many large carp species, including common carp, black carp (*Mylopharyngodon piceus*), grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Hypophthalmichthys nobilis*) are widely introduced for commercial fishery as they can provide food resources for local community. They have also been reported to escape from aquaculture facilities into ecosystems like the Great Lakes Basin (Chapman et al., 2021; Li et al., 2021). Not only fish, but also crocodilians (e.g., Nile crocodile; *Crocodylus niloticus*, spectacled caiman; *Caiman crocodilus* and Siamese crocodile; *Crocodylus siamensis*), Chinese giant salamander (*Andrias davidianus*) and American beaver (*Castor canadensis*) are introduced for farming as their meat, skin and fur have high market value (Chen et al., 2018; Fukumoto et al., 2015; Huang et al., 2018; Schüttler et al., 2011; Zhang et al., 2021). The commercial farming pathway is expected to play an increasingly significant role in the future. This is propelled by the growing development of hatchery programs globally and the expansion of alien megafish aquaculture, especially in developing countries (Bernery et al., 2022; Kang et al., 2023; Vitule et al., 2019). Consequently, more alien freshwater megafauna species are likely to be introduced outside of their native ranges.

The global distribution of alien freshwater megafauna is also significantly influenced by pet trading and recreational fishing/hunting. Enthusiasts and hobbyists, motivated by the allure of these remarkable species as pets or for sport, often introduce them to non-native ranges. For example, crocodilians (e.g., spectacled caiman, Nile crocodile and dwarf caiman; *Paleosuchus palpebrosus*), turtles (e.g., common snapping turtle; *Chelydra serpentina* and alligator snapping turtle; *Macrochelys temminckii*) and megafish (e.g., alligator gar; *Atractosteus spatula*, ocellate river stingray; *Potamotrygon motoro* and redtail catfish;

Phractocephalus hemioliopterus) have been introduced for pet trading (Dickey et al., 2023; Jerikho et al., 2023; Koo et al., 2020, 2021; Roberto et al., 2021). Many of them established self-sustainable populations after escaping to wild environments. For example, alien hippopotamuses (*Hippopotamus amphibius*) escaped from personal zoo of deceased drug dealer Pablo Escobar and established population in Colombia (Mega, 2023). One study estimated that the population of hippopotamuses could reach more than 700 individuals in the next ten years (Castelblanco-Martínez et al., 2021). Some alien megafish species are intentionally released into the wild for recreational fishing/hunting. For example, flathead catfish (*Pylodictis olivaris*) were introduced to coastal rivers in North Carolina exclusively for recreational fishing and established self-sustained populations (Lucchesi et al., 2017; Pine et al., 2005).

Freshwater megafauna have been used as biological control agents to manage detrimental organisms, including alien aquatic plants, phytoplankton and alien fish (**Chapter 4**). For instance, Chinook salmon were introduced to regulate alewife (*Alosa pseudoharengus*), an invasive species that caused negative impacts on native species in the Great Lakes (Ivanova et al., 2022). However, the use of certain alien freshwater megafauna species, such as grass carp, black carp and silver carp, for biological control has led to unintended consequences. Some of these species have become established and become invasive, causing catastrophic ecological impacts, as discussed in **Chapter 3**.

The widespread distribution of alien freshwater megafauna is intricately connected to economic drivers. Understanding these drivers sheds light on the patterns and motivations behind intentional introductions and also shows the challenges associated with both deliberate and unintentional releases. As global trade and aquaculture practices continue to expand, the complexities of preventing these introductions demand nuanced strategies and heightened awareness.

5.6 Major environmental impacts of alien freshwater megafauna

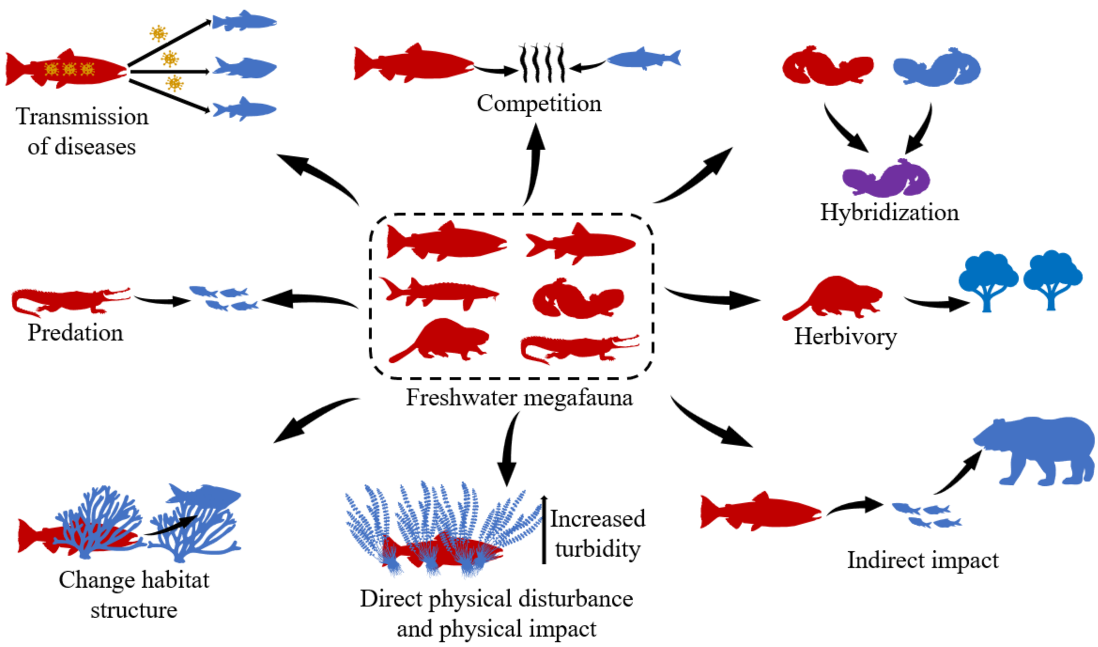

Fig. 5.2 Schematic representation of negative environmental impact of alien freshwater megafauna.

Alien freshwater megafauna have profound impacts on native species through a broad range of mechanisms, including competition, predation, hybridisation, transmission of diseases to native species, direct physical disturbance, herbivory, physical impact on ecosystem, structural impact on ecosystem and indirect impacts through interactions with other species (Fig. 5.2). Predation is the predominant mechanism as many freshwater megafauna species occupy high trophic levels and prey on various organisms. Northern pike (*Esox lucius*), lake trout (*Salvelinus namaycush*), flathead catfish and Wels catfish (*Silurus glanis*) all contributed to the population decline of native species through predation (Castaldelli et al., 2013; Dobbins et al., 2012; Findlay et al., 2005; Koel et al., 2019; Zelasko et al., 2016) while Nile perch caused irreversible extinctions of numerous cichlids through predation (Witte et al., 1992). Competition for food or habitat with native species has also been documented for many alien freshwater megafauna species. The silver carp and brown trout have shown remarkable adaptability in the introduced regions, outcompeting native species in the U.S. (DeBoer et al., 2018; Houde et al., 2015) and Himalayan rivers (Johal et al., 2021). They pose strong influences on species that they directly compete with and also affect other species through trophic cascades (Koel et al., 2005, 2019). Hybridisation further complicates the ecological impact of alien freshwater megafauna. For instance, over 60% of the salamanders sampled in the Katsura River were found to be hybrids of the alien Chinese giant salamanders and native Japanese giant salamanders, causing genetic pollution of the native species (Fukumoto et al., 2015). Alien freshwater megafauna also act as carriers, transmitting diseases to native species, such as *Triaenophorus crassus* carried by northern pikes, leading to health crises among native lake char (*Salvelinus umbla*; Schaufler et al., 2014). Additionally, habitat alterations, often induced by burrowing behaviours or the removal of aquatic plants, affect the performance or population dynamics of native species. For instance, removing aquatic plant by grass carp can lead to a decline in the populations of native fishes in Ball Pond, U.S., by affecting their spawning and defence against predators (June-Wells et al., 2017).

Compared to their negative ecological impact, the positive environmental impacts of alien freshwater megafauna have received limited research attention. In the identified literature, alien freshwater megafauna mainly posed positive impacts on native species through three mechanisms (i.e., indirect impacts through interactions with other taxa, provision of trophic resources and epibiosis or other direct provisioning of habitat). The limited research on positive impacts may underestimate their significance (Vimercati et al., 2020). However, acknowledging positive ecological impacts does not imply a justification for the introduction of alien freshwater megafauna as the target native species benefiting from positive interactions may not align across diverse ecosystems. For instance, common carps can serve as food resources for birds like great crested grebes (*Podiceps cristatus*) and red-necked grebes (*Podiceps grisegena*) in Poland (Kloskowski et al., 2021). However, they can also have detrimental effects on native fish and plants due to competition, predation and physical disturbance in other regions (Bajer et al., 2016; Maceda-Veiga et al., 2017). Therefore, it is essential to recognize that the positive impacts of alien freshwater megafauna should not be viewed as counterbalancing their negative impacts. The assessment of their impact should be context-specific, considering the particular species involved and the dynamics of the ecosystem.

5.7 Natures' contribution to people associated with alien freshwater megafauna

While understanding the environmental impacts of alien freshwater megafauna is crucial, it is equally important to investigate interactions between them and human communities in the introduced region. A comprehensive understanding of their environmental and socio-economic impacts will facilitate effective management strategies for alien species. In total, 429 records documenting beneficial NCP provided by alien freshwater megafauna were identified. The provision of food and materials by certain megafauna species (e.g., crocodilians, common carp and African catfish) can have profound positive effects on human communities (Chen et al., 2018; Dauda et al., 2018; Vilizzi et al., 2015). Beyond the material benefits, the companionship provided by these species (e.g. turtles) as pets, adds a valuable social dimension to their contributions (Koo et al., 2020). Alien freshwater megafauna such as silver carp also have been used to regulate water quality by controlling populations of detrimental organisms through their predatory or herbivory behaviours (e.g., grass carp, silver carp, northern pike; Chen et al., 2023; Dibble & Kovalenko, 2009; Lieberman, 1996). Furthermore, the enhanced physical and psychological experiences, often observed in recreational fishing and ecotourism and derived from interacting with alien freshwater megafauna (e.g., salmonids and hippopotamuses) in natural settings enrich the well-being of individuals (Arismendi et al., 2014; Jackson et al., 2010). In some regions (e.g., Tierra del Fuego), alien freshwater megafauna (e.g., American beaver) also play a role in supporting cultural identities, providing unique connections to nature for local communities (Schüttler et al., 2011; Zhu et al., 2018).

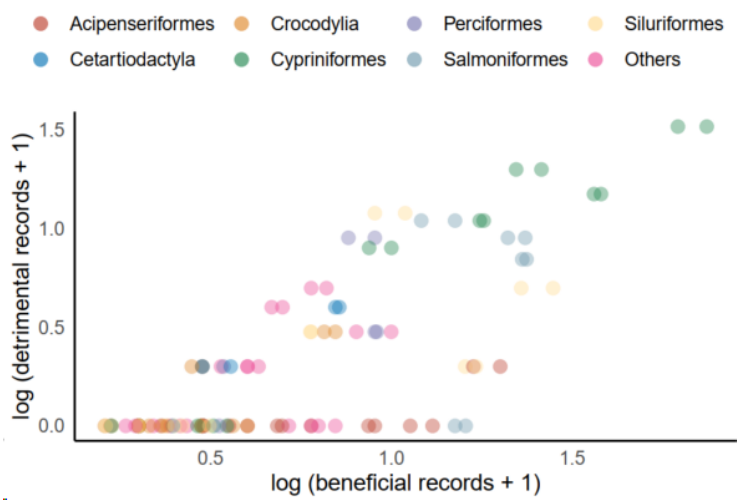

Fig. 5.3 Relationship between the number of records for detrimental NCP and beneficial NCP for each species.

Apart from beneficial NCP, alien freshwater megafauna also are associated with detrimental NCP, such as reduced food resources, damage to properties, reduced physical and psychological experiences and risk to health and safety. Compared to beneficial NCP, we identified much fewer records of detrimental NCP across many families (Fig. 5.3). The limited records are mainly associated with reduced food resources, damage to properties, decline in physical and psychological experiences and risks to health and safety, suggesting a critical gap in our understanding of the full spectrum of human-alien megafauna interactions. More than 60% of the records indicate the potential for alien freshwater megafauna to have detrimental NCPs. Our results suggest a potential underestimation of their detrimental NCP and an overemphasis on their beneficial NCP, possibly influencing decisions regarding their introduction (Gozlan, 2008). This observation emphasizes the necessity for a more comprehensive investigation of the multifaceted relationships between alien freshwater megafauna and human societies. Addressing this gap is essential not only for a more accurate assessment of the risks associated with introductions of alien freshwater megafauna but also for fostering a more balanced understanding of the trade-offs involved in their interactions with human communities (Sax et al., 2022; Vimercati et al., 2020).

5.8 Paradox and management of introductions of alien freshwater megafauna

Introductions of freshwater megafauna species represent a conservation paradox. On the one hand, introducing threatened freshwater megafauna to new habitats could enhance their survival. The market demand for species introduction might further facilitate more research on their life history and advancement in artificial breeding technology, which could potentially prevent species from extinction, particularly for species that could not naturally reproduce in the wild. This is exemplified by many sturgeon species, which, assessed as Vulnerable, Endangered, or Critically Endangered on the IUCN Red List, face declining populations in their native ranges (He et al., 2017). Sturgeon cultivation has emerged as a potential lifeline, rescuing certain species from the brink of extinction and reducing the pressure of overexploitation on natural populations (Jarić et al., 2018). However, through activities such as pet trading and commercial fishery, many sturgeon species are introduced outside their native ranges, where they may exert adverse effects on native species (Kang et al., 2023; Lockwood et al., 2019). For instance, alien Siberian sturgeons have been observed reproducing and hybridising with native sterlets in the Danube River, thereby posing a risk of extinction for this endangered species (Ludwig et al., 2009). Furthermore, Siberian sturgeons can negatively impact native species through predation and act as a central host for parasites like *Raphidascaris acus* (Skóra et al., 2018). This conservation paradox raises ethical questions. While introductions of freshwater megafauna species may provide support for their populations, such actions must be carefully assessed before implementation. Prioritizing the ex-situ preservation of one species at the expense of many others is not the best conservation practice.

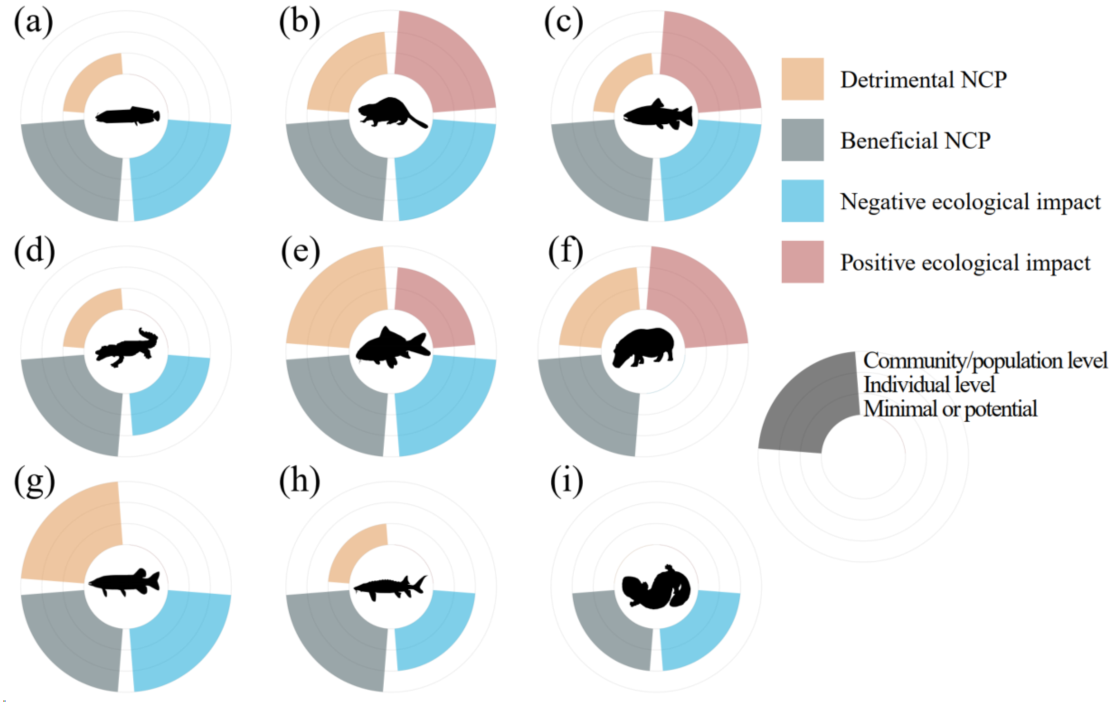

Fig. 5.4 Magnitude of nature's contribution to people (NCP) and environmental impact associated with some alien freshwater megafauna species: (a) African catfish, (b) American beaver, (c) brown trout, (d) spectacled caiman, (e) common carp, (f) hippopotamus, (g) northern pike, (h) Siberian sturgeon, (i) Chinese giant salamander. The heights of the bars indicate the levels of impact magnitude, which are adapted from chapter 3 and chapter 4. MO, MR, MV, MO+, MR+ and MV+ are classified as the population level; MN and MN+ are classified as the individual level; MC and ML+ are classified as the minimal.

Introductions of alien freshwater megafauna also create a complex paradox with both positive and negative impacts on native species and socio-economic aspects (Fig. 5.4). This paradox is evident in the conflict between beneficial NCP and negative environmental consequences. For instance, introductions of northern pike in the Northwestern U.S., driven by their value as sport fishes, have led to the local extinction of the three-spined stickleback (*Gasterosteus aculeatus*) in Prator Lake, Alaska (McMahon & Bennett, 1996; Patankar et al., 2006). Similar tensions between ecological and socio-economic aspects are seen in various alien freshwater megafauna species, such as the alien Chinook salmon in southern Chilean rivers (Arismendi et al., 2009). Conservationists aim to control it, considering it invasive, while the tourism and fishing industries view it as a valuable resource (Cid-Aguayo et al., 2021; Pascual et al., 2009). Acknowledging and respecting these opposite positions is critical for a balanced socio-environmental management strategy that benefit both people and biodiversity (Gozlan, 2008; Vitule et al., 2009).

To mitigate environmental impacts and maximise the NCP, various methods are used to manage alien freshwater megafauna. One important approach involves interrupting the reproductive processes of these species. For instance, in response to the proliferation of the hippopotamuses population in Colombia, considered one of the largest invasive species, researchers have undertaken the surgical removal of ovaries as a targeted method of population control (Hernández et al., 2015). Chemical interventions, such as rotenone, constitute another method of management for alien freshwater megafauna. For example, rotenone has been utilized to control invasive northern pike in Alaska (U.S.; Couture et al., 2022). However, the use of rotenone is not without its drawbacks; it is toxic to non-target species and poses potential harm to human health (Couture et al., 2022; Vasquez et al., 2012). In contrast, carbon dioxide barriers have emerged as a moderate and non-toxic method to deter the movement of bighead carp (Suski, 2020). These barriers can act as a "fence" or “wall” by inducing avoidance behaviours in bighead carp because they tend to swim away from areas of high carbon dioxide once a certain threshold has been reached (Donaldson et al., 2016; Suski, 2020). Moreover, both radio and acoustic telemetry offer potential methods for tracking and managing the movement of alien freshwater megafauna (Dennis & Sorensen, 2020; Vetter et al., 2019; Zielinski & Sorensen, 2017). Direct use strategies, which include encouraging local people to harvest and consume alien freshwater megafauna, is another potential method for management. In Yellowstone, for instance, approximately 3.35 million lake trout were eradicated through suppression efforts, primarily involving gillnetting, between 1995 and 2019 (Koel et al., 2020). Compared with the aforementioned methods, biological control is less commonly used to control alien freshwater megafauna. One example is that Cyprinid herpesvirus has been used to control alien common carp in Australia (Pera et al., 2021).

5.8 Outlook

This thesis highlights the vulnerability of native freshwater megafauna to alien species and the environmental and socio-economic impacts of alien freshwater megafauna. The short-term nature of many assessments may underestimate the potentially severe, population-level impacts of alien species, particularly in the Global South including many megafauna-rich basins (e.g., the Amazon, Congo, Mekong and Ganges-Brahmaputra). Long-term monitoring studies are critical to comprehensively assess the severity of alien-species impacts, particularly in understudied regions where impacts on freshwater megafauna may be overlooked. Considering the scarcity of comprehensive data for assessing the environmental impacts of all alien freshwater megafauna, using life history traits to predict their potential distributions and environmental impacts might be potential research. Additionally, a challenge arises from the fact that many alien freshwater megafauna are introduced within countries or specific regions. In these cases, local communities may not perceive them as alien species, leading to a lack of awareness and preventive measures. For example, the introduction of Asian carps, although native and widespread in most parts of China, has seen them extensively introduced to many lakes in Yunnan for aquaculture, resulting in declines in native species populations (Xie & Chen, 2001). Bridging this awareness gap becomes crucial for developing effective and locally sensitive management practices in the biosecurity aspect.

5.9 References (Chapter 5)

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Appendix A: Supporting information for Chapter 2

Table S2.1 EICAT assessment results for 44 impacted native freshwater megafauna species [a].

Binomial name	Common name	IUCN Red List category	Impact mechanisms	Highest impact magnitude	Frequency of the highest impact
Acipenser fulvescens	Lake sturgeon	Least Concern	Predation/Structural impact	Minor	5/5
Acipenser medirostris	Green sturgeon	Near Threatened	Predation/Physical impact	Minor	3/3
Acipenser naccarii	Adriatic sturgeon	Critically Endangered	Predation	Minor	1/1
Acipenser nudiventris	Ship sturgeon	Critically Endangered	Parasitism	Massive	1/3
Acipenser oxyrinchus	Gulf Sturgeon	Near Threatened	Predation	Minor	1/1
Acipenser stellatus	Stellate sturgeon	Critically Endangered	Competition	Minor	3/3
Acipenser transmontanus	White sturgeon	Least Concern	Predation	Minor	2/3
Alligator mississippiensis	American alligator	Least Concern	Predation	Minor	5/5
Andrias japonicus	Japanese giant salamander	Near Threatened	Hybridization	Minor	3/3
Bagrus docmak	Sudan catfish	Least Concern	Competition/predation	Moderate	2/2
Caiman latirostris	Broad-snouted caiman	Least Concern	Predation	Minor	1/1
Caiman yacare	Yacaré	Least Concern	Predation	Minor	2/2
Castor fiber	Eurasian beaver	Least Concern	Competition	Moderate	1/1
Clarias gariepinus	African catfish	Least Concern	Predation	Moderate	1/1

Binomial name	Common name	IUCN Red List category	Impact mechanisms	Highest impact magnitude	Frequency of the highest impact
Clarias macrocephalus	Broadhead catfish	Data Deficient	Hybridisation	Minor	2/3
Crocodylus acutus	American crocodile	Vulnerable	Competition/predation	Minor	3/3
Crocodylus johnsoni	Freshwater crocodile	Least Concern	Poisoning/ toxicity	Moderate	2/12
Crocodylus niloticus	Nile crocodile	Least Concern	Physical impact	Minor	1/1
Crocodylus novaeguineae	New Guinea crocodile	Least Concern	Predation	Minor	1/1
Crocodylus porosus	Saltwater crocodile	Least Concern	Poisoning/ toxicity	Minor	2/2
Crocodylus rhombifer	Cuban crocodile	Critically Endangered	Competition/predation	Minor	2/2
Crocodylus siamensis	Siamese crocodile	Critically Endangered	Hybridisation	Minor	1/1
Esox lucius	Northern pike	Least Concern	Competition/predation	Minor	2/2
Esox masquinongy	Muskellunge	Least Concern	Transmission of diseases	Minor	1/1
Hydrochoerus hydrochaeris	Capybara	Least Concern	Direct physical disturbance	Minimal Concern	1/1
Hypophthalmichthys nobilis	Bighead carp	Data Deficient	Competition	Minimal Concern	1/1
Ictiobus cyprinellus	Bigmouth buffalo	Least Concern	Competition	Minor	2/3
Kobus leche	Southern lechwe	Near Threatened	Physical impact	Moderate	1/1
Labeo rohita	Rohu	Least Concern	Predation/ transmission of diseases	Minor	2/2
Lates calcarifer	Barramundi	Least Concern	Predation	Minor	2/3
Lota lota	Burbot	Least Concern	Competition/predation/ poisoning/ toxicity	Minor	6/6

Binomial name	Common name	IUCN Red List category	Impact mechanisms	Highest impact magnitude	Frequency of the highest impact
Morone saxatilis	Striped bass	Least Concern	Indirect impacts	Minor	2/2
Oncorhynchus tshawytscha	Chinook salmon	Not Evaluated	Predation	Moderate	1/25
Polyodon spathula	Paddlefish	Vulnerable	Competition	Minor	3/3
Protopterus aethiopicus	Marbled lungfish	Least Concern	Predation	Moderate	1/1
Pseudoplatystoma corruscans	Spotted sorubim	Not Evaluated	Hybridisation	Minor	1/1
Ptychocheilus lucius	Colorado pikeminnow	Vulnerable	Competition/predation	Moderate	3/4
Pusa caspica	Caspian seal	Endangered	Indirect impacts	Moderate	1/1
Salmo marmoratus	Marble trout	Least Concern	Hybridisation	Moderate	1/13
Salmo salar	Atlantic salmon	Least Concern	Parasitism	Moderate	6/56
Salmo trutta	Brown trout	Least Concern	Competition/predation	Moderate	5/25
Salvelinus namaycush	Lake trout	Not Evaluated	Competition/predation	Moderate	9/44
Scaphirhynchus albus	Pallid sturgeon	Endangered	Predation	Minor	1/1
Tomistoma schlegelii	False gharial	Vulnerable	Predation	Minor	1/1

[a] Species are classified under EICAT by the most severe impact they sustained.

Table S2.2 Contingency table (chi-squared test) showing the actual and expected number of each taxonomic group of freshwater megafauna for less severe impacts and harmful impacts [a, b].

	Megafauna fishes	Megafauna reptiles	Megafauna mammals	Total
Less severe impacts (Minimal Concern and Minor)	25	11	1	37
	25.39	*8.71*	*2.90*	
	(0.01)	(0.61)	(1.28)	
Harmful impacts (Moderate, Major and Massive)	10	1	3	14
	9.61	*3.30*	*1.10*	
	(0.02)	(1.60)	(3.30)	
Total	35	12	4	51

[a] χ^2 = 2.69, df = 2, P = 0.16, estimates = 0.19

[b] Expected values are displayed in italics. Individual χ^2 values are displayed in parentheses. Due to small sample sizes, impacts for freshwater megafauna amphibian were excluded from the test.

Table S2.3 Contingency table (chi-squared test) showing the actual and expected number of each impact mechanism for less severe impacts and harmful impacts [a, b].

	Competition	Predation	Hybridization	Poisoning/ toxicity	Other impacts	Total
Less severe impacts (Minimal Concern and Minor)	30	43	7	6	12	98
	30.47	*42.82*	*6.59*	*5.76*	*12.35*	
	(0.01)	(0.01)	(0.03)	(0.01)	(0.01)	
Harmful impacts (Moderate, Major and Massive)	7	9	1	1	3	22
	6.53	*9.18*	*1.41*	*1.24*	*2.65*	
	(0.03)	(0.01)	(0.12)	(0.05)	(0.05)	
Total	37	52	8	7	15	120

[a] $\chi^2 = 0.17$, df=4, P = 0.99, estimates = 0.02.

[b] Expected values are displayed in italics. Individual χ^2 values are displayed in parentheses. Due to small sample sizes, “Transmission of diseases to native species”, “Direct physical disturbance”, “Structural Impact on ecosystem”, and “Indirect impacts through interactions with other species”, “physical impact on ecosystem” were combined as “other impacts”.

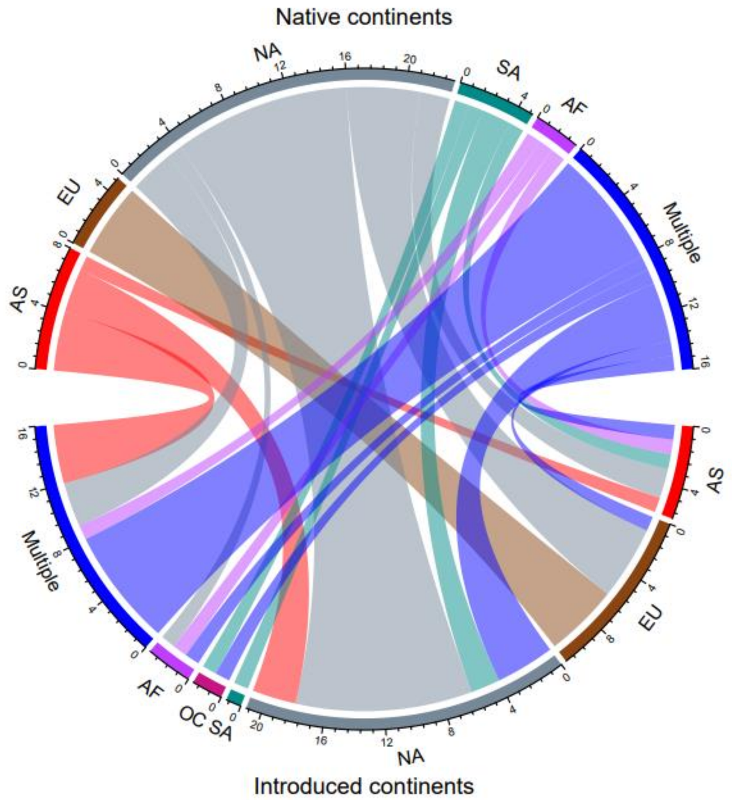

Fig. S2.1 Alien species introduced from native continents (upper half) to introduced continents (lower half). AF, Africa; AS, Asia; OC, Oceania; EU, Europe; NA, North (and Central) America; SA, South America; Multiple, more than one continent. The width of the arrow represents the number of species introduced from native continents to introduced continents.

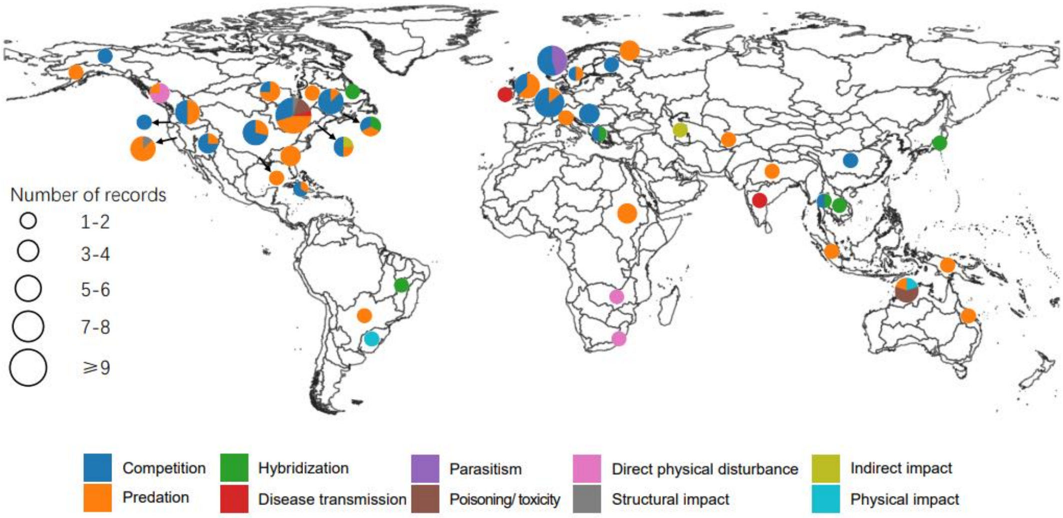

Fig. S2.2 Number of unique interaction records categorized by the mechanism of their impacts on native freshwater megafauna.

References documents

The following reference documents were used to collate data on impacts of alien species on native freshwater megafauna during the EICAT assessment:

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Appendix B: Supporting information for Chapter 3

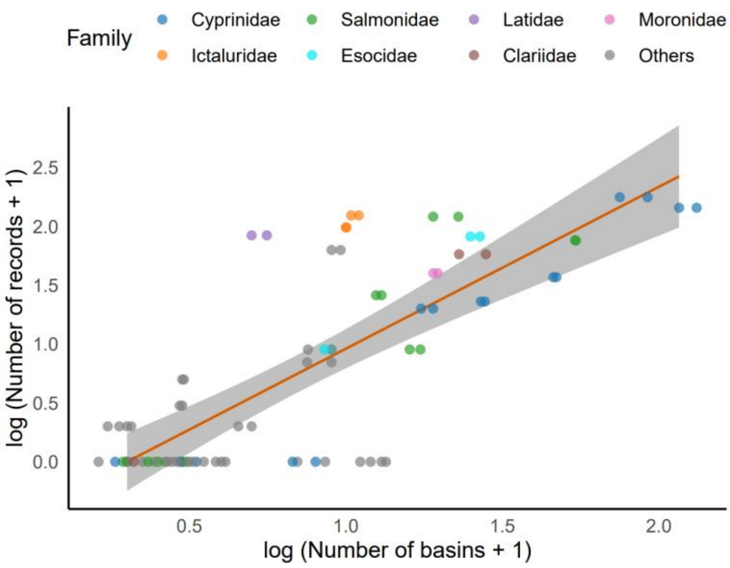

Fig. S3.1 Relationship between the number of impact records for each species and the number of basins to which they have introduced.

Table S3.1 Categorisation of introduction pathways of alien freshwater megafish. We adapted the framework proposed by Harrower et al. (2018) and grouped instances labelled as "aquaculture" and "fishery in wild" into the category "commercial fishery" when the "fishery in wild" pathway involved the introduction of alien megafish for food resources. In cases where records were previously designated as "fishery in wild" but also included the creation of opportunities for recreational fishing, we reclassified them as "recreational fishing".

Categories in our study	Categories from Harrower et al. (2018)	Example of megafish introduction
Commercial fishery	"Fishery in wild", "Aquaculture"	Atlantic salmon introduced to Chile for aquaculture; production reached 532,000 tons in 2016 (Quiñones et al., 2019).
Aquarium	"Zoo/Aquaria/Botan", "Pet", "Ornamental"	Alligator gar introduced as pets in China and released in urban ponds (Han, 2022).
Biological control	"Biological control"	Black carp introduced to the U.S. for controlling snails (Ledford & Kelly, 2006).
Recreational fishing	"Fishery in wild"	Brown trout introduced to New Zealand for recreational fishing (P. Jones & Closs, 2017).
Research	"Research"	Tarpon introduced into Victor Brauning Reservoir in Texas for cold tolerance experiments (Fuller et al., 2023).
Waterways	"Waterways"	African catfish entered eastern South Africa via a water tunnel connecting Orange and Great Fish rivers (J. Cambray, 2003).

Table S3.2 Contingency table showing observed and expected (in *italic*) numbers of records to each impact mechanism by family of megafish. Families with a few species including Acipenseridae, Channidae, Lotidae, Pangasiidae, Pimelodidae, Polyodontidae, Protopteridae and Siluridae were grouped as ‘Others’. Data for structural impact on ecosystem (n = 37), direct physical impact (n = 21), and physical impact on ecosystem (n = 11) were not included in the test due to low sample size.

Family	Competition	Predation	Hybridization	Disease transmission	Herbivory	Interaction with other species
Cyprinidae	36	92	2	30	149	18
	36.74	*213.70*	*7.85*	*13.46*	*43.31*	*10.94*
Ictaluridae	4	214	0	0	2	0
	24.72	*143.77*	*5.28*	*9.06*	*29.81*	*7.36*
Salmonidae	51	81	14	6	1	19
	29.44	*171.22*	*6.29*	*10.79*	*35.50*	*8.76*
Esocidae	2	84	1	1	0	1
	10.00	*58.16*	*2.14*	*3.66*	*12.06*	*2.98*
Latidae	7	75	0	0	0	1
	9.33	*54.24*	*1.99*	*3.42*	*11.25*	*2.78*
Clariidae	2	42	6	1	6	0
	6.40	*37.25*	*1.37*	*2.35*	*7.72*	*1.91*
Moronidae	0	35	2	2	0	0
	4.38	*25.49*	*0.94*	*1.61*	*5.28*	*1.30*
Others	1	79	3	8	0	0
	10.00	*58.16*	*2.14*	*3.66*	*12.06*	*2.98*

$\chi2 = 720.40$, df = 35, $p < 0.01$, estimate = 0.50

Table S3.3 Results of the generalized linear mixed model (GLMM) testing the association between direct or indirect mechanisms and harmful impacts. Direct impact mechanisms = predation, hybridisation, direct physical disturbance and herbivory. Indirect impact mechanisms = competition, transmission of diseases, physical impact on ecosystem, structural impact on ecosystem, and interaction with other species. Moderate (MO), Major (MR), and Massive (MV) were classified as 'harmful'; Minimal Concern (MC) and Minor (MN) were classified as 'less harmful'. Model term: Harmful or less harmful impacts ~ mechanisms type (Direct or indirect) +1(1|continent), family = binomial, Harmful impacts were marked as "1", less harmful impacts were marked as "0". Positive estimate value means mechanism type associated with harmful impacts, vice versa.

Fixed effects	Estimate	Std. Error	Z value	p
Indirect impact mechanism	0.798	0.176	4.536	<0.001
Intercept	-1.760	0.211	-8.344	<0.001

Random effect	Variance	Std. Dev
Intercept	0.178	0.422

Table S3.4 Contingency table showing observed and expected (in *italic*) number of records to each impact mechanism by harmful and less harmful impact categories. Moderate (MO), Major (MR), and Massive (MV) were classified as 'harmful'; Minimal Concern (MC) and Minor (MN) were classified as 'less harmful'.

Impact mechanisms	Harmful	Less harmful
Competition	43	74
	22.42	*94.58*
Predation	102	631
	140.44	*592.56*
Hybridization	1	26
	5.17	*21.83*
Disease transmission	1	46
	9.01	*37.99*
Direct physical disturbance	6	15
	4.02	*16.98*
Herbivory	39	119
	30.27	*127.73*
Physical impact on ecosystem	0	11
	2.11	*8.89*
Structural impact on ecosystem	26	11
	7.09	*29.91*
Interaction with other species	10	29
	7.47	*31.53*

$\chi 2 = 119.74$, df = 8, $p < 0.01$, estimate = 0.32

Table S3.5 Contingency table showing observed and expected (in *italic*) numbers of records to each family of megafish by 'harmful' and 'less harmful' impact categories. The 'Others' group included Acipenseridae, Channidae, Lotidae, Pangasiidae, Pimelodidae, Polyodontidae, Protopteridae and Siluridae. Moderate (MO), Major (MR), and Massive (MV) impacts were classified as 'harmful'; Minimal Concern (MC) and Minor (MN) impacts were classified as 'less harmful'.

Family	Harmful	Less harmful
Cyprinidae	91	305
	71.88	*324.12*
Ictaluridae	8	212
	39.93	*180.07*
Salmonidae	48	169
	39.39	*177.61*
Esocidae	25	64
	15.07	*67.93*
Latidae	32	51
	15.44	*67.56*
Clariidae	2	55
	10.35	*46.65*
Moronidae	5	34
	7.08	*31.92*
Others	5	84
	16.15	*72.85*

$\chi 2 = 90.50$, df = 7, $p < 0.01$, estimate = 0.27

References documents

The following reference documents were used in Table S3.1:

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Appendix C: EICAT assessments for alien freshwater megafish

Table C1 Alien freshwater megafish EICAT assessment (modified from chapter 3).

Impact categories: MC = Minimal Concern; MN = Minor; MO = Moderate; MR = Major; MV = Massive

Impact mechanisms: Com = Competition; Pred = Predation; Hybr = Hybridisation; Dis = Transmission of diseases to native species; Dire = direct physical disturbance; Graz = Grazing/herbivory/browsing; Phys = Physical impact on ecosystem; Struc = Structural impact on ecosystem; Int = Indirect impacts through interactions with other species

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Acipenser baerii	Siberian sturgeon	*Acipenser ruthenus*	Hybr	MN	Ludwig et al., 2009
Acipenser baerii	Siberian sturgeon	*Neomysis integer*	Pred	MN	Skóra et al., 2018
Acipenser baerii	Siberian sturgeon	*Osmerus eperlanus*	Pred	MN	Skóra et al., 2018
Acipenser baerii	Siberian sturgeon	*Cercopagis pengoi*	Pred	MN	Skóra et al., 2018
Acipenser baerii	Siberian sturgeon	Inverterbrates	Pred	MN	Skóra et al., 2018
Acipenser baerii	Siberian sturgeon	Fishes	Dis	MC	Skóra et al., 2018
Acipenser stellatus	Stellate sturgeon	*Acipenser nudiventris*	Hybr	MN	Gesner et al., 2010
Channa marulius	Bullseye snakehead	Fishes	Dis	MC	Saylor et a., 2010
Clarias gariepinus	African catfish	*Clarias batrachus*	Hybr	MN	Rahman et al., 1995
Clarias gariepinus	African catfish	*Leptodactylus ocellatus*	Pred	MN	Vitule et al., 2008

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Clarias gariepinus	African catfish	*Clarias anguillaris*	Hybr	MN	Nwafili & Gao, 2007
Clarias gariepinus	African catfish	*Hyperolius marmoratus*	Pred	MN	Alexander et al., 2014
Clarias gariepinus	African catfish	*Sarotherodon mossambicus*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Pseudocrenilabrus philander*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	Fishes	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Glossogobius giurus*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Croilia mossambica*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Gilchristella aestuarius*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Tilapia sparrmanii*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Glossogobius giuris*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Hymenosoma orbiculare*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Potamon sidneyi*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Caridina nilotica*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Grandidierella lignorum*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Afrochiltonia capensis*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Apseudes digitalis*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Cyathura carinata*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Pontogeloides latipes*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Povilla adusta*	Pred	MN	Bruton, 1979

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Clarias gariepinus	African catfish	Invertebrates	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Melanoides tuberculatus*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Bellamya capillata*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Bulinus* sp.	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	*Corbicula africana*	Pred	MN	Bruton, 1979
Clarias gariepinus	African catfish	Aquatic plants	Graz	MN	Bruton, 1979
Clarias gariepinus	African catfish	Diatoms	Graz	MN	Bruton, 1979
Clarias gariepinus	African catfish	Invertebrates	Pred	MO	Kadye & Booth, 2012a
Clarias gariepinus	African catfish	*Barbus pallidus*	Pred	MN	Kadye & Booth, 2012b
Clarias gariepinus	African catfish	*Oreochromis mossambicus*	Pred	MN	Kadye & Booth, 2012b
Clarias gariepinus	African catfish	*Labeo umbratus*	Pred	MN	Kadye & Booth, 2012b
Clarias gariepinus	African catfish	Invertebrates	Pred	MN	Kadye & Booth, 2012b
Clarias gariepinus	African catfish	Phytoplankton	Graz	MN	Kadye & Booth, 2012b
Clarias gariepinus	African catfish	Macrophytes	Graz	MN	Kadye & Booth, 2012b
Clarias gariepinus	African catfish	*Glossogobius callidus*	Pred	MN	Potts et al., 2008
Clarias gariepinus	African catfish	*Labeo umbratus*	Pred	MN	Potts et al., 2008
Clarias gariepinus	African catfish	Fishes	Pred	MN	Potts et al., 2008
Clarias gariepinus	African catfish	Phytoplankton	Graz	MN	Potts et al., 2008
Clarias gariepinus	African catfish	Terrestrial plant	Graz	MN	Potts et al., 2008

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Clarias gariepinus	African catfish	Insects	Pred	MN	Potts et al., 2008
Clarias gariepinus	African catfish	Birds	Pred	MN	Potts et al., 2008
Clarias gariepinus	African catfish	Crabs	Pred	MN	Potts et al., 2008
Clarias gariepinus	African catfish	Frogs	Pred	MN	Potts et al., 2008
Clarias gariepinus	African catfish	Zooplankton	Pred	MN	Potts et al., 2008
Clarias gariepinus	African catfish	*Glossogobius giuris*	Pred	MN	Whitfield & Blaber, 1978
Clarias gariepinus	African catfish	Fishes	Pred	MN	Whitfield & Blaber, 1978
Clarias gariepinus	African catfish	*Pomadasys commersonni*	Pred	MN	Whitfield & Blaber, 1978
Clarias gariepinus	African catfish	*Rhabdosargus sarba*	Pred	MN	Whitfield & Blaber, 1978
Clarias gariepinus	African catfish	*Thryssa vitrirostris*	Pred	MN	Whitfield & Blaber, 1978
Clarias gariepinus	African catfish	Fishes	Dis	MC	Ribeiro et al., 2019
Clarias gariepinus	African catfish	*Clarias batrachus*	Com	MR	Low et al., 2022
Clarias gariepinus	African catfish	*Clarias leiacanthus*	Com	MC	Low et al., 2022
Clarias gariepinus	African catfish	*Clarias batrachus*	Hybr	MN	Parvez et al., 2022
Clarias gariepinus	African catfish	*Clarias macrocephalus*	Hybr	MN	Senanan et al., 2004
Clarias gariepinus	African catfish	*Clarias macrocephalus*	Hybr	MN	Na-Nakorn et al., 2004
Ctenopharyngodon idella	Grass carp	*Cladophora globulina*	Graz	MN	Pípalová, 2002
Ctenopharyngodon idella	Grass carp	*Eleocharis acicularis*	Graz	MN	Pípalová, 2002
Ctenopharyngodon idella	Grass carp	*Potamogeton pusillus*	Graz	MN	Pípalová, 2002

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ctenopharyngodon idella	Grass carp	*Stuckenia pectinata*	Graz	MN	Pípalová, 2002
Ctenopharyngodon idella	Grass carp	*Myriophyllum spicatum*	Graz	MN	Pípalová, 2002
Ctenopharyngodon idella	Grass carp	*Ceratophyllum demersum*	Graz	MN	Pípalová, 2002
Ctenopharyngodon idella	Grass carp	*Elatine hydropiper*	Graz	MN	Pípalová, 2002
Ctenopharyngodon idella	Grass carp	*Cladophora globulina*	Graz	MN	Pípalová et al., 2009
Ctenopharyngodon idella	Grass carp	*Eleocharis acicularis*	Graz	MN	Pípalová et al., 2009
Ctenopharyngodon idella	Grass carp	*Potamogeton pusillus*	Graz	MN	Pípalová et al., 2009
Ctenopharyngodon idella	Grass carp	*Phoxinellus epiroticus*	Struc	MO	Leonardos et al., 2008
Ctenopharyngodon idella	Grass carp	*Phoxinellus pamvoticus*	Struc	MO	Leonardos et al., 2008
Ctenopharyngodon idella	Grass carp	*Luciobarbus albanicus*	Struc	MO	Leonardos et al., 2008
Ctenopharyngodon idella	Grass carp	*Najas indica*	Graz	MN	Singh et al., 1967
Ctenopharyngodon idella	Grass carp	*Nymphoides indica*	Graz	MN	Singh et al., 1967
Ctenopharyngodon idella	Grass carp	*Ceratophyllum demersum*	Graz	MN	Singh et al., 1967
Ctenopharyngodon idella	Grass carp	*Vallisneria spiralis*	Graz	MN	Singh et al., 1967
Ctenopharyngodon idella	Grass carp	*Ottelia alismoides*	Graz	MN	Singh et al., 1967
Ctenopharyngodon idella	Grass carp	*Nechamandra alternifolia*	Graz	MN	Singh et al., 1967
Ctenopharyngodon idella	Grass carp	*Utricularia inflexa*	Graz	MN	Singh et al., 1967
Ctenopharyngodon idella	Grass carp	*Myriophyllum tuberculatum*	Graz	MN	Singh et al., 1967
Ctenopharyngodon idella	Grass carp	*Trapa* sp.	Graz	MN	Singh et al., 1967

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ctenopharyngodon idella	Grass carp	*Salvinia cucllata*	Graz	MN	Singh et al., 1967
Ctenopharyngodon idella	Grass carp	*Azolla pinnata*	Graz	MN	Singh et al., 1967
Ctenopharyngodon idella	Grass carp	*Leander paucidens*	Struc	MN	Kuronuma & Nakamura, 1957
Ctenopharyngodon idella	Grass carp	*Hydrilla verticillata*	Graz	MN	Prowse, 1971
Ctenopharyngodon idella	Grass carp	Fishes	Dis	MC	Scholz & Salgado-Maldonado, 2000
Ctenopharyngodon idella	Grass carp	*Chara aspera*	Graz	MN	Dorenbosch & Bakker, 2012
Ctenopharyngodon idella	Grass carp	*Stuckenia pectinata*	Graz	MN	Dorenbosch & Bakker, 2012
Ctenopharyngodon idella	Grass carp	*Nitella hookeri*	Graz	MN	Edwards, 1974
Ctenopharyngodon idella	Grass carp	*Paspalum* sp.	Graz	MN	Edwards, 1974
Ctenopharyngodon idella	Grass carp	*Azolla rubra*	Graz	MN	Edwards, 1974
Ctenopharyngodon idella	Grass carp	*Myriophyllum propinquum*	Graz	MN	Edwards, 1974
Ctenopharyngodon idella	Grass carp	*Potamogeton ochreatus*	Graz	MN	Mitchell, 1980
Ctenopharyngodon idella	Grass carp	*Eleocharis sphacelata*	Graz	MN	Mitchell, 1980
Ctenopharyngodon idella	Grass carp	*Nitella hookeri*	Graz	MN	Mitchell, 1980
Ctenopharyngodon idella	Grass carp	*Retropinna retropinna*	Int	MO	Mitchell, 1986
Ctenopharyngodon idella	Grass carp	*Gobiomorphus cotidianus*	Int	MN	Mitchell, 1986
Ctenopharyngodon idella	Grass carp	Zooplankton	Struc	MN	Branford & Duggan, 2017
Ctenopharyngodon idella	Grass carp	*Stuckenia pectinata*	Graz	MN	Catarino et al., 1997
Ctenopharyngodon idella	Grass carp	*Myriophyllum spicatum*	Graz	MN	Catarino et al., 1997

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ctenopharyngodon idella	Grass carp	*Acipenser stellatus*	Com	MN	Patriche et al., 2002
Ctenopharyngodon idella	Grass carp	Invertebrates	Pred	MN	Weyl & Martin, 2016
Ctenopharyngodon idella	Grass carp	*Stuckenia pectinata*	Graz	MO	Weyl & Martin, 2016
Ctenopharyngodon idella	Grass carp	*Stuckenia pectinata*	Graz	MO	Venter & Schoonbee, 1991
Ctenopharyngodon idella	Grass carp	*Lagarosiphon* spp.	Graz	MO	Venter & Schoonbee, 1991
Ctenopharyngodon idella	Grass carp	*Potamogeton perfoliatus*	Graz	MN	George, 1982
Ctenopharyngodon idella	Grass carp	*Potamogeton nodosus*	Graz	MN	George, 1982
Ctenopharyngodon idella	Grass carp	*Potamogeton crispus*	Graz	MN	George, 1982
Ctenopharyngodon idella	Grass carp	*Stuckenia pectinata*	Graz	MN	George, 1982
Ctenopharyngodon idella	Grass carp	*Panicum repens*	Graz	MN	George, 1982
Ctenopharyngodon idella	Grass carp	*Cyperus rotundus*	Graz	MN	George, 1982
Ctenopharyngodon idella	Grass carp	*Bulinus* sp.	Int	MN	George, 1982
Ctenopharyngodon idella	Grass carp	*Biomphalaria* sp.	Int	MN	George, 1982
Ctenopharyngodon idella	Grass carp	*Stuckenia pectinata*	Graz	MN	Fowler & Robson, 1978
Ctenopharyngodon idella	Grass carp	*Potamogeton berchtoldii*	Graz	MN	Fowler & Robson, 1978
Ctenopharyngodon idella	Grass carp	*Ranunculus trichophyllus*	Graz	MN	Fowler & Robson, 1978
Ctenopharyngodon idella	Grass carp	*Potamogeton natans*	Graz	MN	Fowler & Robson, 1978
Ctenopharyngodon idella	Grass carp	*Groenlandia densa*	Graz	MN	Fowler & Robson, 1978
Ctenopharyngodon idella	Grass carp	*Myriophyllum spicatum*	Graz	MN	Fowler & Robson, 1978

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ctenopharyngodon idella	Grass carp	*Myriophyllum verticillatum*	Graz	MN	Stott & Robson, 1970
Ctenopharyngodon idella	Grass carp	*Callitriche* sp.	Graz	MN	Stott & Robson, 1970
Ctenopharyngodon idella	Grass carp	*Lemna trisulca*	Graz	MN	Stott & Robson, 1970
Ctenopharyngodon idella	Grass carp	*Stuckenia pectinata*	Graz	MN	Stott & Robson, 1970
Ctenopharyngodon idella	Grass carp	*Zannichellia palustris*	Graz	MN	Stott & Robson, 1970
Ctenopharyngodon idella	Grass carp	*Ceratophyllum demersum*	Graz	MN	Stott & Robson, 1970
Ctenopharyngodon idella	Grass carp	*Typha latifolia*	Graz	MN	Stott & Robson, 1970
Ctenopharyngodon idella	Grass carp	*Sparganium erectum*	Graz	MN	Stott & Robson, 1970
Ctenopharyngodon idella	Grass carp	*Alisma plantago*	Graz	MN	Stott & Robson, 1970
Ctenopharyngodon idella	Grass carp	Zooplankton	Int	MN	Petridis, 1990
Ctenopharyngodon idella	Grass carp	Invertebrates	Int	MN	Petridis, 1990
Ctenopharyngodon idella	Grass carp	*Ceratophyllum demersum*	Graz	MO	Maceina et al., 1992
Ctenopharyngodon idella	Grass carp	Zooplankton	Struc	MO	Maceina et al., 1992
Ctenopharyngodon idella	Grass carp	*Elodea canadensi*	Graz	MO	Mitzner, 1978
Ctenopharyngodon idella	Grass carp	*Najas flexilis*	Graz	MO	Mitzner, 1978
Ctenopharyngodon idella	Grass carp	*Ceratophyllum demersum*	Graz	MO	Mitzner, 1978
Ctenopharyngodon idella	Grass carp	*Stuckenia pectinata*	Graz	MO	Mitzner, 1978
Ctenopharyngodon idella	Grass carp	Vegetation	Graz	MO	Small et al., 1985
Ctenopharyngodon idella	Grass carp	Vegetation	Graz	MO	Small et al., 1985

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ctenopharyngodon idella	Grass carp	Zooplankton	Struc	MO	Richard et al., 1985
Ctenopharyngodon idella	Grass carp	*Chara* sp.	Graz	MN	Kilgen & Smitherman, 1971
Ctenopharyngodon idella	Grass carp	*Potamogeton diversifolius*	Graz	MN	Kilgen & Smitherman, 1971
Ctenopharyngodon idella	Grass carp	Insects	Pred	MN	Kilgen & Smitherman, 1971
Ctenopharyngodon idella	Grass carp	*Ictalurus punctatus*	Com	MC	Kilgen & Smitherman, 1971
Ctenopharyngodon idella	Grass carp	*Micropterus salmoides*	Com	MC	Kilgen & Smitherman, 1971
Ctenopharyngodon idella	Grass carp	*Micropterus coosae*	Com	MC	Kilgen & Smitherman, 1971
Ctenopharyngodon idella	Grass carp	*Micropterus punctulatus*	Com	MC	Kilgen & Smitherman, 1971
Ctenopharyngodon idella	Grass carp	*Pimephales promelas*	Com	MC	Kilgen & Smitherman, 1971
Ctenopharyngodon idella	Grass carp	*Utricularia inflata*	Graz	MO	Leslie et al., 1983
Ctenopharyngodon idella	Grass carp	*Ceratophyllum demersum*	Graz	MO	Leslie et al., 1983
Ctenopharyngodon idella	Grass carp	*Typha latifolia*	Graz	MO	Leslie et al., 1983
Ctenopharyngodon idella	Grass carp	*Potamogeton illinoensis*	Graz	MO	Leslie et al., 1983
Ctenopharyngodon idella	Grass carp	*Najas flexilis*	Graz	MN	Buck et al., 1975
Ctenopharyngodon idella	Grass carp	*Najas gracillima*	Graz	MN	Buck et al., 1975
Ctenopharyngodon idella	Grass carp	*Potamogeton foliosus*	Graz	MN	Buck et al., 1975
Ctenopharyngodon idella	Grass carp	*Potamogeton pusillus*	Graz	MN	Buck et al., 1975
Ctenopharyngodon idella	Grass carp	*Potamogeton foliosus*	Graz	MN	Lembi et al., 1978
Ctenopharyngodon idella	Grass carp	*Myriophyllum verticillatum*	Graz	MN	Lembi et al., 1978

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ctenopharyngodon idella	Grass carp	*Chara* sp.	Graz	MN	Lembi et al., 1978
Ctenopharyngodon idella	Grass carp	*Najas flexilis*	Graz	MN	Wiley et al., 1986
Ctenopharyngodon idella	Grass carp	*Potamogeton foliosus*	Graz	MN	Wiley et al., 1986
Ctenopharyngodon idella	Grass carp	*Chara* sp.	Graz	MN	Wiley et al., 1986
Ctenopharyngodon idella	Grass carp	*Elodea canadensis*	Graz	MN	Wiley et al., 1986
Ctenopharyngodon idella	Grass carp	*Stuckenia pectinata*	Graz	MN	Wiley et al., 1986
Ctenopharyngodon idella	Grass carp	*Myriophyllum* sp.	Graz	MN	Wiley et al., 1986
Ctenopharyngodon idella	Grass carp	*Ceratophyllurn demersum*	Graz	MN	Wiley et al., 1986
Ctenopharyngodon idella	Grass carp	*Najas guadalupensis*	Graz	MO	Hanlon et al., 2000
Ctenopharyngodon idella	Grass carp	*Cabomba caroliniana*	Graz	MO	Hanlon et al., 2000
Ctenopharyngodon idella	Grass carp	*Ceratophyllum demersum*	Graz	MO	Hanlon et al., 2000
Ctenopharyngodon idella	Grass carp	*Myriophyllum heterophyllum*	Graz	MO	Hanlon et al., 2000
Ctenopharyngodon idella	Grass carp	*Mayaca fluviatilis*	Graz	MO	Hanlon et al., 2000
Ctenopharyngodon idella	Grass carp	Vegetation	Graz	MO	Bancroft et al., 1983
Ctenopharyngodon idella	Grass carp	*Procambarus clarkii*	Com	MN	Forester & Avault, 1978
Ctenopharyngodon idella	Grass carp	*Pithophora* sp.	Graz	MN	Lewis, 1978
Ctenopharyngodon idella	Grass carp	*Sphaerium* sp.	Pred	MN	Lewis, 1978
Ctenopharyngodon idella	Grass carp	*Lepomis macrochirus*	Struc	MN	Baur et al., 1979
Ctenopharyngodon idella	Grass carp	*Micropterus salmoides*	Struc	MN	Baur et al., 1979

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ctenopharyngodon idella	Grass carp	*Lepomis macrochirus*	Struc	MN	Forester & Avault, 1978
Ctenopharyngodon idella	Grass carp	*Labidesthes sicculus*	Int	MO	Bettoli et al., 1991
Ctenopharyngodon idella	Grass carp	*Potamogeton illinoensis*	Graz	MO	Hardin et al., 1987
Ctenopharyngodon idella	Grass carp	*Nitella furcata*	Graz	MN	Hardin et al., 1987
Ctenopharyngodon idella	Grass carp	*Lepomis marginatus*	Struc	MO	Bettoli et al., 1993
Ctenopharyngodon idella	Grass carp	*Lepomis symmetricus*	Struc	MO	Bettoli et al., 1993
Ctenopharyngodon idella	Grass carp	*Lepomis punctatus*	Struc	MO	Bettoli et al., 1993
Ctenopharyngodon idella	Grass carp	*Lepomis gulosus*	Struc	MO	Bettoli et al., 1993
Ctenopharyngodon idella	Grass carp	*Lepomis microlophus*	Struc	MN	Bettoli et al., 1993
Ctenopharyngodon idella	Grass carp	*Lepisosteus oculatus*	Struc	MO	Bettoli et al., 1993
Ctenopharyngodon idella	Grass carp	*Pomoxis nigromaculatus*	Struc	MO	Bettoli et al., 1993
Ctenopharyngodon idella	Grass carp	*Lepomis megalotis*	Struc	MO	Bettoli et al., 1993
Ctenopharyngodon idella	Grass carp	*Pomoxis annularis*	Struc	MO	Bettoli et al., 1993
Ctenopharyngodon idella	Grass carp	*Lepomis macrochirus*	Struc	MN	Bettoli et al., 1993
Ctenopharyngodon idella	Grass carp	*Micropterus salmoides*	Struc	MO	Bettoli et al., 1993
Ctenopharyngodon idella	Grass carp	*Labidesthes sicculus*	Int	MO	Bettoli et al., 1993
Ctenopharyngodon idella	Grass carp	*Najas guadalupensis*	Graz	MN	McKnight & Hepp, 1995
Ctenopharyngodon idella	Grass carp	*Eleocharis acicularis*	Graz	MN	McKnight & Hepp, 1995
Ctenopharyngodon idella	Grass carp	*Potamogeton* spp.	Graz	MN	McKnight & Hepp, 1995

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ctenopharyngodon idella	Grass carp	Vegetation	Graz	MO	Bonar et al., 2002
Ctenopharyngodon idella	Grass carp	Vegetation	Graz	MN	Bonar et al., 2002
Ctenopharyngodon idella	Grass carp	*Elodea canadensis*	Graz	MN	Bonar et al., 2002
Ctenopharyngodon idella	Grass carp	*Potamogeton illinoensis*	Graz	MO	Leslie et al., 1985
Ctenopharyngodon idella	Grass carp	Vegetation	Graz	MN	Cassani, 1995
Ctenopharyngodon idella	Grass carp	*Ceratophyllum demersum*	Graz	MO	Henson & Sliger, 1993
Ctenopharyngodon idella	Grass carp	*Elodea nuttallii*	Graz	MO	Henson & Sliger, 1993
Ctenopharyngodon idella	Grass carp	*Potamogeton pusillus*	Graz	MO	Henson & Sliger, 1993
Ctenopharyngodon idella	Grass carp	*Cabomba caroliniana*	Graz	MO	Henson & Sliger, 1993
Ctenopharyngodon idella	Grass carp	*Najas flexilis*	Graz	MN	Colle et al., 1978
Ctenopharyngodon idella	Grass carp	Vegetation	Graz	MN	Colle et al., 1978
Ctenopharyngodon idella	Grass carp	*Sagittaria graminea*	Graz	MN	Colle et al., 1978
Ctenopharyngodon idella	Grass carp	*Potamogeton illinoensis*	Graz	MN	Colle et al., 1978
Ctenopharyngodon idella	Grass carp	*Ceratophyllum demersum*	Graz	MN	Hestand & Carter, 1978
Ctenopharyngodon idella	Grass carp	*Najas guadalupensis*	Graz	MN	Hestand & Carter, 1978
Ctenopharyngodon idella	Grass carp	*Vallisneria americana*	Graz	MN	Hestand & Carter, 1978
Ctenopharyngodon idella	Grass carp	*Ceratophyllum demersum*	Graz	MN	Bonar et al., 1993
Ctenopharyngodon idella	Grass carp	*Elodea canadensis*	Graz	MN	Bonar et al., 1993
Ctenopharyngodon idella	Grass carp	*Vallisneria americana*	Graz	MN	Bonar et al., 1993

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ctenopharyngodon idella	Grass carp	Fishes	Int	MC	Killgore et al., 1998
Ctenopharyngodon idella	Grass carp	*Morone americana*	Struc	MO	June-Wells et al., 2017
Ctenopharyngodon idella	Grass carp	*Notemigonus crysoleucas*	Struc	MO	June-Wells et al., 2017
Ctenopharyngodon idella	Grass carp	*Eleocharis acicularis*	Graz	MO	Gasaway & Drda, 1978
Ctenopharyngodon idella	Grass carp	*Panicum hemitomon*	Graz	MO	Gasaway & Drda, 1978
Ctenopharyngodon idella	Grass carp	*Fuirena scirpoidea*	Graz	MO	Gasaway & Drda, 1978
Ctenopharyngodon idella	Grass carp	*Cabomba caroliniana*	Graz	MO	Gasaway & Drda, 1978
Ctenopharyngodon idella	Grass carp	*Utricularia gibba*	Graz	MO	Gasaway & Drda, 1978
Ctenopharyngodon idella	Grass carp	*Brasenia schreberi*	Graz	MO	Gasaway & Drda, 1978
Ctenopharyngodon idella	Grass carp	*Utricularia purpurea*	Graz	MO	Gasaway & Drda, 1978
Ctenopharyngodon idella	Grass carp	*Nuphar macrophylla*	Graz	MO	Gasaway & Drda, 1978
Ctenopharyngodon idella	Grass carp	*Nymphaea odorata*	Graz	MO	Gasaway & Drda, 1978
Ctenopharyngodon idella	Grass carp	Fishes	Dis	MC	Riley, 1978
Ctenopharyngodon idella	Grass carp	Vegetation	Graz	MN	Kırkağaç & Demir, 2004
Ctenopharyngodon idella	Grass carp	*Stuckenia pectinata*	Graz	MN	Kırkağaç & Demir, 2006
Ctenopharyngodon idella	Grass carp	*Ceratophyllum submersum*	Graz	MN	Kırkağaç & Demir, 2006
Ctenopharyngodon idella	Grass carp	*Lemna trisulca*	Graz	MN	Kırkağaç & Demir, 2006
Ctenopharyngodon idella	Grass carp	Fishes	Dis	MC	Shamsi et al., 2009
Ctenopharyngodon idella	Grass carp	Fishes	Dis	MC	Kaur & Katoch, 2016

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Cyprinus carpio	Common carp	*Pyrgula annulata*	Pred	MN	Stein et al., 1975
Cyprinus carpio	Common carp	*Valvata piscinalis*	Pred	MN	Stein et al., 1975
Cyprinus carpio	Common carp	*Pisidium* sp.	Pred	MN	Stein et al., 1975
Cyprinus carpio	Common carp	*Dreissencia plymorpha*	Pred	MN	Stein et al., 1975
Cyprinus carpio	Common carp	*Radix auricularia*	Pred	MN	Stein et al., 1975
Cyprinus carpio	Common carp	*Amphimelania holandri*	Pred	MN	Stein et al., 1975
Cyprinus carpio	Common carp	Vegetation	Dire	MN	Sidorkewicj et al., 1998
Cyprinus carpio	Common carp	*Stuckenia pectinata*	Phys	MN	Sidorkewicj et al., 1999
Cyprinus carpio	Common carp	*Stuckenia pectinata*	Dire	MN	Sidorkewicj et al., 1996
Cyprinus carpio	Common carp	Fishes	Dis	MC	Rauque et al., 2018
Cyprinus carpio	Common carp	Vegetation	Dire	MN	Roberts et al., 1995
Cyprinus carpio	Common carp	*Daphnia carinata*	Pred	MN	Khan, 2003
Cyprinus carpio	Common carp	*Boeckella triarticulata*	Pred	MN	Khan, 2003
Cyprinus carpio	Common carp	*Mesocyclops leuckarti*	Pred	MN	Khan, 2003
Cyprinus carpio	Common carp	*Austrochiltonia subtenuis*	Pred	MN	Khan, 2003
Cyprinus carpio	Common carp	Invertebrates	Pred	MN	Khan, 2003
Cyprinus carpio	Common carp	*Chironomus australis*	Pred	MN	Khan, 2003
Cyprinus carpio	Common carp	*Chironomus duplex*	Pred	MN	Khan, 2003
Cyprinus carpio	Common carp	Vegetation	Graz	MO	Fletcher et al., 1985

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Cyprinus carpio	Common carp	Vegetation	Dire	MO	Fletcher et al., 1985
Cyprinus carpio	Common carp	*Chara* sp.	Dire	MN	Evelsizer & Turner, 2006
Cyprinus carpio	Common carp	*Stuckenia pectinata*	Dire	MN	Evelsizer & Turner, 2006
Cyprinus carpio	Common carp	Vegetation	Phys	MN	Badiou & Goldsborough, 2015
Cyprinus carpio	Common carp	*Potamogeton crispus*	Phys	MN	Zhang et al., 2022
Cyprinus carpio	Common carp	*Potamogeton crispus*	Graz	MN	Zhang et al., 2022
Cyprinus carpio	Common carp	*Cyprinus qionghaiensis*	Com	MN	Jia et al., 2008
Cyprinus carpio	Common carp	Vegetation	Dire	MN	Crivelli, 1983
Cyprinus carpio	Common carp	Vegetation	Graz	MN	Singh et al., 2010
Cyprinus carpio	Common carp	*Labeo rohita*	Dis	MN	Kumari et al., 2009
Cyprinus carpio	Common carp	*Barbus sharpeyi*	Dis	MN	Shamsi et al., 2009
Cyprinus carpio	Common carp	Vegetation	Dire	MN	Matsuzaki et al., 2009
Cyprinus carpio	Common carp	Invertebrates	Pred	MN	Matsuzaki et al., 2009
Cyprinus carpio	Common carp	*Stuckenia pectinata*	Int	MN	Matsuzaki et al., 2007
Cyprinus carpio	Common carp	Invertebrates	Struc	MN	Matsuzaki et al., 2007
Cyprinus carpio	Common carp	*Cambarellus montezumae*	Pred	MO	Hinojosa-Garro & Zambrano, 2004
Cyprinus carpio	Common carp	*Cambarellus montezumae*	Struc	MO	Hinojosa-Garro & Zambrano, 2004
Cyprinus carpio	Common carp	*Sagittaria mexicana*	Graz	MN	Zambrano & Hinojosa, 1999
Cyprinus carpio	Common carp	*Elodea canadensis*	Graz	MN	Zambrano & Hinojosa, 1999

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Cyprinus carpio	Common carp	Invertebrates	Pred	MN	Zambrano & Hinojosa, 1999
Cyprinus carpio	Common carp	Vegetation	Dire	MN	Zambrano et al., 1998
Cyprinus carpio	Common carp	Zooplankton	Pred	MN	Zambrano et al., 1998
Cyprinus carpio	Common carp	*Ambystoma mexicanum*	Pred	MN	Zambrano et al., 2010
Cyprinus carpio	Common carp	Fishes	Dis	MC	Scholz & Salgado-Maldonado, 2000
Cyprinus carpio	Common carp	Zooplankton	Pred	MN	Meijer et al., 1990
Cyprinus carpio	Common carp	*Pelobates fuscus*	Phys	MN	Kloskowski, 2011
Cyprinus carpio	Common carp	*Hyla arborea*	Phys	MC	Kloskowski, 2011
Cyprinus carpio	Common carp	Invertebrates	Pred	MN	Kloskowski, 2011
Cyprinus carpio	Common carp	*Pelobates fuscus*	Pred	MN	Kloskowski, 2009
Cyprinus carpio	Common carp	*Hyla arborea*	Pred	MN	Kloskowski, 2009
Cyprinus carpio	Common carp	*Rana temporaria*	Pred	MN	Kloskowski, 2009
Cyprinus carpio	Common carp	*Rana arvalis*	Pred	MN	Kloskowski, 2009
Cyprinus carpio	Common carp	*Rana esculenta*	Pred	MN	Kloskowski, 2009
Cyprinus carpio	Common carp	*Bufo bufo*	Pred	MN	Kloskowski, 2009
Cyprinus carpio	Common carp	*Bombina bombina*	Pred	MN	Kloskowski, 2010
Cyprinus carpio	Common carp	*Pelobates fuscus*	Pred	MN	Kloskowski, 2010
Cyprinus carpio	Common carp	*Hyla arborea*	Pred	MN	Kloskowski, 2010
Cyprinus carpio	Common carp	*Rana esculenta*	Pred	MN	Kloskowski, 2010

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Cyprinus carpio	Common carp	*Acipenser stellatus*	Com	MN	Patriche et al., 2002
Cyprinus carpio	Common carp	*Carassius gibelio*	Hybr	MN	Balashov et al., 2017
Cyprinus carpio	Common carp	Zooplankton	Pred	MN	Chapman & Fernando, 1994
Cyprinus carpio	Common carp	Invertebrates	Pred	MN	Chapman & Fernando, 1994
Cyprinus carpio	Common carp	Vegetation	Graz	MN	Chapman & Fernando, 1994
Cyprinus carpio	Common carp	*Lepomis macrochirus*	Struc	MN	Forester & Lawrence, 1978
Cyprinus carpio	Common carp	Invertebrates	Pred	MO	Bonneau & Scarnecchia, 2015
Cyprinus carpio	Common carp	Invertebrates	Pred	MN	Wilcox & Hornbach, 1991
Cyprinus carpio	Common carp	Invertebrates	Struc	MN	Wilcox & Hornbach, 1991
Cyprinus carpio	Common carp	Invertebrates	Pred	MN	Batzer et al., 2000
Cyprinus carpio	Common carp	Vegetation	Dire	MN	Miller & Crowl, 2006
Cyprinus carpio	Common carp	Invertebrates	Int	MN	Miller & Crowl, 2006
Cyprinus carpio	Common carp	Vegetation	Dire	MN	Parkos III et al., 2003
Cyprinus carpio	Common carp	Vegetation	Phys	MN	Parkos III et al., 2003
Cyprinus carpio	Common carp	Invertebrates	Pred	MN	Parkos III et al., 2003
Cyprinus carpio	Common carp	Invertebrates	Pred	MN	Eder & Carlson, 1977
Cyprinus carpio	Common carp	Zooplankton	Pred	MN	Eder & Carlson, 1977
Cyprinus carpio	Common carp	Vegetation	Dire	MO	Bajer et al., 2009
Cyprinus carpio	Common carp	Waterfowl	Int	MO	Bajer et al., 2009

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Cyprinus carpio	Common carp	*Micropterus dolomieu*	Com	MC	Haines, 1973
Cyprinus carpio	Common carp	Vegetation	Dire	MN	King & Hunt, 1967
Cyprinus carpio	Common carp	Vegetation	Dire	MN	Threinen & Helm, 1954
Cyprinus carpio	Common carp	*Micropterus salmoides*	Com	MN	Wolfe et al., 2009
Cyprinus carpio	Common carp	*Lepomis macrochirus*	Com	MN	Wolfe et al., 2009
Cyprinus carpio	Common carp	*Micropterus salmoides*	Int	MN	Wolfe et al., 2009
Cyprinus carpio	Common carp	*Lepomis macrochirus*	Int	MN	Wolfe et al., 2009
Cyprinus carpio	Common carp	Vegetation	Dire	MN	Tryon, 1954
Cyprinus carpio	Common carp	Invertebrates	Pred	MN	Batzer, 1998
Cyprinus carpio	Common carp	Invertebrates	Pred	MN	Richardson et al., 1990
Cyprinus carpio	Common carp	*Stuckenia pectinata*	Phys	MN	Weber & Brown, 2015
Cyprinus carpio	Common carp	*Stuckenia pectinata*	Dire	MN	Weber & Brown, 2015
Cyprinus carpio	Common carp	Zooplankton	Pred	MN	Weber & Brown, 2015
Cyprinus carpio	Common carp	*Micropterus salmoides*	Phys	MN	Wahl et al., 2011
Cyprinus carpio	Common carp	*Lepomis macrochirus*	Phys	MN	Wahl et al., 2011
Cyprinus carpio	Common carp	*Stuckenia pectinata*	Phys	MN	Wahl et al., 2011
Cyprinus carpio	Common carp	*Najas* sp.	Phys	MN	Wahl et al., 2011
Cyprinus carpio	Common carp	*Stuckenia pectinata*	Graz	MN	Miller & Provenza, 2007
Cyprinus carpio	Common carp	*Schoenoplectus*	Graz	MN	Miller & Provenza, 2007

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
		tabernaemontani			
Cyprinus carpio	Common carp	*Chara aspera*	Graz	MN	Miller & Provenza, 2007
Cyprinus carpio	Common carp	*Ceratophyllum demersum*	Graz	MN	Miller & Provenza, 2007
Cyprinus carpio	Common carp	Zooplankton	Pred	MN	Collins et al., 2018
Cyprinus carpio	Common carp	*Entosphenus tridentatus*	Pred	MN	Arakawa & Lampman, 2020
Cyprinus carpio	Common carp	*Lampetra richardsoni*	Pred	MN	Arakawa & Lampman, 2020
Cyprinus carpio	Common carp	Fishes	Dis	MC	Amin & Minckley, 1996
Cyprinus carpio	Common carp	*Acipenser transmontanus*	Pred	MN	Miller & Beckman, 1996
Cyprinus carpio	Common carp	*Salvelinus namaycush*	Pred	MN	Marsden, 1997
Cyprinus carpio	Common carp	Fishes	Dis	MC	Shamsi et al., 2009
Cyprinus carpio	Common carp	Fishes	Dis	MC	Scholz et al., 2015
Cyprinus carpio	Common carp	Macrophyte	Dire	MO	Bajer et al., 2018
Cyprinus carpio	Common carp	Macrophyte	Dire	MO	Larkin et al., 2020
Cyprinus carpio	Common carp	*Lepomis macrochirus*	Com	MC	Weber & Brown, 2018
Cyprinus carpio	Common carp	*Perca flavescens*	Com	MN	Weber & Brown, 2018
Cyprinus carpio	Common carp	Macrophyte	Dire	MN	Fischer et al., 2013
Cyprinus carpio	Common carp	Zooplankton	Int	MN	Fischer et al., 2013
Cyprinus carpio	Common carp	Invertebrates	Pred	MN	Fischer et al., 2013
Cyprinus carpio	Common carp	Invertebrates	Pred	MN	García-Berthou, 2001

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Cyprinus carpio	Common carp	Zooplankton	Pred	MO	Florian et al, 2016
Cyprinus carpio	Common carp	Fishes	Dis	MC	Scholz & Saraiva, 2008
Cyprinus carpio	Common carp	Fishes	Dis	MC	Das et al., 2006
Cyprinus carpio	Common carp	Fishes	Dis	MC	Oros et al., 2004
Cyprinus carpio	Common carp	*Fulica atra*	Struc	MO	Maceda-Veiga et al., 2017
Cyprinus carpio	Common carp	*Aythya ferina*	Struc	MO	Maceda-Veiga et al., 2017
Cyprinus carpio	Common carp	*Oxyura leucocephala*	Struc	MO	Maceda-Veiga et al., 2017
Cyprinus carpio	Common carp	*Netta rufina*	Struc	MO	Maceda-Veiga et al., 2017
Cyprinus carpio	Common carp	*Anas strepera*	Struc	MO	Maceda-Veiga et al., 2017
Cyprinus carpio	Common carp	*Tachybaptus ruficollis*	Struc	MO	Maceda-Veiga et al., 2017
Cyprinus carpio	Common carp	*Podiceps nigricollis*	Struc	MO	Maceda-Veiga et al., 2017
Cyprinus carpio	Common carp	*Phoenicopterus ruber*	Struc	MO	Maceda-Veiga et al., 2017
Cyprinus carpio	Common carp	Zooplankton	Int	MN	Angeler et al., 2002
Cyprinus carpio	Common carp	Fishes	Dis	MC	Waicheim et al., 2014
Cyprinus carpio	Common carp	Macrophyte	Dire	MO	Bajer et al., 2016
Cyprinus carpio	Common carp	*Labeobarbus aeneus*	Dis	MC	Dos Santos et al., 2022
Cyprinus carpio	Common carp	Fishes	Dis	MC	Barčák et al., 2021
Cyprinus carpio	Common carp	Macrophyte	Dire	MO	Vilizzi et al., 2014
Cyprinus carpio	Common carp	Zooplankton	Int	MO	Vilizzi et al., 2014

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Cyprinus carpio	Common carp	Invertebrates	Int	MO	Vilizzi et al., 2014
Cyprinus carpio	Common carp	Fishes	Dis	MC	Otachi et al., 2014
Cyprinus carpio	Common carp	*Litoria booroolongensis*	Pred	MN	Hunter et al., 2011
Cyprinus carpio	Common carp	*Cyprinus pellegrini*	Hybr	MN	Tang & Chen, 2012
Cyprinus carpio	Common carp	Fishes	Dis	MC	Uhrovič et al., 2022
Cyprinus carpio	Common carp	Fishes	Dis	MC	Garrido-Olvera et al., 2017
Cyprinus carpio	Common carp	*Netta rufina*	Struc	MO	Laguna et al., 2016
Cyprinus carpio	Common carp	Fishes	Dis	MC	Sanyal et al., 2018
Cyprinus carpio	Common carp	Fishes	Dis	MC	Kaur & Katoch, 2016
Esox lucius	Northern pike	*Oncorhynchus clarkii lewisi*	Pred	MO	McMahon & Bennett, 1996
Esox lucius	Northern pike	*Salvelinus confluentus*	Pred	MO	McMahon & Bennett, 1996
Esox lucius	Northern pike	Fishes	Pred	MO	Chapleau et al., 1997
Esox lucius	Northern pike	*Margariscus margarita*	Pred	MR	Findlay et al., 2005
Esox lucius	Northern pike	*Perca flavescens*	Pred	MO	Findlay et al., 2005
Esox lucius	Northern pike	Zooplankton	Int	MO	Findlay et al., 2005
Esox lucius	Northern pike	Salmo trutta	Pred	MO	Hesthagen et al., 2015
Esox lucius	Northern pike	*Salvelinus alpinus*	Pred	MR	Byström et al., 2007
Esox lucius	Northern pike	*Salvelinus alpinus*	Com	MR	Byström et al., 2007
Esox lucius	Northern pike	*Pungitius pungitius*	Pred	MO	Byström et al., 2007

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Esox lucius	Northern pike	*Chrosomus eos*	Pred	MN	He & Kitchell, 1990
Esox lucius	Northern pike	*Pimephales promelas*	Pred	MN	He & Kitchell, 1990
Esox lucius	Northern pike	*Chrosomus neogaeus*	Pred	MN	He & Kitchell, 1990
Esox lucius	Northern pike	*Hybognathus hankinsoni*	Pred	MN	He & Kitchell, 1990
Esox lucius	Northern pike	*Esox masquinongy*	Hybr	MN	Becker, 1983
Esox lucius	Northern pike	*Semotilus atromaculatus*	Pred	MO	Findlay et al., 2000
Esox lucius	Northern pike	*Chrosomus eos*	Pred	MO	Findlay et al., 2000
Esox lucius	Northern pike	*Rhinichthys atratulus*	Pred	MO	Findlay et al., 2000
Esox lucius	Northern pike	*Luxilus cornutus*	Pred	MO	Findlay et al., 2000
Esox lucius	Northern pike	*Margariscus margarita*	Pred	MO	Findlay et al., 2000
Esox lucius	Northern pike	Fishes	Pred	MN	He & Wright, 1992
Esox lucius	Northern pike	Invertebrates	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	*Thymallus arcticus*	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	*Oncorhynchus kisutch*	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	*Oncorhynchus tshawytscha*	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	*Oncorhynchus mykiss*	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	*Prosopium cylindraceum*	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	*Lethenteron camtschaticum*	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	*Catostomus catostomus*	Pred	MN	Sepulveda et al., 2013

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Esox lucius	Northern pike	*Cottus cognatus*	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	*Gasterosteus aculeatus*	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	*Myodes rutilus*	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	*Sorex* spp.	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	*Lithobates sylvaticus*	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	Zooplankton	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	*Oncorhynchus nerka*	Pred	MN	Sepulveda et al., 2013
Esox lucius	Northern pike	*Gasterosteus aculeatus*	Pred	MR	Patankar et al., 2006
Esox lucius	Northern pike	*Catostomus discobolus*	Pred	MN	Johnson et al., 2008
Esox lucius	Northern pike	*Ptychocheilus lucius*	Pred	MN	Johnson et al., 2008
Esox lucius	Northern pike	*Catostomus latipinnis*	Pred	MN	Johnson et al., 2008
Esox lucius	Northern pike	*Gila cypha*	Pred	MN	Johnson et al., 2008
Esox lucius	Northern pike	*Xyrauchen texanus*	Pred	MN	Johnson et al., 2008
Esox lucius	Northern pike	*Gila robusta*	Pred	MN	Johnson et al., 2008
Esox lucius	Northern pike	*Rhinichthys osculus*	Pred	MN	Johnson et al., 2008
Esox lucius	Northern pike	*Cottus bairdii*	Pred	MN	Johnson et al., 2008
Esox lucius	Northern pike	*Gasterosteus aculeatus*	Pred	MO	Haught & von Hippel, 2011
Esox lucius	Northern pike	*Lithobates sylvaticus*	Pred	MN	Haught & von Hippel, 2011
Esox lucius	Northern pike	Mammals	Pred	MN	Haught & von Hippel, 2011

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Esox lucius	Northern pike	*Cottus cognatus*	Pred	MN	Haught & von Hippel, 2011
Esox lucius	Northern pike	*Catostomus catostomus*	Pred	MN	Haught & von Hippel, 2011
Esox lucius	Northern pike	Invertebrates	Pred	MN	Haught & von Hippel, 2011
Esox lucius	Northern pike	*Perca flavescens*	Pred	MO	DeBates et al., 2003
Esox lucius	Northern pike	*Micropterus salmoides*	Pred	MO	DeBates et al., 2003
Esox lucius	Northern pike	*Catostomus latipinnis*	Pred	MN	Tyus & Beard, 1990
Esox lucius	Northern pike	*Rhinichthys osculus*	Pred	MN	Tyus & Beard, 1990
Esox lucius	Northern pike	*Catostomus discobolus*	Pred	MN	Tyus & Beard, 1990
Esox lucius	Northern pike	*Lithobates pipiens*	Pred	MN	Tyus & Beard, 1990
Esox lucius	Northern pike	*Lampropeltis* spp.	Pred	MN	Tyus & Beard, 1990
Esox lucius	Northern pike	*Perca flavescens*	Pred	MO	Paukert & Willis, 2003
Esox lucius	Northern pike	*Oncorhynchus tshawytscha*	Pred	MO	Sepulveda et al., 2015
Esox lucius	Northern pike	*Oncorhynchus kisutch*	Pred	MN	Sepulveda et al., 2015
Esox lucius	Northern pike	*Oncorhynchus mykiss*	Pred	MN	Sepulveda et al., 2015
Esox lucius	Northern pike	*Thymallus arcticus*	Pred	MN	Sepulveda et al., 2015
Esox lucius	Northern pike	*Lethenteron camtschaticum*	Pred	MN	Sepulveda et al., 2015
Esox lucius	Northern pike	*Lota lota*	Pred	MN	Sepulveda et al., 2015
Esox lucius	Northern pike	*Catostomus catostomus*	Pred	MN	Sepulveda et al., 2015
Esox lucius	Northern pike	*Prosopium cylindraceum*	Pred	MN	Sepulveda et al., 2015

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Esox lucius	Northern pike	*Cottus cognatus*	Pred	MN	Sepulveda et al., 2015
Esox lucius	Northern pike	*Gasterosteus aculeatus*	Pred	MN	Sepulveda et al., 2015
Esox lucius	Northern pike	*Pungitius pungitius*	Pred	MN	Sepulveda et al., 2015
Esox lucius	Northern pike	*Oncorhynchus clarkii*	Pred	MN	Muhlfeld et al., 2008
Esox lucius	Northern pike	*Salvelinus confluentus*	Pred	MN	Muhlfeld et al., 2008
Esox lucius	Northern pike	Whitefishes	Pred	MN	Muhlfeld et al., 2008
Esox lucius	Northern pike	Suckers	Pred	MN	Muhlfeld et al., 2008
Esox lucius	Northern pike	*Ptychocheilus oregonensis*	Pred	MN	Muhlfeld et al., 2008
Esox lucius	Northern pike	*Ptychocheilus lucius*	Com	MN	Zelasko et al., 2016
Esox lucius	Northern pike	*Ptychocheilus lucius*	Pred	MN	Zelasko et al., 2016
Esox lucius	Northern pike	*Salmo salar*	Pred	MO	Fuller & Neilson, 2022
Esox lucius	Northern pike	*Oncorhynchus tshawytscha*	Pred	MN	Rutz, 1999
Esox lucius	Northern pike	*Gasterosteus aculeatus*	Pred	MN	Heins et al., 2016
Esox lucius	Northern pike	*Salvelinus umbla*	Dis	MO	Schaufler et al., 2014
Esox masquinongy	Muskellunge	*Salmo salar*	Pred	MN	Curry et al., 2007
Esox masquinongy	Muskellunge	*Micropterus salmoides*	Pred	MO	Gammon & Hasler, 1965
Esox masquinongy	Muskellunge	*Perca flavescens*	Pred	MO	Gammon & Hasler, 1965
Esox masquinongy	Muskellunge	*Perca flavescens*	Pred	MN	Andrews et al., 2018
Esox masquinongy	Muskellunge	*Morone americana*	Pred	MN	Andrews et al., 2018

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Esox masquinongy	Muskellunge	*Anguilla rostrata*	Pred	MN	Andrews et al., 2018
Esox masquinongy	Muskellunge	*Alosa pseudoharengus*	Pred	MN	Andrews et al., 2018
Esox masquinongy	Muskellunge	*Alosa sapidissima*	Pred	MN	Andrews et al., 2018
Huso dauricus	Kaluga	*Limnoperna fortunei*	Pred	MN	Li et al., 2019
Huso dauricus	Kaluga	*Pelteobagrus spp.*	Pred	MN	Li et al., 2019
Huso dauricus	Kaluga	*Mystus macropterus*	Pred	MN	Li et al., 2019
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MN	Starling & Rocha, 1990
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MN	Starling, 1993
Hypophthalmichthys molitrix	Silver carp	Phytoplankton	Graz	MN	Starling, 1993
Hypophthalmichthys molitrix	Silver carp	*Cyprinus qionghaiensis*	Com	MO	Xie & Chen, 2001
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MN	Domaizon & Dévaux, 1999a
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MN	Domaizon & Dévaux, 1999b
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MN	Radke & Kahl, 2002
Hypophthalmichthys molitrix	Silver carp	Phytoplankton	Graz	MN	Leventer & Teltsch, 1990
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MN	Leventer & Teltsch, 1990
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MN	Milstein et al., 1988
Hypophthalmichthys molitrix	Silver carp	Phytoplankton	Graz	MN	Milstein et al., 1988
Hypophthalmichthys molitrix	Silver carp	Fishes	Dis	MC	Scholz & Salgado-Maldonado, 2000
Hypophthalmichthys molitrix	Silver carp	*Acipenser stellatus*	Com	MN	Patriche et al., 2002

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Hypophthalmichthys molitrix	Silver carp	Fishes	Dis	MC	Cakic et al., 2004
Hypophthalmichthys molitrix	Silver carp	Phytoplankton	Graz	MO	DeBoer et al., 2018
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MO	DeBoer et al., 2018
Hypophthalmichthys molitrix	Silver carp	Fishes	Com	MO	Solomon et al., 2016
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MO	Sass et al., 2014
Hypophthalmichthys molitrix	Silver carp	*Ictiobus cyprinellus*	Com	MN	Irons et al., 2007
Hypophthalmichthys molitrix	Silver carp	*Dorosoma cepedianum*	Com	MN	Irons et al., 2007
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MN	Williamson & Garvey, 2005
Hypophthalmichthys molitrix	Silver carp	Phytoplankton	Graz	MN	Williamson & Garvey, 2005
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MN	Burke et al., 1986
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MN	Lieberman, 1996
Hypophthalmichthys molitrix	Silver carp	Phytoplankton	Graz	MN	Lieberman, 1996
Hypophthalmichthys molitrix	Silver carp	Phytoplankton	Graz	MN	Pongruktham et al., 2010
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MN	Pongruktham et al., 2010
Hypophthalmichthys molitrix	Silver carp	*Dorosoma cepedianum*	Com	MO	Love et al., 2018
Hypophthalmichthys molitrix	Silver carp	*Lampsilis siliquoidea*	Com	MN	Tristano et al., 2019
Hypophthalmichthys molitrix	Silver carp	Phytoplankton	Graz	MN	Tumolo & Flinn, 2017
Hypophthalmichthys molitrix	Silver carp	Fishes	Com	MO	Chick et al., 2020
Hypophthalmichthys molitrix	Silver carp	Zooplankton	Pred	MN	Calkins et al., 2012

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Hypophthalmichthys molitrix	Silver carp	*Polyodon spathula*	Com	MN	Kinlock et al., 2020
Hypophthalmichthys molitrix	Silver carp	*Ictiobus cyprinellus*	Com	MC	Coulter et al., 2019
Hypophthalmichthys molitrix	Silver carp	*Ictiobus cyprinellus*	Com	MN	Pendleton et al., 2017
Hypophthalmichthys molitrix	Silver carp	*Dorosoma cepedianum*	Com	MN	Pendleton et al., 2017
Hypophthalmichthys molitrix	Silver carp	Fishes	Dis	MC	Shamsi et al., 2009
Hypophthalmichthys molitrix	Silver carp	Fishes	Dis	MC	Kaur & Katoch, 2016
Hypophthalmichthys nobilis	Bighead carp	*Cyprinus qionghaiensis*	Com	MO	Xie & Chen, 2001
Hypophthalmichthys nobilis	Bighead carp	Phytoplankton	Graz	MN	Leventer & Teltsch, 1990
Hypophthalmichthys nobilis	Bighead carp	Zooplankton	Pred	MN	Leventer & Teltsch, 1990
Hypophthalmichthys nobilis	Bighead carp	Zooplankton	Pred	MN	Collins & Wahl, 2018
Hypophthalmichthys nobilis	Bighead carp	Fishes	Com	MO	Solomon et al., 2016
Hypophthalmichthys nobilis	Bighead carp	*Dorosoma cepedianum*	Com	MN	Pendleton et al., 2017
Hypophthalmichthys nobilis	Bighead carp	*Ictiobus cyprinellus*	Com	MN	Pendleton et al., 2017
Hypophthalmichthys nobilis	Bighead carp	Zooplankton	Pred	MO	Sass et al., 2014
Hypophthalmichthys nobilis	Bighead carp	*Polyodon spathula*	Com	MN	Schrank et al., 2003
Hypophthalmichthys nobilis	Bighead carp	*Ictiobus cyprinellus*	Com	MN	Irons et al., 2007
Hypophthalmichthys nobilis	Bighead carp	*Dorosoma cepedianum*	Com	MN	Irons et al., 2007
Hypophthalmichthys nobilis	Bighead carp	Zooplankton	Pred	MN	Burke et al., 1986
Hypophthalmichthys nobilis	Bighead carp	Zooplankton	Pred	MN	Collins & Wahl, 2017

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Hypophthalmichthys nobilis	Bighead carp	Zooplankton	Pred	MN	Cooke et al., 2009
Hypophthalmichthys nobilis	Bighead carp	*Dorosoma cepedianum*	Com	MO	Love et al., 2018
Hypophthalmichthys nobilis	Bighead carp	Zooplankton	Pred	MN	Collins & Wahl, 2018
Hypophthalmichthys nobilis	Bighead carp	*Lepomis macrochirus*	Com	MN	Fletcher et al., 2019
Hypophthalmichthys nobilis	Bighead carp	*Polyodon spathula*	Com	MN	Kinlock et al., 2020
Hypophthalmichthys nobilis	Bighead carp	Zooplankton	Pred	MO	Tillotson et al., 2022
Hypophthalmichthys nobilis	Bighead carp	Fishes	Dis	MC	Shamsi et al., 2009
Ictalurus furcatus	Blue catfish	*Alosa pseudoharengus*	Pred	MN	MacAvoy et al., 2000
Ictalurus furcatus	Blue catfish	*Alosa aestivalis*	Pred	MN	MacAvoy et al., 2000
Ictalurus furcatus	Blue catfish	*Alosa sapidissima*	Pred	MN	MacAvoy et al., 2000
Ictalurus furcatus	Blue catfish	*Ictalurus catus*	Com	MO	Schloesser et al., 2011
Ictalurus furcatus	Blue catfish	*Leptocheirus plumulosus*	Pred	MN	Schloesser et al., 2011
Ictalurus furcatus	Blue catfish	*Rhithropanopeus harrisii*	Pred	MN	Schloesser et al., 2011
Ictalurus furcatus	Blue catfish	*Trinectes maculatus*	Pred	MN	Schloesser et al., 2011
Ictalurus furcatus	Blue catfish	*Brevoortia tyrannus*	Pred	MN	Schloesser et al., 2011
Ictalurus furcatus	Blue catfish	Invertebrates	Pred	MN	Schloesser et al., 2011
Ictalurus furcatus	Blue catfish	*Callinectes sapidus*	Pred	MN	Schloesser et al., 2011
Ictalurus furcatus	Blue catfish	*Micropogonias undulatus*	Pred	MN	Schloesser et al., 2011
Ictalurus furcatus	Blue catfish	*Morone americana*	Pred	MN	Schloesser et al., 2011

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ictalurus furcatus	Blue catfish	*Anguilla rostrata*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Anchoa mitchilli*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Alosa aestivalis*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Alosa pseudoharengus*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Alosa sapidissima*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Brevoortia tyrannus*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Dorosoma cepedianum*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Carassius auratus*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Notropis hudsonius*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Ameiurus nebulosus*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Ictalurus punctatus*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Fundulus diaphanus*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Morone americana*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Morone saxatilis*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Lepomis gibbosus*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Micropterus salmoides*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Etheostoma olmstedi*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Trinectes maculatus*	Pred	MN	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	*Phalacrocorax auritus*	Pred	MN	Aguilar et al., 2017

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ictalurus furcatus	Blue catfish	Fishes	Pred	MN	Belkoski et al., 2021
Ictalurus furcatus	Blue catfish	Invertebrates	Pred	MN	Belkoski et al., 2021
Ictalurus furcatus	Blue catfish	Frogs	Pred	MN	Belkoski et al., 2021
Ictalurus furcatus	Blue catfish	Fishes	Pred	MN	Bonvechio et al., 2011
Ictalurus furcatus	Blue catfish	Invertebrates	Pred	MN	Bonvechio et al., 2011
Ictalurus furcatus	Blue catfish	*Rana* spp.	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Leptocheirus plumulosus*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	Zooplankton	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	Vegetation	Graz	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	Birds	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Aurelia aurita*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Cyathura polita*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	Mammals	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Callinectes sapidus*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Palaemonetes pugio*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Orconectes limosus*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Rhithropanopeus harrisii*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Panopeus herbstii*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	Invertebrates	Pred	MN	Schmitt et al., 2017

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ictalurus furcatus	Blue catfish	Fishes	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Trinectes maculatus*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Anguilla rostrata*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Menidia menidia*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Lepomis gibbosus*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Lepomis microlophus*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Alosa aestivalis*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Alosa mediocris*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Alosa pseudoharengus*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Alosa sapidissima*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Dorosoma cepedianum*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Hybognathus regius*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Nocomis micropogon*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Ictalurus punctatus*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Ameiurus catus*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Lepisosteus osseus*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Morone saxatilis*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Morone americana*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Etheostoma flabellare*	Pred	MN	Schmitt et al., 2017

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ictalurus furcatus	Blue catfish	*Etheostoma olmstedi*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Perca flavescens*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Petromyzon marinus*	Pred	MN	Schmitt et al., 2017
Ictalurus furcatus	Blue catfish	*Charaphytin* sp.	Graz	MN	Grist, 2002
Ictalurus furcatus	Blue catfish	Invertebrates	Pred	MN	Grist, 2002
Ictalurus furcatus	Blue catfish	Fishes	Pred	MN	Grist, 2002
Ictalurus furcatus	Blue catfish	*Dorosoma cepedianum*	Pred	MN	Grist, 2002
Ictalurus furcatus	Blue catfish	*Dorosoma petenense*	Pred	MN	Grist, 2002
Ictalurus furcatus	Blue catfish	*Morone Americana*	Pred	MN	Grist, 2002
Ictalurus furcatus	Blue catfish	*Rana clamitans*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Leptocheirus plumulosus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Aurelia aurita*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Orconectes limosus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Palaemonetes pugio*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Dyspanopeus sayi*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Panopeus herbstii*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Rhithropanopeus harrisii*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Callinectes sapidus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Uca minax*	Pred	MN	Schmitt et al., 2019b

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ictalurus furcatus	Blue catfish	*Cyathura polita*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Ondatra zibethicus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Rictaxis punctostriatus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Mytilopsis leucophaeata*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Geukensia demissa*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Trinectes maculatus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Anguilla rostrata*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Menidia menidia*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Moxostoma macrolepidotum*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Lepomis gibbosus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Lepomis macrochirus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Lepomis microlophus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Lepomis* spp.	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Alosa aestivalis*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Alosa mediocris*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Alosa pseudoharengus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Brevoortia tyrannus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Dorosoma cepedianum*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Carpoides cyprinus*	Pred	MN	Schmitt et al., 2019b

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Ictalurus furcatus	Blue catfish	*Hybognathus regius*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Notropis hudsonius*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Ameiurus catus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Ameiurus nebulosus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Ictalurus punctatu*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Noturus gyrinus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Lepisosteus osseus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Morone americana*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Morone saxatilis*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Etheostoma flabellare*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Perca flavescens*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Leiostomus xanthurus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	*Micropogonias undulatus*	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	Invertebrates	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	Vertebrates	Pred	MN	Schmitt et al., 2019b
Ictalurus furcatus	Blue catfish	Fishes	Pred	MN	Chandler, 1998
Lates niloticus	Nile perch	Fishes	Pred	MR	Witte et al., 1992a
Lates niloticus	Nile perch	Fishes	Pred	MR	Witte et al., 1992b
Lates niloticus	Nile perch	*Bagrus docmak*	Pred	MO	Hughes, 1983

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Lates niloticus	Nile perch	*Bagrus docmak*	Com	MO	Hughes, 1983
Lates niloticus	Nile perch	*Clarias gariepinus*	Pred	MO	Hughes, 1983
Lates niloticus	Nile perch	*Clarias gariepinus*	Com	MO	Hughes, 1983
Lates niloticus	Nile perch	*Ceryle rudis*	Com	MC	Wanink, 1992
Lates niloticus	Nile perch	*Lutra maculicollis*	Com	MC	Kruuk & Goudswaard, 1990
Lates niloticus	Nile perch	*Caridina nilotica*	Pred	MN	Hughes, 1986
Lates niloticus	Nile perch	*Rastrineobola argentea*	Pred	MN	Hughes, 1986
Lates niloticus	Nile perch	*Potamon niloticus*	Pred	MN	Hughes, 1986
Lates niloticus	Nile perch	*Bagrus docmak*	Pred	MN	Hughes, 1986
Lates niloticus	Nile perch	Fishes	Pred	MN	Hughes, 1986
Lates niloticus	Nile perch	Invertebrates	Pred	MN	Hughes, 1986
Lates niloticus	Nile perch	*Caridina nilotica*	Pred	MN	Mkumbo & Ligtvoet, 1992
Lates niloticus	Nile perch	*Rastrineobola argentea*	Pred	MN	Mkumbo & Ligtvoet, 1992
Lates niloticus	Nile perch	*Bagrus docmak*	Pred	MN	Mkumbo & Ligtvoet, 1992
Lates niloticus	Nile perch	Invertebrates	Pred	MN	Mkumbo & Ligtvoet, 1992
Lates niloticus	Nile perch	*Caridina nilotica*	Pred	MN	Ogari & Dadzie, 1988
Lates niloticus	Nile perch	*Povilla adusta*	Pred	MN	Ogari & Dadzie, 1988
Lates niloticus	Nile perch	Invertebrates	Pred	MN	Ogari & Dadzie, 1988
Lates niloticus	Nile perch	Zooplankton	Pred	MN	Ogari & Dadzie, 1988

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Lates niloticus	Nile perch	*Clarias gariepinus*	Pred	MN	Ogari & Dadzie, 1988
Lates niloticus	Nile perch	Fishes	Pred	MN	Ogari & Dadzie, 1988
Lates niloticus	Nile perch	*Protopterus aethiopicus*	Pred	MN	Ogari & Dadzie, 1988
Lates niloticus	Nile perch	*Labeo victoriannus*	Pred	MN	Ogari & Dadzie, 1988
Lates niloticus	Nile perch	Fishes	Pred	MV	Witte et al., 2007
Lates niloticus	Nile perch	*Mastacembelus frenatus*	Pred	MN	Ogutu-Ohwayo, 1993
Lates niloticus	Nile perch	Fishes	Pred	MR	Seehausen et al., 1997
Lates niloticus	Nile perch	*Prognathochromis venator*	Pred	MV	Chapman et al., 2003
Lates niloticus	Nile perch	*Oreochromis esculentus*	Pred	MV	Chapman et al., 2003
Lates niloticus	Nile perch	*Oreochromis variabilis*	Pred	MV	Chapman et al., 2003
Lates niloticus	Nile perch	*Marcusenius nigricans*	Pred	MV	Chapman et al., 2003
Lates niloticus	Nile perch	*Barbus magdalenae*	Pred	MV	Chapman et al., 2003
Lates niloticus	Nile perch	*Barbus neumayeri*	Pred	MR	Chapman et al., 2003
Lates niloticus	Nile perch	*Bagrus docmak*	Pred	MV	Chapman et al., 2003
Lates niloticus	Nile perch	*Rastrineobola argentea*	Pred	MN	Wanink, 1999
Lates niloticus	Nile perch	Fishes	Pred	MO	Goudswaard et al., 2008
Lates niloticus	Nile perch	*Bagrus docmak*	Pred	MO	Goudswaard & Witte, 1997
Lates niloticus	Nile perch	*Clarias gariepinus*	Pred	MO	Goudswaard & Witte, 1997
Lates niloticus	Nile perch	*Synodontis victoriae*	Pred	MO	Goudswaard & Witte, 1997

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Lates niloticus	Nile perch	*Synodontis afrofischeri*	Pred	MN	Goudswaard & Witte, 1997
Lates niloticus	Nile perch	*Xenoclarias eupogon*	Pred	MO	Goudswaard & Witte, 1997
Lates niloticus	Nile perch	*Oreochromis esculentus*	Pred	MO	Goudswaard et al., 2002
Lates niloticus	Nile perch	*Oreochromis variabilis*	Pred	MO	Goudswaard et al., 2002
Lates niloticus	Nile perch	*Protopterus aethiopicus*	Pred	MO	Goudswaard et al., 2002
Lates niloticus	Nile perch	Fishes	Pred	MO	Wanink, 1991
Lates niloticus	Nile perch	*Rastrineobola argentea*	Pred	MN	Wanink, 1991
Lates niloticus	Nile perch	*Ceryle rudis*	Int	MC	Wanink & Goudswaard, 1994
Lates niloticus	Nile perch	Fishes	Pred	MV	Kaufman & Ochumba, 1993
Lates niloticus	Nile perch	Fishes	Pred	MO	Achieng, 1990
Lates niloticus	Nile perch	*Caridina nilotica*	Pred	MN	Ogutu-Ohwayo, 1990
Lates niloticus	Nile perch	*Rastrineobola argentea*	Pred	MN	Ogutu-Ohwayo, 1990
Lates niloticus	Nile perch	Invertebrates	Pred	MN	Ogutu-Ohwayo, 1990
Lates niloticus	Nile perch	Fishes	Pred	MN	Ogutu-Ohwayo, 1990
Lates niloticus	Nile perch	*Bagrus docmak*	Com	MN	Olowo & Chapman, 1999
Lates niloticus	Nile perch	*Schilbe intermedius*	Com	MO	Olowo & Chapman, 1999
Lates niloticus	Nile perch	Invertebrates	Pred	MN	Kishe-Machumu et al., 2012
Lates niloticus	Nile perch	*Caridina nilotica*	Pred	MN	Kishe-Machumu et al., 2012
Lates niloticus	Nile perch	*Rastrineobola argentea*	Pred	MN	Kishe-Machumu et al., 2012

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Lates niloticus	Nile perch	Fishes	Pred	MN	Kishe-Machumu et al., 2012
Lates niloticus	Nile perch	*Rastrineobola argentea*	Pred	MN	Katunzi et al., 2006
Lates niloticus	Nile perch	*Caridina nilotica*	Pred	MN	Katunzi et al., 2006
Lates niloticus	Nile perch	Zooplankton	Pred	MN	Katunzi et al., 2006
Lates niloticus	Nile perch	Invertebrates	Pred	MN	Katunzi et al., 2006
Lates niloticus	Nile perch	Fishes	Pred	MN	Katunzi et al., 2006
Lates niloticus	Nile perch	*Caridina nilotica*	Pred	MN	Katunzi et al., 2006
Lates niloticus	Nile perch	*Rastrineobola argentea*	Pred	MN	Katunzi et al., 2006
Lates niloticus	Nile perch	*Rastrineobola argentea*	Pred	MN	Ngupula & Mlaponi, 2010
Lates niloticus	Nile perch	*Caridina nilotica*	Pred	MN	Ngupula & Mlaponi, 2010
Lates niloticus	Nile perch	Fishes	Pred	MN	Ngupula & Mlaponi, 2010
Lates niloticus	Nile perch	*Caridina nilotica*	Pred	MN	Goudswaard et al., 2006
Lates niloticus	Nile perch	*Rastrineobola argentea*	Pred	MN	Schofield & Chapman, 1999
Lates niloticus	Nile perch	*Brycinus sadleri*	Pred	MN	Schofield & Chapman, 1999
Lates niloticus	Nile perch	Fishes	Pred	MN	Schofield & Chapman, 1999
Lates niloticus	Nile perch	Invertebrates	Pred	MN	Schofield & Chapman, 1999
Lates niloticus	Nile perch	*Caridina nilotica*	Pred	MN	Hughes, 1992
Lates niloticus	Nile perch	*Rastrineobola argentea*	Pred	MN	Sharpe et al., 2012
Lates niloticus	Nile perch	*Bagrus docmak*	Com	MO	FishBase & Geelhand, 2016

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Lates niloticus	Nile perch	*Bagrus docmak*	Pred	MO	FishBase & Geelhand, 2016
Lates niloticus	Nile perch	*Tilapia esculenta*	Pred	MO	Arunga, 1981
Lates niloticus	Nile perch	*Tilapia nilotica*	Pred	MO	Arunga, 1981
Lates niloticus	Nile perch	*Haplochromis*	Pred	MO	Arunga, 1981
Lota lota	Burbot	Invertebrates	Pred	MN	McBaine et al., 2018
Lota lota	Burbot	*Rhinichthys cataractae*	Pred	MN	McBaine et al., 2018
Lota lota	Burbot	*Rhinichthys osculus*	Pred	MN	McBaine et al., 2018
Lota lota	Burbot	*Richardsonius balteatus*	Pred	MN	McBaine et al., 2018
Lota lota	Burbot	*Gila atraria*	Pred	MN	McBaine et al., 2018
Lota lota	Burbot	*Prosopium williamsoni*	Pred	MN	McBaine et al., 2018
Lota lota	Burbot	*Cottus bairdii*	Pred	MN	McBaine et al., 2018
Lota lota	Burbot	Fishes	Pred	MN	McBaine et al., 2018
Morone saxatilis	Striped bass	*Neomysis mercedis*	Pred	MO	Feyrer et al., 2003
Morone saxatilis	Striped bass	*Pogonichthys macrolepidotus*	Pred	MO	Feyrer et al., 2003
Morone saxatilis	Striped bass	*Catostomus occidentalis*	Pred	MO	Feyrer et al., 2003
Morone saxatilis	Striped bass	*Hysterocarpus traski*	Pred	MO	Feyrer et al., 2003
Morone saxatilis	Striped bass	*Cottus asper*	Pred	MO	Feyrer et al., 2003
Morone saxatilis	Striped bass	*Engraulis mordax*	Pred	MN	Feyrer et al., 2003
Morone saxatilis	Striped bass	*Cymatogaster aggregata*	Pred	MN	Thomas, 1967

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Morone saxatilis	Striped bass	*Clupea pallasii*	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	*Lepiocottus armatus*	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	*Hypomesus pretiosus*	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	*Spirinchus thaleichthys*	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	*Oncorhynchus tshawytscha*	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	*Lampetra ayresii*	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	*Microgadus proximus*	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	*Genyonemus lineatus*	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	*Platichthys stellatus*	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	*Pacifastacus leniusculus*	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	*Neomysis awatschensis*	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	*Callianassa californiensis*	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	*Cancer magister*	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	Invertebrates	Pred	MN	Thomas, 1967
Morone saxatilis	Striped bass	*Oncorhynchus tshawytscha*	Pred	MN	Lindley & Mohr, 2003
Morone saxatilis	Striped bass	Invertebrates	Pred	MN	Nobriga & Feyrer, 2008
Morone saxatilis	Striped bass	Fishes	Pred	MN	Nobriga & Feyrer, 2008
Morone saxatilis	Striped bass	*Oncorhyncus tschawytscha*	Pred	MN	Nobriga & Feyrer, 2008
Morone saxatilis	Striped bass	*Hypomesus transpacificus*	Pred	MN	Nobriga & Feyrer, 2008

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Morone saxatilis	Striped bass	*Cottus asper*	Pred	MN	Nobriga & Feyrer, 2008
Morone saxatilis	Striped bass	*Pogonichthys macrolepidotus*	Pred	MN	Nobriga & Feyrer, 2008
Morone saxatilis	Striped bass	*Platyichthys stellatus*	Pred	MN	Nobriga & Feyrer, 2008
Morone saxatilis	Striped bass	*Hysterocarpus traski*	Pred	MN	Nobriga & Feyrer, 2008
Morone saxatilis	Striped bass	Invertebrates	Pred	MN	Zeug et al., 2017
Morone saxatilis	Striped bass	Fishes	Pred	MN	Zeug et al., 2017
Morone saxatilis	Striped bass	*Oncorhyncus tschawytscha*	Pred	MN	Stevens, 1966
Morone saxatilis	Striped bass	*Oncorhyncus tschawytscha*	Pred	MN	Cavallo et al., 2013
Morone saxatilis	Striped bass	*Acipenser medirostris*	Pred	MN	Baird et al., 2020
Morone saxatilis	Striped bass	*Morone chrysops*	Hybr	MN	Taylor et al., 2013
Morone saxatilis	Striped bass	*Morone mississippiensis*	Hybr	MN	Taylor et al., 2013
Morone saxatilis	Striped bass	Fishes	Dis	MC	Amin & Minckley, 1996
Morone saxatilis	Striped bass	Fishes	Dis	MC	Tripathi et al., 2014
Mylopharyngodon piceus	Black carp	Fishes	Dis	MC	Cakic et al., 2004
Mylopharyngodon piceus	Black carp	Invertebrates	Pred	MN	Poulton et al., 2019
Mylopharyngodon piceus	Black carp	*Arcidens confragosus*	Pred	MN	Poulton et al., 2019
Mylopharyngodon piceus	Black carp	*Leptodea fragilis*	Pred	MN	Poulton et al., 2019
Mylopharyngodon piceus	Black carp	*Potamilus alatus*	Pred	MN	Poulton et al., 2019
Mylopharyngodon piceus	Black carp	*Pyganodon grandis*	Pred	MN	Poulton et al., 2019

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Mylopharyngodon piceus	Black carp	*Toxolasma lividum*	Pred	MN	Poulton et al., 2019
Mylopharyngodon piceus	Black carp	*Hexagenia bilineata*	Pred	MN	Poulton et al., 2019
Mylopharyngodon piceus	Black carp	*Hydropsyche orris*	Pred	MN	Poulton et al., 2019
Mylopharyngodon piceus	Black carp	*Potamyia flava*	Pred	MN	Poulton et al., 2019
Mylopharyngodon piceus	Black carp	Invertebrates	Pred	MN	Poulton et al., 2021
Mylopharyngodon piceus	Black carp	*Hamiota perovalis*	Pred	MN	Porreca et al., 2022
Mylopharyngodon piceus	Black carp	*Elimia livescens*	Pred	MN	Porreca et al., 2022
Mylopharyngodon piceus	Black carp	Invertebrates	Pred	MN	Porreca et al., 2022
Mylopharyngodon piceus	Black carp	*Lampsilis cariosa*	Pred	MN	Porreca et al., 2022
Mylopharyngodon piceus	Black carp	*Lampsilis cardium*	Pred	MN	Porreca et al., 2022
Mylopharyngodon piceus	Black carp	Invertebrates	Pred	MN	Hodgins et al., 2014
Mylopharyngodon piceus	Black carp	Fishes	Dis	MC	Poulton et al., 2021
Mylopharyngodon piceus	Bighead carp	Fishes	Dis	MC	Shamsi et al., 2009
Oncorhynchus tshawytscha	Chinook salmon	Fishes	Dis	MC	Rauque et al., 2018
Oncorhynchus tshawytscha	Chinook salmon	*Salmo salar*	Com	MN	Scott et al., 2003
Oncorhynchus tshawytscha	Chinook salmon	*Salmo salar*	Com	MN	Scott et al., 2003
Oncorhynchus tshawytscha	Chinook salmon	*Salmo salar*	Com	MC	Houde et al., 2015a
Oncorhynchus tshawytscha	Chinook salmon	*Salmo salar*	Com	MC	Houde et al., 2015b
Oncorhynchus tshawytscha	Chinook salmon	*Salmo salar*	Com	MN	Houde et al., 2015c

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Oncorhynchus tshawytscha	Chinook salmon	*Salmo salar*	Com	MN	Scott et al., 2005a
Oncorhynchus tshawytscha	Chinook salmon	*Salmo salar*	Com	MC	Scott et al., 2005b
Oncorhynchus tshawytscha	Chinook salmon	*Salmo salar*	Com	MC	Di Prinzio & Arismendi, 2018
Oncorhynchus tshawytscha	Chinook salmon	*Salmo salar*	Com	MC	Johnson & Chalupnicki, 2014
Oncorhynchus tshawytscha	Chinook salmon	*Salmo salar*	Com	MC	Lagrue et al., 2018
Oncorhynchus tshawytscha	Chinook salmon	Invertebrates	Pred	MN	Power, 1992
Oncorhynchus tshawytscha	Chinook salmon	Fishes	Dis	MC	Sagar & Glova, 1988
Oncorhynchus tshawytscha	Chinook salmon	Invertebrates	Pred	MN	Sagar & Glova, 1988
Oncorhynchus tshawytscha	Chinook salmon	Invertebrates	Pred	MN	Sagar & Glova, 1988
Oncorhynchus tshawytscha	Chinook salmon	*Zealandobius furcillatus*	Pred	MN	Sagar & Glova, 1988
Oncorhynchus tshawytscha	Chinook salmon	*Aoteapsyche tepoka*	Pred	MN	Sagar & Glova, 1988
Oncorhynchus tshawytscha	Chinook salmon	*Aoteapsyche colonicu*	Pred	MN	Sagar & Glova, 1988
Oncorhynchus tshawytscha	Chinook salmon	*Hydrobiosis frater*	Pred	MN	Sagar & Glova, 1988
Oncorhynchus tshawytscha	Chinook salmon	*Oxyethira albiceps*	Pred	MN	Sagar & Glova, 1988
Oncorhynchus tshawytscha	Chinook salmon	*Aplochiton zebra*	Pred	MO	Arismendi et al., 2009
Oncorhynchus tshawytscha	Chinook salmon	*Aplochiton taeniatus*	Pred	MO	Arismendi et al., 2009
Oncorhynchus tshawytscha	Chinook salmon	*Odontesthes mauleanum*	Pred	MO	Arismendi et al., 2009
Oncorhynchus tshawytscha	Chinook salmon	*Basilichthys australis*	Pred	MO	Arismendi et al., 2009
Oncorhynchus tshawytscha	Chinook salmon	*Percichthys trucha*	Pred	MO	Arismendi et al., 2009

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Oncorhynchus tshawytscha	Chinook salmon	*Galaxias maculatus*	Pred	MO	Arismendi et al., 2009
Oncorhynchus tshawytscha	Chinook salmon	*Galaxias platei*	Pred	MO	Arismendi et al., 2009
Pangasianodon hypophthalmus	Striped catfish	Fishes	Dis	MC	Tripathi et al., 2014
Pangasianodon hypophthalmus	Striped catfish	Fishes	Dis	MC	Mendoza-Franco et al., 2018
Polyodon spathula	Paddlefish	*Hypophthalmichthys nobilis*	Com	MC	Zhu et al., 2014
Protopterus aethiopicus	Marbled lungfish	*Oreochromis niloticus*	Pred	MN	Mlewa & Green, 2004
Protopterus aethiopicus	Marbled lungfish	*Clarias gariepinus*	Pred	MN	Mlewa & Green, 2004
Protopterus aethiopicus	Marbled lungfish	*Labeo cylindricus*	Pred	MN	Mlewa & Green, 2004
Protopterus aethiopicus	Marbled lungfish	*Barbus grerorii*	Pred	MN	Mlewa & Green, 2004
Pseudoplatystoma fasciatum	Barred sorubim	*Pseudoplatystoma corruscans*	Hybr	MN	Alves et al., 2007
Pylodictis olivaris	Flathead catfish	Fishes	Pred	MN	Belkoski et al., 2021
Pylodictis olivaris	Flathead catfish	Invertebrates	Pred	MN	Belkoski et al., 2021
Pylodictis olivaris	Flathead catfish	Snakes	Pred	MN	Belkoski et al., 2021
Pylodictis olivaris	Flathead catfish	Fishes	Pred	MN	Schmitt et al., 2017
Pylodictis olivaris	Flathead catfish	*Anguilla rostrata*	Pred	MN	Schmitt et al., 2017
Pylodictis olivaris	Flathead catfish	*Alosa aestivalis*	Pred	MN	Schmitt et al., 2017
Pylodictis olivaris	Flathead catfish	*Alosa mediocris*	Pred	MN	Schmitt et al., 2017

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Pylodictis olivaris	Flathead catfish	*Alosa pseudoharengus*	Pred	MN	Schmitt et al., 2017
Pylodictis olivaris	Flathead catfish	*Alosa sapidissima*	Pred	MN	Schmitt et al., 2017
Pylodictis olivaris	Flathead catfish	*Dorosoma cepedianum*	Pred	MN	Schmitt et al., 2017
Pylodictis olivaris	Flathead catfish	*Etheostoma flabellare*	Pred	MN	Schmitt et al., 2017
Pylodictis olivaris	Flathead catfish	*Ictalurus punctatus*	Pred	MN	Schmitt et al., 2017
Pylodictis olivaris	Flathead catfish	*Morone saxatilis*	Pred	MN	Schmitt et al., 2017
Pylodictis olivaris	Flathead catfish	*Morone americana*	Pred	MN	Schmitt et al., 2017
Pylodictis olivaris	Flathead catfish	Invertebrates	Pred	MN	Ashley & Buff, 1987
Pylodictis olivaris	Flathead catfish	Fishes	Pred	MN	Ashley & Buff, 1987
Pylodictis olivaris	Flathead catfish	*Lepisosteus osseus*	Pred	MN	Ashley & Buff, 1987
Pylodictis olivaris	Flathead catfish	*Alosa sapidissima*	Pred	MN	Ashley & Buff, 1987
Pylodictis olivaris	Flathead catfish	*Dorosoma cepedianum*	Pred	MN	Ashley & Buff, 1987
Pylodictis olivaris	Flathead catfish	*Ictalurus brunneus*	Pred	MN	Ashley & Buff, 1987
Pylodictis olivaris	Flathead catfish	*Ictalurus catus*	Pred	MN	Ashley & Buff, 1987
Pylodictis olivaris	Flathead catfish	*Ictalurus punetatus*	Pred	MN	Ashley & Buff, 1987
Pylodictis olivaris	Flathead catfish	*Lepomis microlophus*	Pred	MN	Ashley & Buff, 1987
Pylodictis olivaris	Flathead catfish	*Perca flavescens*	Pred	MN	Ashley & Buff, 1987
Pylodictis olivaris	Flathead catfish	*Leiostomus xanthurus*	Pred	MN	Ashley & Buff, 1987
Pylodictis olivaris	Flathead catfish	*Paralichthys lethostigma*	Pred	MN	Ashley & Buff, 1987

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Pylodictis olivaris	Flathead catfish	Invertebrates	Pred	MN	Baumann & Kwak, 2011
Pylodictis olivaris	Flathead catfish	Fishes	Pred	MN	Baumann & Kwak, 2011
Pylodictis olivaris	Flathead catfish	*Micropterus salmoides*	Pred	MN	Baumann & Kwak, 2011
Pylodictis olivaris	Flathead catfish	*Dorosoma cepedianum*	Pred	MN	Baumann & Kwak, 2011
Pylodictis olivaris	Flathead catfish	*Cyprinella analostana*	Pred	MN	Baumann & Kwak, 2011
Pylodictis olivaris	Flathead catfish	*Notropis scepticus*	Pred	MN	Baumann & Kwak, 2011
Pylodictis olivaris	Flathead catfish	*Ictalurus punctatus*	Pred	MN	Baumann & Kwak, 2011
Pylodictis olivaris	Flathead catfish	*Ameiurus serracanthus*	Pred	MO	Dobbins et al., 2012
Pylodictis olivaris	Flathead catfish	Invertebrates	Pred	MN	Guier et al., 1984
Pylodictis olivaris	Flathead catfish	Fishes	Pred	MO	Guier et al., 1984
Pylodictis olivaris	Flathead catfish	Fishes	Pred	MN	Pine III et al., 2005
Pylodictis olivaris	Flathead catfish	Invertebrates	Pred	MN	Pine III et al., 2005
Pylodictis olivaris	Flathead catfish	Invertebrates	Pred	MN	Quinn, 1987
Pylodictis olivaris	Flathead catfish	Fishes	Pred	MN	Quinn, 1987
Pylodictis olivaris	Flathead catfish	*Dorosoma cepedianum*	Pred	MN	Quinn, 1987
Pylodictis olivaris	Flathead catfish	*Dorosoma petenense*	Pred	MN	Quinn, 1987
Pylodictis olivaris	Flathead catfish	*Minytrema melanops*	Pred	MN	Quinn, 1987
Pylodictis olivaris	Flathead catfish	*Noturus gyrinus*	Pred	MN	Quinn, 1987
Pylodictis olivaris	Flathead catfish	*Ictalurus punctatus*	Pred	MN	Quinn, 1987

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Pylodictis olivaris	Flathead catfish	*Ictalurus brunneus*	Pred	MN	Quinn, 1987
Pylodictis olivaris	Flathead catfish	*Lepomis macrochirus*	Pred	MN	Quinn, 1987
Pylodictis olivaris	Flathead catfish	*Trinectes maculatus*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Anguilla rostrata*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Menidia beryllina*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Alosa aestivalis*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Alosa mediocris*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Alosa pseudoharengus*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Alosa sapidissima*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Brevoortia tyrannus*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Dorosoma cepedianum*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Hybognathus regius*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Nocomis micropogon*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Fundulus heteroclitus*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Ictalurus punctatus*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Morone americana*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Morone saxatilis*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	*Etheostoma flabellare*	Pred	MN	Schmitt et al., 2019a
Pylodictis olivaris	Flathead catfish	Fishes	Pred	MN	Schmitt et al., 2019a

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Pylodictis olivaris	Flathead catfish	Fishes	Pred	MN	Weller & Robbins, 1999
Pylodictis olivaris	Flathead catfish	*Ictalurus punctatus*	Pred	MN	Weller & Robbins, 1999
Pylodictis olivaris	Flathead catfish	*Micropterus salmoides*	Pred	MN	Weller & Robbins, 1999
Pylodictis olivaris	Flathead catfish	*Lepomis macrochirus*	Pred	MN	Weller & Robbins, 1999
Pylodictis olivaris	Flathead catfish	*Lepomis microlophus*	Pred	MN	Weller & Robbins, 1999
Pylodictis olivaris	Flathead catfish	*Lepomis punctatus*	Pred	MN	Weller & Robbins, 1999
Pylodictis olivaris	Flathead catfish	*Anguilla rostrata*	Pred	MN	Weller & Robbins, 1999
Pylodictis olivaris	Flathead catfish	*Trinectes maculatus*	Pred	MN	Weller & Robbins, 1999
Pylodictis olivaris	Flathead catfish	Invertebrates	Pred	MN	Weller & Robbins, 1999
Pylodictis olivaris	Flathead catfish	*Micropterus salmoides*	Pred	MO	Bonvechio et al., 2009
Pylodictis olivaris	Flathead catfish	*Micropterus salmoides*	Com	MO	Bonvechio et al., 2009
Pylodictis olivaris	Flathead catfish	*Lepomis auritus*	Com	MO	Bonvechio et al., 2009
Pylodictis olivaris	Flathead catfish	*Lepomis auritus*	Pred	MO	Bonvechio et al., 2009
Pylodictis olivaris	Flathead catfish	*Lepomis macrochirus*	Com	MN	Bonvechio et al., 2009
Pylodictis olivaris	Flathead catfish	*Lepomis macrochirus*	Pred	MN	Bonvechio et al., 2009
Pylodictis olivaris	Flathead catfish	*Acipenser oxyrinchus*	Pred	MN	Flowers et al., 2011
Pylodictis olivaris	Flathead catfish	*Lepomis auritus*	Pred	MO	Thomas, 1993
Pylodictis olivaris	Flathead catfish	*Lepomis macrochirus*	Pred	MN	Herndon & Waters, 2002
Pylodictis olivaris	Flathead catfish	*Lepomis gulosus*	Pred	MN	Herndon & Waters, 2002

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Pylodictis olivaris	Flathead catfish	*Leopmis microlophus*	Pred	MN	Herndon & Waters, 2002
Pylodictis olivaris	Flathead catfish	*Pomoxis nigromaculatus*	Pred	MN	Herndon & Waters, 2002
Pylodictis olivaris	Flathead catfish	*Micropterus salmoides*	Pred	MN	Herndon & Waters, 2002
Pylodictis olivaris	Flathead catfish	*Perca flavescens*	Pred	MN	Herndon & Waters, 2002
Pylodictis olivaris	Flathead catfish	Fishes	Pred	MN	Herndon & Waters, 2002
Pylodictis olivaris	Flathead catfish	Invertebrates	Pred	MN	Lucchesi et al., 2017
Pylodictis olivaris	Flathead catfish	Fishes	Pred	MN	Lucchesi et al., 2017
Pylodictis olivaris	Flathead catfish	Invertebrates	Pred	MN	Chandler, 1998
Pylodictis olivaris	Flathead catfish	Fishes	Pred	MN	Chandler, 1998
Pylodictis olivaris	Flathead catfish	*Dorosoma cepedianum*	Pred	MN	Chandler, 1998
Pylodictis olivaris	Flathead catfish	*Morone americana*	Pred	MN	Chandler, 1998
Pylodictis olivaris	Flathead catfish	*Anguilla rostrata*	Pred	MN	Chandler, 1998
Pylodictis olivaris	Flathead catfish	Fishes	Pred	MN	Walker et al., 2015
Salmo salar	Atlantic salmon	Fishes	Dis	MC	Rauque et al., 2018
Salmo salar	Atlantic salmon	Fishes	Pred	MN	Abrantes et al., 2011
Salmo salar	Atlantic salmon	Invertebrates	Pred	MN	Abrantes et al., 2011
Salmo salar	Atlantic salmon	Phytoplankton	Graz	MN	Abrantes et al., 2011
Salmo salar	Atlantic salmon	*Oncorhynchus mykiss*	Com	MN	Volpe et al., 2001
Salmo salar	Atlantic salmon	*Aplochiton zebra*	Com	MN	Young et al., 2009

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Salmo salar	Atlantic salmon	*Oncorhynchus gorbuscha*	Dis	MN	Price et al., 2010
Salmo salar	Atlantic salmon	*Oncorhynchus keta*	Dis	MN	Price et al., 2010
Salmo trutta	Brown trout	*Galaxias maculatus*	Pred	MN	Macchi et al., 2007
Salmo trutta	Brown trout	Fishes	Dis	MC	Rauque et al., 2018
Salmo trutta	Brown trout	*Galaxias truttaceus*	Com	MO	Ault & White, 1994
Salmo trutta	Brown trout	*Galaxias truttaceus*	Pred	MO	Ault & White, 1994
Salmo trutta	Brown trout	*Galaxias auratus*	Pred	MN	Stuart-Smith et al., 2007
Salmo trutta	Brown trout	*Salmo salar*	Hybr	MN	Verspoor, 1988
Salmo trutta	Brown trout	*Salmo salar*	Com	MN	Houde et al., 2015a
Salmo trutta	Brown trout	*Salmo salar*	Com	MN	Houde et al., 2015b
Salmo trutta	Brown trout	*Salmo salar*	Com	MN	Houde et al., 2015c
Salmo trutta	Brown trout	*Salmo salar*	Com	MN	Van Zwol et al., 2012a
Salmo trutta	Brown trout	*Salmo salar*	Com	MN	Van Zwol et al., 2012b
Salmo trutta	Brown trout	*Salmo salar*	Com	MC	Scott et al., 2005b
Salmo trutta	Brown trout	*Salmo salar*	Hybr	MN	Beland et al., 1981
Salmo trutta	Brown trout	*Aplochiton zebra*	Pred	MO	Young et al., 2010
Salmo trutta	Brown trout	*Aplochiton taeniatus*	Pred	MO	Young et al., 2010
Salmo trutta	Brown trout	Invertebrates	Pred	MN	Milardi et al., 2016
Salmo trutta	Brown trout	*Salmo marmoratus*	Hybr	MN	Meraner & Gandolfi, 2018

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Salmo trutta	Brown trout	*Schizothorax richardsonii*	Com	MN	Johal et al., 2021
Salmo trutta	Brown trout	*Salvelinus leucomaenis*	Hybr	MN	Kitano et al., 2009
Salmo trutta	Brown trout	*Salvelinus leucomaenis*	Com	MN	Hasegawa, 2017
Salmo trutta	Brown trout	*Salvelinus leucomaenis*	Com	MO	Morita, 2018
Salmo trutta	Brown trout	*Salvelinus leucomaenis*	Com	MN	Hasegawa et al., 2004
Salmo trutta	Brown trout	*Oncorhynchus masou*	Com	MN	Hasegawa et al., 2004
Salmo trutta	Brown trout	*Salvelinus leucomaenis*	Com	MN	Hasegawa & Maekawa, 2006a
Salmo trutta	Brown trout	*Oncorhynchus masou*	Com	MN	Hasegawa & Maekawa, 2006b
Salmo trutta	Brown trout	*Salvelinus leucomaenis*	Com	MN	Hasegawa & Maekawa, 2009
Salmo trutta	Brown trout	*Oncorhynchus masou*	Com	MN	Hasegawa & Maekawa, 2018
Salmo trutta	Brown trout	*Oncorhynchus masou*	Com	MN	Hasegawa et al., 2012
Salmo trutta	Brown trout	*Salvelinus leucomaenis*	Com	MO	Morita et al., 2004
Salmo trutta	Brown trout	Periphyton	Int	MN	Biggs et al., 2000
Salmo trutta	Brown trout	Invertebrates	Pred	MN	Flecker & Townsend, 1994
Salmo trutta	Brown trout	Fishes	Pred	MN	McIntosh, 2000
Salmo trutta	Brown trout	Invertebrates	Pred	MN	McIntosh & Townsend, 1996
Salmo trutta	Brown trout	Invertebrates	Pred	MN	Wissinger et al., 2006
Salmo trutta	Brown trout	*Nesameletus ornatus*	Pred	MN	McIntosh & Townsend, 1994
Salmo trutta	Brown trout	*Paranephrops zealandicus*	Pred	MO	Whitmore et al., 2000

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Salmo trutta	Brown trout	*Zelandopsyche ingens*	Pred	MN	Greig et al., 2006
Salmo trutta	Brown trout	*Zelandopsyche ingens*	Pred	MO	Mcintosh et al., 2005
Salmo trutta	Brown trout	*Galaxias maculatus*	Pred	MN	Glova, 2003
Salmo trutta	Brown trout	*Galaxias vulgaris*	Pred	MO	Townsend & Crowl, 1991
Salmo trutta	Brown trout	*Galaxias vulgaris*	Com	MO	McIntosh et al., 1992
Salmo trutta	Brown trout	*Deleatidium spp.*	Pred	MN	McIntosh & Townsend, 1995
Salmo trutta	Brown trout	Invertebrates	Pred	MN	Nyström & McIntosh, 2003
Salmo trutta	Brown trout	*Galaxias vulgaris*	Com	MN	Edge et al., 1993
Salmo trutta	Brown trout	*Salmo marmoratus*	Hybr	MN	Simčič et al., 2017
Salmo trutta	Brown trout	*Salmo marmoratus*	Hybr	MN	Meldgaard et al., 2007
Salmo trutta	Brown trout	*Salmo marmoratus*	Hybr	MN	Berrebi et al., 2000
Salmo trutta	Brown trout	*Salmo marmoratus*	Hybr	MN	Jug et al., 2005
Salmo trutta	Brown trout	*Salmo marmoratus*	Hybr	MN	Bajec et al., 2015
Salmo trutta	Brown trout	*Salmo marmoratus*	Hybr	MN	Povz, 1995
Salmo trutta	Brown trout	*Salmo marmoratus*	Hybr	MO	Fumagalli et al., 2002
Salmo trutta	Brown trout	*Salmo marmoratus*	Hybr	MN	Jug et al., 2004
Salmo trutta	Brown trout	*Salmo marmoratus*	Hybr	MN	Meraner et al., 2010
Salmo trutta	Brown trout	*Salmo marmoratus*	Hybr	MN	Berrebi et al., 2000
Salmo trutta	Brown trout	Invertebrates	Pred	MO	Osorio et al., 2022

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Salmo trutta	Brown trout	*Salvelinus fontinalis*	Com	MO	Waters, 1983
Salmo trutta	Brown trout	*Salvelinus fontinalis*	Com	MN	Dewald & Wilzbach, 1992
Salmo trutta	Brown trout	*Catostomus microps*	Pred	MN	Moyle & Marciochi, 1975
Salmo trutta	Brown trout	*Gila robusta*	Pred	MN	Laske et al., 2012
Salmo trutta	Brown trout	*Cottus cognatus*	Com	MN	Zimmerman & Vondracek, 2007
Salmo trutta	Brown trout	*Salvelinus fontinalis*	Com	MO	Hoxmeier & Dieterman, 2016
Salmo trutta	Brown trout	Fishes	Pred	MN	Garman & Nielsen, 1982
Salmo trutta	Brown trout	*Thoburnia rhothoeca*	Pred	MN	Garman & Nielsen, 1982
Salmo trutta	Brown trout	*Campostoma anomalum*	Pred	MN	Garman & Nielsen, 1982
Salmo trutta	Brown trout	*Cottus cognatus*	Com	MN	Ruetz III et al., 2003
Salmo trutta	Brown trout	*Gammarus pseudolimnaeus*	Int	MN	Ruetz III et al., 2003
Salmo trutta	Brown trout	*Oncorhynchus clarkii*	Com	MO	Budy et al., 2007
Salmo trutta	Brown trout	*Oncorhynchus clarkii*	Com	MO	de la Hoz Franco & Budy, 2005
Salmo trutta	Brown trout	*Oncorhynchus clarkii*	Com	MO	Hepworth et al., 2001
Salmo trutta	Brown trout	*Oncorhynchus clarkii*	Com	MN	McHugh & Budy, 2005
Salmo trutta	Brown trout	*Oncorhynchus clarkii*	Com	MN	McHugh & Budy, 2006
Salmo trutta	Brown trout	*Oncorhynchus clarkii*	Com	MO	Quist & Hubert, 2005
Salmo trutta	Brown trout	*Oncorhynchus clarkii*	Com	MN	Shemai et al., 2007
Salmo trutta	Brown trout	*Oncorhynchus clarkii*	Com	MN	Wang & White, 1994

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Salmo trutta	Brown trout	Fishes	Pred	MN	Meredith et al., 2015
Salmo trutta	Brown trout	Invertebrates	Pred	MN	Tiberti & Mori, 2016
Salmo trutta	Brown trout	*Triturus carnifex*	Pred	MN	Tiberti & Mori, 2016
Salmo trutta	Brown trout	*Triturus carnifex*	Pred	MN	Tiberti & Mori, 2016
Salmo trutta	Brown trout	*Neomys fodiens*	Pred	MN	Tiberti & Mori, 2016
Salmo trutta	Brown trout	*Salvelinus fontinalis*	Com	MC	Hoxmeier & Dieterman, 2019
Salmo trutta	Brown trout	*Schizothorax richardsonii*	Com	MN	Sharma et al., 2021a
Salmo trutta	Brown trout	*Galaxias anomalus*	Dis	MN	Paterson et al., 2011
Salmo trutta	Brown trout	*Schizothorax richardsonii*	Com	MN	Sharma et al., 2021b
Salmo trutta	Brown trout	*Salvelinus fontinalis*	Com	MN	Carlson et al., 2007
Salmo trutta	Brown trout	*Cottus gobio*	Pred	MN	Lorenzoni et al., 2018
Salmo trutta	Brown trout	*Oncorhynchus clarkii*	Com	MN	Rasmussen et al., 2011
Salmo trutta	Brown trout	*Oncorhynchus keta*	Pred	MN	Hasegawa et al., 2021
Salmo trutta	Brown trout	*Paranephrops planifrons*	Pred	MO	Olsson et al., 2006
Salmo trutta	Brown trout	Invertebrates	Pred	MN	Olsson et al., 2006
Salmo trutta	Brown trout	*Lepidomeda aliciae*	Pred	MN	Billman et al., 2011
Salmo trutta	Brown trout	*Galaxias auratus*	Pred	MN	Stuart-Smith et al., 2008
Salmo trutta	Brown trout	*Salvelinus fontinalis*	Com	MN	Hitt et al., 2017
Salmo trutta	Brown trout	*Cryptobranchus alleganiensis*	Pred	MN	Gall et al., 2010

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
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Salmo trutta	Brown trout	Invertebrates	Pred	MN	Arismendi et al., 2020
Salmo trutta	Brown trout	*Paranephrops zealandicus*	Pred	MN	Shave et al., 1994
Salmo trutta	Brown trout	Invertebrates	Pred	MN	Ortiz-Sandoval et al., 2017
Salmo trutta	Brown trout	*Galaxias platei*	Com	MN	Ortiz-Sandoval et al., 2017
Salmo trutta	Brown trout	*Oncorhynchus clarkii*	Com	MN	Pennock et al., 2022
Salmo trutta	Brown trout	*Oncorhynchus clarkii bouvieri*	Com	MN	Al-Chokhachy & Sepulveda, 2019
Salmo trutta	Brown trout	*Brachygalaxias bullocki*	Com	MN	Penaluna et al., 2009
Salmo trutta	Brown trout	*Galaxias maculatus*	Com	MN	Penaluna et al., 2009
Salmo trutta	Brown trout	*Trichomycterus areolatus*	Com	MN	Penaluna et al., 2009
Salmo trutta	Brown trout	*Geotria australis*	Com	MC	Penaluna et al., 2009
Salmo trutta	Brown trout	*Litoria phyllochroa*	Pred	MN	Gillespie, 2001
Salmo trutta	Brown trout	*Litoria spenceri*	Pred	MN	Gillespie, 2001
Salmo trutta	Brown trout	*Litoria lesueuri*	Pred	MN	Gillespie, 2001
Salmo trutta	Brown trout	*Litoria peroni*	Pred	MN	Gillespie, 2001
Salmo trutta	Brown trout	*Lepidomeda aliciae*	Pred	MN	Nannini & Belk, 2006
Salmo trutta	Brown trout	*Richardsonius balteatus*	Pred	MN	Nannini & Belk, 2006
Salmo trutta	Brown trout	*Gila cypha*	Pred	MN	Ward & Morton-Starner, 2015
Salmo trutta	Brown trout	*Etheostoma* sp.	Pred	MN	Johnson & Mathis, 2021

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Salmo trutta	Brown trout	Invertebrates	Pred	MN	Di Prinzio & Casaux, 2012
Salmo trutta	Brown trout	*Hadromophryne natalensis*	Pred	MO	Karssing et al., 2012
Salmo trutta	Brown trout	*Oncorhynchus clarkii utah*	Com	MO	Budy et al., 2007
Salmo trutta	Brown trout	*Pimephales promelas*	Pred	MN	Yard et al., 2011
Salmo trutta	Brown trout	*Gila cypha*	Pred	MN	Yard et al., 2011
Salmo trutta	Brown trout	*Rhinichthys osculus*	Pred	MN	Yard et al., 2011
Salmo trutta	Brown trout	*Catostomus latipinnis*	Pred	MN	Yard et al., 2011
Salmo trutta	Brown trout	*Catostomus discobolus jarrowi*	Pred	MN	Yard et al., 2011
Salmo trutta	Brown trout	Vertebrates	Pred	MN	Yard et al., 2011
Salvelinus namaycush	Lake trout	*Salvelinus confluentus*	Com	MR	Donald & Alger, 1993
Salvelinus namaycush	Lake trout	*Pungitius pungitius*	Pred	MN	Eloranta et al., 2015
Salvelinus namaycush	Lake trout	*Esox lucius*	Pred	MN	Eloranta et al., 2015
Salvelinus namaycush	Lake trout	*Coregonus lavaretus*	Pred	MN	Eloranta et al., 2015
Salvelinus namaycush	Lake trout	*Salvelinus alpinus*	Pred	MN	Eloranta et al., 2015
Salvelinus namaycush	Lake trout	*Coregonus albula*	Pred	MN	Eloranta et al., 2015
Salvelinus namaycush	Lake trout	*Lota lota*	Pred	MN	Eloranta et al., 2015
Salvelinus namaycush	Lake trout	Invertebrates	Pred	MN	Eloranta et al., 2015
Salvelinus namaycush	Lake trout	*Gila robusta*	Pred	MN	Laske et al., 2012
Salvelinus namaycush	Lake trout	*Oncorhynchus clarkii*	Pred	MR	Cordone & Frantz, 1966

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Salvelinus namaycush	Lake trout	*Oncorhynchus clarkii*	Pred	MO	Koel et al., 2005
Salvelinus namaycush	Lake trout	*Ursus americanus*	Int	MN	Koel et al., 2005
Salvelinus namaycush	Lake trout	*Ursus arctos horribilis*	Int	MN	Koel et al., 2005
Salvelinus namaycush	Lake trout	*Oncorhynchus clarkii*	Pred	MR	Zanden et al., 2003
Salvelinus namaycush	Lake trout	*Cottus beldingii*	Pred	MN	Frantz & Cordone, 1970
Salvelinus namaycush	Lake trout	*Catostomus tahoensis*	Pred	MN	Frantz & Cordone, 1970
Salvelinus namaycush	Lake trout	*Richardsonius egregius*	Pred	MN	Frantz & Cordone, 1970
Salvelinus namaycush	Lake trout	*Oncorhynchus nerka*	Pred	MN	Frantz & Cordone, 1970
Salvelinus namaycush	Lake trout	*Coregonus williamsoni*	Pred	MN	Frantz & Cordone, 1970
Salvelinus namaycush	Lake trout	Invertebrates	Pred	MN	Frantz & Cordone, 1970
Salvelinus namaycush	Lake trout	*Oncorhynchus clarki*	Pred	MN	Johnson & Martinez, 2000
Salvelinus namaycush	Lake trout	*Oncorhynchus nerka*	Pred	MN	Johnson & Martinez, 2000
Salvelinus namaycush	Lake trout	Invertebrates	Pred	MN	Johnson & Martinez, 2000
Salvelinus namaycush	Lake trout	*Oncorhynchus nerka*	Pred	MO	Beauchamp et al., 2006
Salvelinus namaycush	Lake trout	*Oncorhynchus nerka*	Com	MO	Beauchamp et al., 2006
Salvelinus namaycush	Lake trout	*Oncorhynchus clarki*	Pred	MO	Beauchamp et al., 2006
Salvelinus namaycush	Lake trout	*Salvelinus confluentus*	Pred	MO	Beauchamp et al., 2006
Salvelinus namaycush	Lake trout	*Prosopium coulterii*	Pred	MO	Beauchamp et al., 2006
Salvelinus namaycush	Lake trout	*Ursus arctos horribilis*	Int	MN	Spencer et al., 1991

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Salvelinus namaycush	Lake trout	*Haliaeetus leucocephalus*	Com	MO	Spencer et al., 1991
Salvelinus namaycush	Lake trout	*Oncorhynchus clarkii*	Pred	MN	Ruzycki et al., 2003
Salvelinus namaycush	Lake trout	*Perca flavescens*	Pred	MN	Ruzycki et al., 2003
Salvelinus namaycush	Lake trout	Invertebrates	Pred	MN	Ruzycki et al., 2003
Salvelinus namaycush	Lake trout	*Prosopium gemmifer*	Pred	MN	Ruzycki et al., 2001
Salvelinus namaycush	Lake trout	*Cottus extensus*	Pred	MN	Ruzycki et al., 2001
Salvelinus namaycush	Lake trout	*Prosopium spilonotus*	Pred	MN	Ruzycki et al., 2001
Salvelinus namaycush	Lake trout	*Prosopium abyssicola*	Pred	MN	Ruzycki et al., 2001
Salvelinus namaycush	Lake trout	*Prosopium gemmifer*	Com	MN	Ruzycki et al., 2001
Salvelinus namaycush	Lake trout	*Cottus extensus*	Com	MN	Ruzycki et al., 2001
Salvelinus namaycush	Lake trout	*Prosopium spilonotus*	Com	MN	Ruzycki et al., 2001
Salvelinus namaycush	Lake trout	*Prosopium abyssicola*	Com	MN	Ruzycki et al., 2001
Salvelinus namaycush	Lake trout	*Oncorhynchus nerka*	Pred	MN	Yule & Luecke, 1993
Salvelinus namaycush	Lake trout	*Gila atraria*	Pred	MN	Yule & Luecke, 1993
Salvelinus namaycush	Lake trout	*Oncorhynchus nerka*	Pred	MO	Schoen et al., 2012
Salvelinus namaycush	Lake trout	*Salvelinus confluentus*	Pred	MO	Ferguson et al., 2012
Salvelinus namaycush	Lake trout	*Salvelinus confluentus*	Com	MO	Ferguson et al., 2012
Salvelinus namaycush	Lake trout	Phytoplankton	Int	MO	Tronstad et al., 2010
Salvelinus namaycush	Lake trout	*Oncorhynchus clarki*	Pred	MO	Stapp & Hayward, 2002

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Salvelinus namaycush	Lake trout	*Ursus arctos*	Int	MN	Haroldson et al., 2005
Salvelinus namaycush	Lake trout	*Lontra canadensis*	Int	MC	Wengeler et al., 2010
Salvelinus namaycush	Lake trout	*Haliaeetus leucocephalus*	Int	MN	Baril et al., 2013
Salvelinus namaycush	Lake trout	*Pandion haliaetus*	Int	MO	Baril et al., 2013
Salvelinus namaycush	Lake trout	*Oncorhynchus clarkii*	Pred	MO	Koel et al., 2019
Salvelinus namaycush	Lake trout	*Lontra canadensis*	Int	MC	Koel et al., 2019
Salvelinus namaycush	Lake trout	*Ursus americanus*	Int	MC	Koel et al., 2019
Salvelinus namaycush	Lake trout	*Ursus arctos*	Int	MC	Koel et al., 2019
Salvelinus namaycush	Lake trout	*Pandion haliaetus*	Int	MO	Koel et al., 2019
Salvelinus namaycush	Lake trout	*Haliaeetus leucocephalus*	Int	MN	Koel et al., 2019
Salvelinus namaycush	Lake trout	*Oncorhynchus nerka*	Pred	MO	Ellis et al., 2011
Salvelinus namaycush	Lake trout	*Cervus elaphus*	Int	MN	Middleton et al., 2013
Salvelinus namaycush	Lake trout	*Ursus arctos*	Int	MN	Teisberg et al., 2014
Salvelinus namaycush	Lake trout	*Ursus americanus*	Int	MN	Teisberg et al., 2014
Salvelinus namaycush	Lake trout	*Lontra canadensis*	Int	MN	Crait et al., 2015
Salvelinus namaycush	Lake trout	*Oncoryhynchus clarkii bouvieri*	Pred	MO	Tronstad et al., 2010
Silurus glanis	Wels catfish	*Columba livia*	Pred	MN	Cucherousset et al., 2012
Silurus glanis	Wels catfish	*Petromyzon marinus*	Pred	MN	Boulêtreau et al., 2020
Silurus glanis	Wels catfish	Fishes	Pred	MO	Guillerault et al., 2015

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Silurus glanis	Wels catfish	Vertebrates	Pred	MN	Martino et al., 2011
Silurus glanis	Wels catfish	*Abramis brama*	Pred	MN	Martino et al., 2011
Silurus glanis	Wels catfish	*Atherina boyeri*	Pred	MN	Martino et al., 2011
Silurus glanis	Wels catfish	*Blicca bjoerkna*	Pred	MN	Martino et al., 2011
Silurus glanis	Wels catfish	*Alburnus alburnus*	Pred	MN	Martino et al., 2011
Silurus glanis	Wels catfish	*Chelon ramada*	Pred	MN	Martino et al., 2011
Silurus glanis	Wels catfish	*Alosa fallax*	Pred	MN	Guillerault et al., 2017
Silurus glanis	Wels catfish	*Liza ramada*	Pred	MN	Guillerault et al., 2017
Silurus glanis	Wels catfish	*Petromyzon marinus*	Pred	MN	Guillerault et al., 2017
Silurus glanis	Wels catfish	*Alburnus alburnus*	Pred	MN	Guillerault et al., 2017
Silurus glanis	Wels catfish	*Abramis brama*	Pred	MN	Guillerault et al., 2017
Silurus glanis	Wels catfish	*Carassius* sp.	Pred	MN	Guillerault et al., 2017
Silurus glanis	Wels catfish	*Gymnocephalus cernuus*	Pred	MN	Guillerault et al., 2017
Silurus glanis	Wels catfish	*Rutilus rutilus*	Pred	MN	Guillerault et al., 2017
Silurus glanis	Wels catfish	*Squalius cephalus*	Pred	MN	Guillerault et al., 2017
Silurus glanis	Wels catfish	*Anguilla anguilla*	Pred	MN	Guillerault et al., 2017
Silurus glanis	Wels catfish	Invertebrates	Pred	MN	Syväranta et al., 2010
Silurus glanis	Wels catfish	Vertebrates	Pred	MN	Syväranta et al., 2010
Silurus glanis	Wels catfish	Invertebrates	Pred	MN	Vagnon et al., 2022

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Silurus glanis	Wels catfish	*Lucanus cervus*	Pred	MN	Vagnon et al., 2022
Silurus glanis	Wels catfish	*Coregonus lavaretus*	Pred	MN	Vagnon et al., 2022
Silurus glanis	Wels catfish	*Esox lucius*	Pred	MN	Vagnon et al., 2022
Silurus glanis	Wels catfish	*Lota lota*	Pred	MN	Vagnon et al., 2022
Silurus glanis	Wels catfish	*Perca fluviatilis*	Pred	MN	Vagnon et al., 2022
Silurus glanis	Wels catfish	*Rutilus rutilus*	Pred	MN	Vagnon et al., 2022
Silurus glanis	Wels catfish	*Salaria fluviatilis*	Pred	MN	Vagnon et al., 2022
Silurus glanis	Wels catfish	*Tinca tinca*	Pred	MN	Vagnon et al., 2022
Silurus glanis	Wels catfish	*Natrix maura*	Pred	MN	Vagnon et al., 2022
Silurus glanis	Wels catfish	Fishes	Dis	MC	Galli et al., 2005
Silurus glanis	Wels catfish	*Alburnus arborella*	Pred	MO	Castaldelli et al., 2013
Silurus glanis	Wels catfish	*Scardinius erythrophthalmus*	Pred	MO	Castaldelli et al., 2013
Silurus glanis	Wels catfish	*Tinca tinca*	Pred	MR	Castaldelli et al., 2013
Silurus glanis	Wels catfish	*Rutilus aula*	Pred	MR	Castaldelli et al., 2013
Silurus glanis	Wels catfish	*Alosa agone*	Pred	MN	Antognazza et al., 2022
Silurus glanis	Wels catfish	*Alburnus alburnus*	Pred	MN	Antognazza et al., 2022
Silurus glanis	Wels catfish	*Padogobius bonelli*	Pred	MN	Antognazza et al., 2022
Silurus glanis	Wels catfish	*Perca fluviatilis*	Pred	MN	Antognazza et al., 2022
Silurus glanis	Wels catfish	*Salaria fluviatilis*	Pred	MN	Antognazza et al., 2022

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Silurus glanis	Wels catfish	Invertebrates	Pred	MN	Antognazza et al., 2022
Silurus glanis	Wels catfish	*Alosa agone*	Pred	MN	De Santis & Volta, 2021
Silurus glanis	Wels catfish	*Perca fluviatilis*	Pred	MN	De Santis & Volta, 2021
Silurus glanis	Wels catfish	*Scardinius hesperidicus*	Pred	MN	De Santis & Volta, 2021
Silurus glanis	Wels catfish	*Squalius squalus*	Pred	MN	De Santis & Volta, 2021
Silurus glanis	Wels catfish	*Cottus gobio*	Pred	MN	De Santis & Volta, 2021
Silurus glanis	Wels catfish	*Lota lota*	Pred	MN	De Santis & Volta, 2021
Silurus glanis	Wels catfish	*Acipenser naccarii*	Pred	MN	Puzzi et al., 2009
Silurus glanis	Wels catfish	*Hydropsyche exocellata*	Pred	MN	Carol et al., 2009
Silurus glanis	Wels catfish	*Atyaephyra desmaresti*	Pred	MN	Carol et al., 2009
Silurus glanis	Wels catfish	Invertebrates	Pred	MN	Carol et al., 2009
Silurus glanis	Wels catfish	*Alburnus alburnus*	Pred	MN	Carol et al., 2009
Silurus glanis	Wels catfish	*Luciobarbus graellsii*	Pred	MN	Carol et al., 2009
Silurus glanis	Wels catfish	Birds	Pred	MN	Carol et al., 2009
Silurus glanis	Wels catfish	Fishes	Dis	MC	de Chambrier & Scholz, 2020
Silurus glanis	Wels catfish	*Scardinius hesperidicus*	Pred	MN	Milardi et al., 2022
Silurus glanis	Wels catfish	*Phalacrocorax* spp.	Pred	MN	Milardi et al., 2022
Silurus glanis	Wels catfish	*Cygnus olor*	Pred	MN	Milardi et al., 2022
Silurus glanis	Wels catfish	*Fulica atra*	Pred	MN	Milardi et al., 2022

Binomial name	Common name	Impacted taxa	EICAT impact mechanism	EICAT category	Reference
Silurus glanis	Wels catfish	*Podiceps cristatus*	Pred	MN	Milardi et al., 2022
Silurus glanis	Wels catfish	*Nycticorax nycticorax*	Pred	MN	Milardi et al., 2022

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Appendix D: EICAT+ assessments for alien freshwater megafish

Table D1 Alien freshwater megafish EICAT+ assessment (modified from chapter 3).

Impact categories: MN+ = Minor+; MO+ = Moderate+

Prov = Provision of trophic resources; Epib = Epibiosis or other direct provisioning of habitat; Int = Indirect impacts through interactions with other species.

Binomial name	Common name	Impacted taxa	EICAT+ impact mechanism	EICAT+ category	Reference
Ctenopharyngodon idella	Grass carp	Phytoplankton	Int	MO+	Maceina et al., 1992
Ctenopharyngodon idella	Grass carp	Zooplankton	Int	MO+	Maceina et al., 1992
Ctenopharyngodon idella	Grass carp	Phytoplankton	Int	MN+	Lembi et al., 1978
Ctenopharyngodon idella	Grass carp	Phytoplankton	Int	MN+	Lembi et al., 1978
Ctenopharyngodon idella	Grass carp	*Myriophyllum spicatum*	Int	MN+	Pípalová, 2002
Ctenopharyngodon idella	Grass carp	*Ceratophyllum demersum*	Int	MN+	Pípalová, 2002
Ctenopharyngodon idella	Grass carp	*Spirogyra* sp.	Int	MN+	Pípalová, 2002
Ctenopharyngodon idella	Grass carp	Zooplankton	Int	MO+	Rowe, 1984
Ctenopharyngodon idella	Grass carp	Zooplankton	Int	MN+	Fry & Osborne, 1980
Ctenopharyngodon idella	Grass carp	Zooplankton	Int	MN+	Fry & Osborne, 1980
Ctenopharyngodon idella	Grass carp	Phytoplankton	Int	MN+	Khan et al., 2003
Ctenopharyngodon idella	Grass carp	Macroinvertebrates	Int	MO+	Kırkağaç & Demir, 2006

Binomial name	Common name	Impacted taxa	EICAT+ impact mechanism	EICAT+ category	Reference
Ctenopharyngodon idella	Grass carp	Phytoplankton	Int	MO+	Kırkağaç & Demir, 2006
Ctenopharyngodon idella	Grass carp	Zooplankton	Epib	MO+	Branford & Duggan, 2017
Ctenopharyngodon idella	Grass carp	*Myriophyllum spicatum*	Int	MO+	Weyl & Martin, 2016
Cyprinus carpio	Common carp	Invertebrates	Epib	MN+	Miller & Crowl, 2006
Cyprinus carpio	Common carp	*Podiceps cristatus*	Prov	MO+	Maceda-Veiga et al., 2017
Cyprinus carpio	Common carp	*Podiceps grisegena*	Prov	MN+	Kloskowski et al., 2021
Hypophthalmichthys molitrix	Silver Carp	*Ictalurus furcatus*	Prov	MN+	Yallaly et al., 2015
Hypophthalmichthys molitrix	Silver Carp	*Ictalurus punctatus*	Prov	MN+	Yallaly et al., 2015
Hypophthalmichthys molitrix	Silver Carp	Zooplankton	Int	MN+	Sass et al., 2014
Hypophthalmichthys nobilis	Bighead carp	*Lepomis macrochirus*	Int	MN+	Collins et al., 2017
Hypophthalmichthys nobilis	Bighead carp	Zooplankton	Int	MN+	Sass et al., 2014
Oncorhynchus tshawytscha	Chinook salmon	Invertebrates	Prov	MO+	Collins et al., 2016
Salmo trutta	Brown trout	Zooplankton	Int	MO+	Milardi et al., 2016
Salmo trutta	Brown trout	Invertebrates	Int	MO+	Milardi et al., 2016
Salmo trutta	Brown trout	Invertebrates	Int	MN+	Biggs et al., 2000
Salmo trutta	Brown trout	Phytoplankton	Int	MN+	Nyström & McIntosh, 2003
Salmo trutta	Brown trout	Phytoplankton	Int	MN+	Flecker & Townsend, 1994
Salvelinus namaycush	Lake trout	Zooplankton	Int	MN+	Tronstad et al., 2010
Salvelinus namaycush	Lake trout	Zooplankton	Int	MO+	Tronstad et al., 2010

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The following reference documents were used to collate data on positive impacts of alien freshwater megafish on native species during the EICAT+ assessment:

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Appendix E: Detrimental NCP assessments for alien freshwater megafauna

Table E1 Detrimental NCP associated with alien freshwater megafauna (modified from chapter 4).

NCP1 = Reduced food resources; NCP2 = Damage to properties; NCP3 = Reduced physical and psychological experiences; NCP4 = Risk to health or safety.

Binomial name	Common name	NCP (-) category	NCP (-) magnitude	Reference
Acipenser baerii	Siberian sturgeon	NCP4	Potential	Skóra et al., 2011
Atractosteus spatula	Alligator gar	NCP4	Medium	Han, 2022
Caiman crocodilus	Spectacled caiman	NCP4	Potential	Bunkley-Williams & Williams, 1994
Caiman crocodilus	Spectacled caiman	NCP3	Potential	Bunkley-Williams & Williams, 1994
Castor canadensis	American beaver	NCP3	Potential	Araos et al., 2020
Castor canadensis	American Beaver	NCP1	Medium	Malison et al., 2016
Channa marulius	Great snakehead	NCP4	Potential	Saylor et al., 2010
Chelydra serpentina	Common snapping turtle	NCP4	Potential	Esposito et al., 2022
Clarias gariepinus	African catfish	NCP1	Medium	Xia et al., 2019
Clarias gariepinus	African catfish	NCP4	Potential	Ribeiro et al., 2019
Clarias gariepinus	African catfish	NCP1	Medium	Singh et al., 2013
Clarias gariepinus	African catfish	NCP1	Medium	Khedkar et al., 2016
Crocodylus siamensis	Siamese crocodile	NCP4	Potential	Ticha et al., 2016

Binomial name	Common name	NCP (-) category	NCP (-) magnitude	Reference
Ctenopharyngodon idella	Grass carp	NCP1	Medium	Lusk et al., 2010
Ctenopharyngodon idella	Grass carp	NCP3	Medium	Lauber et al., 2020
Ctenopharyngodon idella	Grass carp	NCP3	Medium	Buck et al., 2010
Ctenopharyngodon idella	Grass carp	NCP4	Potential	Kaur & Katoch, 2016
Ctenopharyngodon idella	Grass carp	NCP1	Medium	Singh et al., 2013
Ctenopharyngodon idella	Grass carp	NCP4	Potential	Kennedy & Pojmanska, 1996
Ctenopharyngodon idella	Grass carp	NCP1	Medium	Shamsi et al., 2009
Ctenopharyngodon idella	Grass carp	NCP4	Potential	Chiary et al., 2014
Ctenopharyngodon idella	Grass carp	NCP1	Potential	Duggan & Pullan, 2017
Ctenopharyngodon idella	Grass carp	NCP1	Potential	De León et al., 2018
Ctenopharyngodon idella	Grass carp	NCP1	Medium	Hossain et al., 2014
Ctenopharyngodon idella	Grass carp	NCP4	Potential	Scholz & Salgado-Maldonado, 2000
Ctenopharyngodon idella	Grass carp	NCP4	Potential	Riley, 1978
Cyprinus carpio	Common carp	NCP1	Medium	Bocklisch et al., 2006
Cyprinus carpio	Common carp	NCP4	Potential	Pérez-Fuentetaja et al., 2010
Cyprinus carpio	Common carp	NCP4	Potential	Sanyal et al., 2018
Cyprinus carpio	Common carp	NCP4	Potential	Kaur & Katoch, 2016
Cyprinus carpio	Common carp	NCP1	Medium	Singh et al., 2013
Cyprinus carpio	Common carp	NCP4	Potential	Kennedy & Pojmanska, 1996
Cyprinus carpio	Common carp	NCP1	Medium	Shamsi et al., 2009

Binomial name	Common name	NCP (-) category	NCP (-) magnitude	Reference
Cyprinus carpio	Common carp	NCP4	Potential	Chiary et al., 2014
Cyprinus carpio	Common carp	NCP4	Potential	Amin & Minckley, 1996
Cyprinus carpio	Common carp	NCP4	Potential	Rauque et al., 2018
Cyprinus carpio	Common carp	NCP1	Potential	Scholz et al., 2018
Cyprinus carpio	Common carp	NCP4	Potential	Waicheim et al., 2014
Cyprinus carpio	Common carp	NCP4	Potential	Scholz et al., 2015
Cyprinus carpio	Common carp	NCP4	Potential	Oros et al., 2004
Cyprinus carpio	Common carp	NCP4	Potential	Dos Santos & Avenant-Oldewage, 2022
Cyprinus carpio	Common carp	NCP4	Potential	Rahmanikhah et al., 2020
Cyprinus carpio	Common carp	NCP4	Potential	Costa et al., 2022
Cyprinus carpio	Common carp	NCP4	Potential	Tolo et al., 2021
Cyprinus carpio	Common carp	NCP4	Potential	Otachi et al., 2014
Cyprinus carpio	Common carp	NCP4	Potential	Singh et al., 2014
Cyprinus carpio	Common carp	NCP4	Potential	Köker, 2022
Cyprinus carpio	Common carp	NCP4	Potential	Flores-Galván et al., 2020
Cyprinus carpio	Common carp	NCP4	Potential	Babut et al., 2012
Cyprinus carpio	Common carp	NCP4	Potential	Das et al., 2006
Cyprinus carpio	Common carp	NCP4	Potential	Visha et al., 2018
Cyprinus carpio	Common carp	NCP4	Potential	Richter & Skinner, 2020
Cyprinus carpio	Common carp	NCP4	Potential	Kumari et al., 2009

Binomial name	Common name	NCP (-) category	NCP (-) magnitude	Reference
Cyprinus carpio	Common carp	NCP4	Potential	Scholz & Salgado-Maldonado, 2000
Cyprinus carpio	Common carp	NCP4	Potential	Scholz et al., 2008
Cyprinus carpio	Common carp	NCP4	Potential	Barčák et al., 2021
Cyprinus carpio	Common carp	NCP4	Potential	Uhrovič et al., 2022
Esox lucius	Northern pike	NCP1	High	Schaufler et al., 2015
Esox lucius	Northern pike	NCP1	High	Schaufler et al., 2014
Esox lucius	Northern pike	NCP1	Medium	Schwörer et al., 2014
Hippopotamus amphibius	Hippopotamus	NCP4	Medium	Subalusky et al., 2021
Hippopotamus amphibius	Hippopotamus	NCP4	Medium	Castelblanco-Martínez et al., 2021
Hippopotamus amphibius	Hippopotamus	NCP4	Medium	Subalusky et al., 2023
Hypophthalmichthys molitrix	Silver carp	NCP3	Medium	Lauber et al., 2020
Hypophthalmichthys molitrix	Silver carp	NCP4	Medium	Vetter et al., 2017a
Hypophthalmichthys molitrix	Silver carp	NCP4	Medium	Buck et al., 2010
Hypophthalmichthys molitrix	Silver carp	NCP2	Medium	Buck et al., 2010
Hypophthalmichthys molitrix	Silver carp	NCP3	Medium	Buck et al., 2010
Hypophthalmichthys molitrix	Silver carp	NCP4	Potential	Kaur & Katoch, 2016
Hypophthalmichthys molitrix	Silver carp	NCP1	Medium	Kaushal, 2007
Hypophthalmichthys molitrix	Silver carp	NCP4	Potential	Kennedy & Pojmanska, 1996
Hypophthalmichthys molitrix	Silver carp	NCP1	Medium	Shamsi et al., 2009
Hypophthalmichthys molitrix	Silver carp	NCP1	Medium	Hossain et al., 2014

Binomial name	Common name	NCP (-) category	NCP (-) magnitude	Reference
Hypophthalmichthys molitrix	Silver carp	NCP4	Medium	Keevin & Garvey, 2019
Hypophthalmichthys molitrix	Silver carp	NCP4	Medium	Vetter et al., 2017b
Hypophthalmichthys molitrix	Silver carp	NCP4	Potential	Rogowski et al., 2009
Hypophthalmichthys molitrix	Silver carp	NCP4	Potential	Das et al., 2006
Hypophthalmichthys molitrix	Silver carp	NCP4	Potential	Levengood et al., 2014
Hypophthalmichthys molitrix	Silver carp	NCP4	Potential	Cakic et al., 2004
Hypophthalmichthys molitrix	Silver carp	NCP4	Potential	Scholz & Salgado-Maldonado, 2000
Hypophthalmichthys nobilis	Bighead carp	NCP1	Medium	Goodwin, 1999
Hypophthalmichthys nobilis	Bighead carp	NCP3	Medium	Lauber et al., 2020
Hypophthalmichthys nobilis	Bighead carp	NCP3	Medium	Buck et al., 2010
Hypophthalmichthys nobilis	Bighead carp	NCP1	Medium	Singh et al., 2013
Hypophthalmichthys nobilis	Bighead carp	NCP4	Potential	Kennedy & Pojmanska, 1996
Hypophthalmichthys nobilis	Bighead carp	NCP1	Medium	Shamsi et al., 2009
Hypophthalmichthys nobilis	Bighead carp	NCP1	Medium	Hossain et al., 2014
Hypophthalmichthys nobilis	Bighead carp	NCP4	Potential	Rogowski et al., 2009
Hypophthalmichthys nobilis	Bighead carp	NCP4	Potential	Levengood et al., 2014
Ictalurus furcatus	Blue catfish	NCP4	Potential	Luellen et al., 2018
Lates niloticus	Nile perch	NCP1	Medium	Riedmiller, 1994
Lates niloticus	Nile perch	NCP3	High	Witte, 2022
Lates niloticus	Nile perch	NCP3	High	Riedmiller, 1994

Binomial name	Common name	NCP (-) category	NCP (-) magnitude	Reference
Lates niloticus	Nile perch	NCP4	High	Johnson, 2010
Lates niloticus	Nile perch	NCP1	High	Riedmiller, 1994
Lates niloticus	Nile perch	NCP1	High	Aloo et al., 2017
Lates niloticus	Nile perch	NCP4	High	Aloo et al., 2017
Morone saxatilis	Striped bass	NCP4	Potential	Amin & Minckley, 1996
Morone saxatilis	Striped bass	NCP4	Potential	Davis et al., 2012
Mylopharyngodon piceus	Black carp	NCP3	Medium	Buck et al., 2010
Mylopharyngodon piceus	Black carp	NCP1	Medium	Hossain et al., 2014
Mylopharyngodon piceus	Black carp	NCP1	Medium	Scholz & Salgado-Maldonado, 2000
Mylopharyngodon piceus	Black carp	NCP4	Potential	Cakic et al., 2004
Mylopharyngodon piceus	Black carp	NCP4	Potential	Scholz & Salgado-Maldonado, 2000
Mylopharyngodon piceus	Black carp	NCP4	Potential	Poulton et al., 2021
Oncorhynchus tshawytscha	Chinook salmon	NCP4	Potential	Montory et al., 2020
Oncorhynchus tshawytscha	Chinook salmon	NCP4	Potential	Miller, 1994
Oncorhynchus tshawytscha	Chinook salmon	NCP4	Potential	Rauque et al., 2018
Oncorhynchus tshawytscha	Chinook salmon	NCP1	Medium	Mullin & Reyda, 2020
Oncorhynchus tshawytscha	Chinook salmon	NCP4	Potential	Lagrue et al., 2018
Oncorhynchus tshawytscha	Chinook salmon	NCP4	Potential	Smith et al., 1994
Oncorhynchus tshawytscha	Chinook salmon	NCP4	Potential	Sepúlveda et al., 2013
Oncorhynchus tshawytscha	Chinook salmon	NCP4	Potential	Visha et al., 2018

Binomial name	Common name	NCP (-) category	NCP (-) magnitude	Reference
Pangasianodon hypophthalmus	Striped catfish	NCP4	Potential	Mendoza-Franco et al., 2018
Pangasianodon hypophthalmus	Striped catfish	NCP4	Potential	Tripathi et al., 2014
Potamotrygon motoro	Ocellate river stingray	NCP4	Medium	Brisset et al., 2006
Potamotrygon motoro	Ocellate river stingray	NCP4	Medium	Choa et al., 2013
Potamotrygon motoro	Ocellate river stingray	NCP4	Medium	Ng et al., 2018
Potamotrygon motoro	Ocellate river stingray	NCP4	Medium	Brisset et al., 2006
Salmo salar	Atlantic salmon	NCP4	Potential	Suarez et al., 2021
Salmo salar	Atlantic salmon	NCP4	Potential	Rauque et al., 2018
Salmo salar	Atlantic salmon	NCP4	Potential	Sepúlveda et al., 2004
Salmo salar	Atlantic salmon	NCP1	Medium	Thakur et al., 2019
Salmo salar	Atlantic salmon	NCP4	Potential	Price et al., 2010
Salmo salar	Atlantic salmon	NCP4	Potential	Price et al., 2010
Salmo trutta	Brown trout	NCP4	Potential	Richter & Skinner, 2020
Salmo trutta	Brown trout	NCP1	Medium	Alvarez & Ward, 2019
Salmo trutta	Brown trout	NCP4	Potential	Arribére et al., 2008
Salmo trutta	Brown trout	NCP4	Potential	Ríos et al., 2022
Salmo trutta	Brown trout	NCP4	Potential	Kristan et al., 2013
Salmo trutta	Brown trout	NCP4	Potential	Arcagni et al., 2018
Salmo trutta	Brown trout	NCP4	Potential	Rizzo et al., 2011
Salmo trutta	Brown trout	NCP4	Potential	Guevara et al., 2005

Binomial name	Common name	NCP (-) category	NCP (-) magnitude	Reference
Salmo trutta	Brown trout	NCP4	Potential	Rauque et al., 2018
Salmo trutta	Brown trout	NCP4	Potential	Paterson et al., 2011
Silurus glanis	Wels catfish	NCP4	Potential	Babut et al., 2012
Silurus glanis	Wels catfish	NCP4	Potential	Huertas et al., 2016
Silurus glanis	Wels catfish	NCP4	Potential	Carrasco et al., 2011
Silurus glanis	Wels catfish	NCP4	Potential	Squadrone et al., 2013a
Silurus glanis	Wels catfish	NCP4	Potential	Squadrone et al., 2013b
Silurus glanis	Wels catfish	NCP4	Potential	Reading et al., 2012
Silurus glanis	Wels catfish	NCP4	Potential	Balzani et al., 2021
Silurus glanis	Wels catfish	NCP4	Potential	Balzani et al., 2022
Silurus glanis	Wels catfish	NCP4	Potential	Squadrone et al., 2016
Silurus glanis	Wels catfish	NCP4	Potential	Galli et al., 2005
Silurus glanis	Wels catfish	NCP4	Potential	de Chambrier et al., 2020
Tragelaphus spekii	Sitatunga	NCP4	Potential	Diaz-Delgado et al., 2021

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Appendix F: Beneficial NCP assessments for alien freshwater megafauna

Table F1 Beneficial NCP associated with alien freshwater megafauna (modified from chapter 4).

NCP1 = Habitat maintenance; NCP2 = Regulation of water quality; NCP3 = Regulation of detrimental organisms; NCP4 = Provision of food; NCP5 = Materials and companionship; NCP6 = Enhanced physical and psychological experience; NCP7 = Supporting identities.

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Acipenser baerii	Siberian sturgeon	NCP4	High	Li et al., 2009
Acipenser baerii	Siberian sturgeon	NCP4	High	Li et al., 2019
Acipenser baerii	Siberian sturgeon	NCP4	High	Kang et al., 2023
Acipenser baerii	Siberian sturgeon	NCP4	Medium	Paaver, 1999
Acipenser baerii	Siberian sturgeon	NCP4	High	Keszka & Panicz, 2018
Acipenser baerii	Siberian sturgeon	NCP4	Potential	Bronzi et al., 1999
Acipenser baerii	Siberian sturgeon	NCP4	High	Arndt et al., 2002
Acipenser baerii	Siberian sturgeon	NCP6	High	Cucherousset et al., 2021
Acipenser baerii	Siberian sturgeon	NCP6	Medium	Gessner et al., 1999
Acipenser baerii	Siberian sturgeon	NCP4	Medium	Arndt et al., 2002
Acipenser baerii	Siberian sturgeon	NCP4	High	Paschos et al., 2008
Acipenser baerii	Siberian sturgeon	NCP4	Potential	Hasanalipour et al., 2013
Acipenser baerii	Siberian sturgeon	NCP4	Medium	Mousavi-Sabet et al., 2019
Acipenser baerii	Siberian sturgeon	NCP4	High	Brevé et al., 2022

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Acipenser baerii	Siberian sturgeon	NCP4	High	Fopp-Bayat, 2010
Acipenser baerii	Siberian sturgeon	NCP4	Medium	Mocanu et al., 2022
Acipenser baerii	Siberian sturgeon	NCP4	Medium	Bui, 2022
Acipenser gueldenstaedtii	Russian sturgeon	NCP4	Potential	Hurvitz et al., 2008
Acipenser gueldenstaedtii	Russian sturgeon	NCP4	Potential	Gorshkova et al., 1996
Acipenser gueldenstaedtii	Russian sturgeon	NCP4	Low	Li et al., 2009
Acipenser gueldenstaedtii	Russian sturgeon	NCP4	High	Kang et al., 2023
Acipenser gueldenstaedtii	Russian sturgeon	NCP4	Medium	Paaver, 1999
Acipenser gueldenstaedtii	Russian sturgeon	NCP4	Medium	Gessner et al., 1999
Acipenser gueldenstaedtii	Russian sturgeon	NCP4	Medium	Arndt et al., 2002
Acipenser gueldenstaedtii	Russian sturgeon	NCP4	Medium	Paschos et al., 2008
Acipenser gueldenstaedtii	Russian sturgeon	NCP4	High	Brevé et al., 2022
Acipenser gueldenstaedtii	Russian sturgeon	NCP4	Medium	Keszka & Panicz, 2018
Acipenser gueldenstaedtii	Russian sturgeon	NCP4	Medium	Bui, 2022
Acipenser nudiventris	Ship sturgeon	NCP5	Medium	Dickey et al., 2023
Acipenser schrenckii	Japanese sturgeon	NCP4	High	Li et al., 2019
Acipenser schrenckii	Japanese sturgeon	NCP4	High	Kang et al., 2023
Acipenser sinensis	Chinese sturgeon	NCP4	Medium	Bui, 2022
Acipenser stellatus	Stellate sturgeon	NCP4	Medium	Arndt et al., 2002
Acipenser stellatus	Stellate sturgeon	NCP5	Medium	Dickey et al., 2023

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Acipenser transmontanus	White sturgeon	NCP5	High	Paschos et al., 2008
Acipenser transmontanus	White sturgeon	NCP4	Low	Bronzi et al., 1999
Acipenser transmontanus	White sturgeon	NCP4	Medium	Arndt et al., 2002
Andrias davidianus	Chinese giant salamander	NCP4	Medium	Fukumoto et al., 2015
Arapaima gigas	Arapaima	NCP4	High	Miranda-Chumacero et al., 2012
Arapaima gigas	Arapaima	NCP4	High	Van Damme et al., 2015
Arapaima gigas	Arapaima	NCP5	Medium	Magalhães et al., 2017
Arapaima gigas	Arapaima	NCP5	Medium	Brosse et al., 2021
Arapaima gigas	Arapaima	NCP4	Medium	Marková et al., 2020
Arapaima gigas	Arapaima	NCP5	Medium	Marková et al., 2020
Atractosteus spatula	Alligator gar	NCP5	Medium	Han, 2022
Atractosteus spatula	Alligator gar	NCP5	Medium	Hasan et al., 2020
Atractosteus spatula	Alligator gar	NCP5	Medium	Salnikov, 2010
Caiman crocodilus	Spectacled caiman	NCP4	High	Huang et al., 2018
Caiman crocodilus	Spectacled caiman	NCP4	High	Zhang et al., 2021
Caiman crocodilus	Spectacled caiman	NCP5	Medium	Ellis, 1980
Caiman crocodilus	Spectacled caiman	NCP5	Medium	Charruau et al., 2016
Caiman crocodilus	Spectacled caiman	NCP5	High	King & Krakauer, 1996
Caiman crocodilus	Spectacled caiman	NCP5	Medium	Roberto et al., 2021
Caiman yacare	Yacaré	NCP4	High	Zhang et al., 2021

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Castor canadensis	American beaver	NCP5	Low	Jusim et al., 2020
Castor canadensis	American beaver	NCP5	Low	Anderson et al., 2009
Castor canadensis	American beaver	NCP1	Medium	Araos et al., 2020
Castor canadensis	American beaver	NCP6	Medium	Araos et al., 2020
Castor canadensis	American beaver	NCP7	High	Schüttler et al., 2011
Castor canadensis	American beaver	NCP4	Medium	Schüttler et al., 2011
Castor canadensis	American beaver	NCP5	Medium	Schüttler et al., 2011
Catla catla	Catla	NCP4	High	Renjithkumar et al., 2011
Catla catla	Catla	NCP4	Medium	Moreau & Costa-Pierce, 1997
Channa marulius	Great snakehead	NCP4	Medium	Courtenay & Williams, 2004
Channa marulius	Great snakehead	NCP5	Medium	Courtenay & Williams, 2004
Chelydra serpentina	Common snapping turtle	NCP5	Medium	Kopecký et al., 2013
Chelydra serpentina	Common snapping turtle	NCP5	Medium	Esposito et al., 2022
Chelydra serpentina	Common snapping turtle	NCP5	Medium	Koo et al., 2020
Clarias gariepinus	African catfish	NCP4	Medium	Parvez et al., 2022
Clarias gariepinus	African catfish	NCP4	High	Tripathi, 1996
Clarias gariepinus	African catfish	NCP4	High	Vitule et al., 2006
Clarias gariepinus	African catfish	NCP4	High	Dauda et al., 2018
Clarias gariepinus	African catfish	NCP4	High	Weyl et al., 2016
Clarias gariepinus	African catfish	NCP4	High	Britton & Orsi, 2012

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Clarias gariepinus	African catfish	NCP4	High	Radhakrishnan et al., 2011
Clarias gariepinus	African catfish	NCP4	High	Gu et al., 2018
Clarias gariepinus	African catfish	NCP4	High	Xia et al., 2019
Clarias gariepinus	African catfish	NCP4	Low	Perdikaris et al., 2010
Clarias gariepinus	African catfish	NCP4	High	Popp et al., 2018
Clarias gariepinus	African catfish	NCP4	Medium	Renjithkumar et al., 2011
Clarias gariepinus	African catfish	NCP4	Low	Pandey et al., 2000
Clarias gariepinus	African catfish	NCP4	High	Singh & Lakra, 2011
Clarias gariepinus	African catfish	NCP4	High	Khedkar et al., 2016
Clarias gariepinus	African catfish	NCP4	High	Sunarma et al., 2016
Clarias gariepinus	African catfish	NCP4	Medium	Richardson et al., 2009
Clarias gariepinus	African catfish	NCP6	High	Barkhuizen et al., 2017
Clarias gariepinus	African catfish	NCP4	High	Wachirachaikarn et al., 2009
Clarias macrocephalus	Broadhead catfish	NCP4	High	Tripathi, 1996
Colossoma macropomum	Catchma	NCP4	High	Brosse et al., 2021
Crocodylus moreletii	Morelet’s crocodile	NCP6	Medium	González-Sánchez et al., 2021
Crocodylus moreletii	Morelet’s crocodile	NCP5	High	González-Sánchez et al., 2021
Crocodylus moreletii	Morelet’s crocodile	NCP4	High	González-Sánchez et al., 2021
Crocodylus niloticus	Nile crocodile	NCP4	High	Chen et al., 2018
Crocodylus niloticus	Nile crocodile	NCP5	Medium	Roberto et al., 2021

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Crocodylus siamensis	Siamese crocodile	NCP4	High	Guo et al., 2018
Crocodylus siamensis	Siamese crocodile	NCP4	High	Chen et al., 2018
Ctenopharyngodon idella	Grass carp	NCP4	High	De Silva et al., 2006
Ctenopharyngodon idella	Grass carp	NCP4	High	Britton & Orsi, 2012
Ctenopharyngodon idella	Grass carp	NCP3	Potential	Sinhababu et al., 2013
Ctenopharyngodon idella	Grass carp	NCP4	High	Lusk et al., 2010
Ctenopharyngodon idella	Grass carp	NCP4	High	Moreau & Costa-Pierce, 1997
Ctenopharyngodon idella	Grass carp	NCP3	High	Moreau & Costa-Pierce, 1997
Ctenopharyngodon idella	Grass carp	NCP6	High	Cucherousset et al., 2021
Ctenopharyngodon idella	Grass carp	NCP2	High	Perdikaris et al., 2010
Ctenopharyngodon idella	Grass carp	NCP4	High	Singh et al., 2010
Ctenopharyngodon idella	Grass carp	NCP4	High	Singh & Lakra, 2011
Ctenopharyngodon idella	Grass carp	NCP3	Medium	Singh & Lakra, 2011
Ctenopharyngodon idella	Grass carp	NCP4	High	Singh et al., 2013
Ctenopharyngodon idella	Grass carp	NCP3	Medium	Gopalakrishnan et al., 2011
Ctenopharyngodon idella	Grass carp	NCP4	High	Jayasankar, 2018
Ctenopharyngodon idella	Grass carp	NCP4	Medium	Jena et al., 2002
Ctenopharyngodon idella	Grass carp	NCP4	High	Salehi, 2009
Ctenopharyngodon idella	Grass carp	NCP4	Medium	Moreau & Costa-Pierce, 1997
Ctenopharyngodon idella	Grass carp	NCP3	Medium	Kırkağaç, 2011

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Ctenopharyngodon idella	Grass carp	NCP3	Medium	Wells et al., 2003
Ctenopharyngodon idella	Grass carp	NCP3	Medium	Hicks et al., 2006
Ctenopharyngodon idella	Grass carp	NCP3	Medium	Catarino et al., 1997
Ctenopharyngodon idella	Grass carp	NCP4	Medium	Patriche et al., 2002
Ctenopharyngodon idella	Grass carp	NCP3	Medium	Moreau & Costa-Pierce, 1997
Ctenopharyngodon idella	Grass carp	NCP2	Medium	Çiçek et al., 2022
Ctenopharyngodon idella	Grass carp	NCP3	Medium	McKnight & Hepp, 1995
Ctenopharyngodon idella	Grass carp	NCP3	Medium	Garner et al., 2013
Ctenopharyngodon idella	Grass carp	NCP3	High	Hanlon et al., 2000
Ctenopharyngodon idella	Grass carp	NCP3	Medium	Venter & Schoonbee, 1991
Ctenopharyngodon idella	Grass carp	NCP3	Medium	June-Wells et al., 2017
Ctenopharyngodon idella	Grass carp	NCP4	Medium	Chapman et al., 2021
Ctenopharyngodon idella	Grass carp	NCP5	Medium	Dickey et al., 2023
Cyprinus carpio	Common carp	NCP4	High	Stuart & Conallin, 2018
Cyprinus carpio	Common carp	NCP4	Medium	Wahab et al., 2002
Cyprinus carpio	Common carp	NCP4	High	Alam et al., 2019
Cyprinus carpio	Common carp	NCP4	High	Jeney & Jian, 2009
Cyprinus carpio	Common carp	NCP4	High	De Silva et al., 2006
Cyprinus carpio	Common carp	NCP4	High	Britton & Orsi, 2012
Cyprinus carpio	Common carp	NCP4	High	Moreau & Costa-Pierce, 1997

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Cyprinus carpio	Common carp	NCP3	Potential	Sinhababu et al., 2013
Cyprinus carpio	Common carp	NCP4	High	Kang et al., 2023
Cyprinus carpio	Common carp	NCP4	High	Lusk et al., 2010
Cyprinus carpio	Common carp	NCP6	Medium	Jankovský et al., 2011
Cyprinus carpio	Common carp	NCP6	High	Cucherousset et al., 2021
Cyprinus carpio	Common carp	NCP4	High	Singh et al., 2010
Cyprinus carpio	Common carp	NCP4	High	Pathak et al., 2011
Cyprinus carpio	Common carp	NCP4	High	Gowsalya et al., 2020
Cyprinus carpio	Common carp	NCP4	Medium	Jena et al., 2002
Cyprinus carpio	Common carp	NCP4	High	Singh & Lakra, 2011
Cyprinus carpio	Common carp	NCP4	High	Singh et al., 2013
Cyprinus carpio	Common carp	NCP4	High	Jayasankar, 2018
Cyprinus carpio	Common carp	NCP4	High	Salehi, 2009
Cyprinus carpio	Common carp	NCP4	High	Goren & Galil, 2005
Cyprinus carpio	Common carp	NCP4	High	Shelton & Rothbard, 2005
Cyprinus carpio	Common carp	NCP4	High	Hickley et al., 2015
Cyprinus carpio	Common carp	NCP4	Medium	Moreau & Costa-Pierce, 1997
Cyprinus carpio	Common carp	NCP4	High	Zambrano et al., 2010
Cyprinus carpio	Common carp	NCP4	Medium	Patriche et al., 2002
Cyprinus carpio	Common carp	NCP6	High	Barkhuizen et al., 2017

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Cyprinus carpio	Common carp	NCP3	Potential	Wong et al., 2009
Cyprinus carpio	Common carp	NCP5	Medium	Maceda-Veiga et al., 2013
Cyprinus carpio	Common carp	NCP6	Medium	Ateşşahin & Dürrani, 2023
Cyprinus carpio	Common carp	NCP6	High	Williams & Moss, 2001
Cyprinus carpio	Common carp	NCP4	Medium	Bhavsar et al., 2018
Cyprinus carpio	Common carp	NCP3	Potential	Quoc et al., 2012
Cyprinus carpio	Common carp	NCP4	High	Garvey et al., 2010
Cyprinus carpio	Common carp	NCP4	High	Nedoluzhko et al., 2021
Cyprinus carpio	Common carp	NCP5	Medium	Dickey et al., 2023
Esox lucius	Northern pike	NCP6	Potential	Martelo et al., 2021
Esox lucius	Northern pike	NCP3	Potential	Elvira et al., 1996
Esox lucius	Northern pike	NCP6	Medium	Muhlfeld et al., 2008
Esox lucius	Northern pike	NCP6	High	McMahon & Bennett, 1996
Esox masquinongy	Muskellunge	NCP6	Medium	Zelman et al., 2023
Esox masquinongy	Muskellunge	NCP6	High	Curry et al., 2007
Eunectes murinus	Green anaconda	NCP5	Medium	Hunter et al., 2015
Eunectes notaeus	Yellow anaconda	NCP5	Medium	Hunter et al., 2015
Eunectes notaeus	Yellow anaconda	NCP5	Medium	Fuller, 2023
Hippopotamus amphibius	Hippopotamus	NCP6	High	Subalusky et al., 2021
Hippopotamus amphibius	Hippopotamus	NCP6	High	Subalusky et al., 2023

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Hippopotamus amphibius	Hippopotamus	NCP6	Medium	Fazal et al., 2014
Hippopotamus amphibius	Hippopotamus	NCP6	Medium	Flack, 2013
Hippopotamus amphibius	Hippopotamus	NCP7	Medium	Flack, 2013
Huso huso	Beluga	NCP4	Potential	Gorshkova et al., 1996
Huso huso	Beluga	NCP4	High	Li et al., 2019
Huso huso	Beluga	NCP4	Medium	Paaver, 1999
Huso huso	Beluga	NCP4	Medium	Arndt et al., 2002
Huso huso	Beluga	NCP4	High	Paschos et al., 2008
Huso huso	Beluga	NCP4	Medium	Mousavi-Sabet et al., 2019
Huso huso	Beluga	NCP4	Medium	Bui, 2022
Hypophthalmichthys molitrix	Silver carp	NCP4	High	De Silva et al., 2006
Hypophthalmichthys molitrix	Silver carp	NCP4	High	Hamilton, 2021
Hypophthalmichthys molitrix	Silver carp	NCP4	Potential	de Almeida-Toledo et al., 1995
Hypophthalmichthys molitrix	Silver carp	NCP4	High	Lusk et al., 2010
Hypophthalmichthys molitrix	Silver carp	NCP4	High	Moreau & Costa-Pierce, 1997
Hypophthalmichthys molitrix	Silver carp	NCP6	High	Cucherousset et al., 2021
Hypophthalmichthys molitrix	Silver carp	NCP2	High	Perdikaris et al., 2010
Hypophthalmichthys molitrix	Silver carp	NCP4	High	Singh et al., 2010
Hypophthalmichthys molitrix	Silver carp	NCP4	High	Kaushal, 2007
Hypophthalmichthys molitrix	Silver carp	NCP4	High	Jayasankar, 2018

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Hypophthalmichthys molitrix	Silver carp	NCP4	Medium	Jena et al., 2002
Hypophthalmichthys molitrix	Silver carp	NCP4	High	Salehi, 2009
Hypophthalmichthys molitrix	Silver carp	NCP4	High	Goren & Galil, 2005
Hypophthalmichthys molitrix	Silver carp	NCP4	Medium	Moreau & Costa-Pierce, 1997
Hypophthalmichthys molitrix	Silver carp	NCP4	Medium	Patriche et al., 2002
Hypophthalmichthys molitrix	Silver carp	NCP4	Medium	Innal & Erk'akan, 2006
Hypophthalmichthys molitrix	Silver carp	NCP2	Medium	Çiçek et al., 2022
Hypophthalmichthys molitrix	Silver carp	NCP3	Potential	Datta & Jana, 1998
Hypophthalmichthys molitrix	Silver carp	NCP4	High	Garvey et al., 2010
Hypophthalmichthys molitrix	Silver carp	NCP4	Medium	Trindade et al., 2019
Hypophthalmichthys molitrix	Silver carp	NCP3	Medium	Freeze & Henderson, 1982
Hypophthalmichthys molitrix	Silver carp	NCP3	Medium	Lieberman, 1996
Hypophthalmichthys molitrix	Silver carp	NCP4	High	Phan & De Silva, 2000
Hypophthalmichthys molitrix	Silver carp	NCP5	Medium	Dickey et al., 2023
Hypophthalmichthys nobilis	Bighead carp	NCP4	High	Britton & Orsi, 2012
Hypophthalmichthys nobilis	Bighead carp	NCP4	Potential	de Almeida-Toledo et al., 1995
Hypophthalmichthys nobilis	Bighead carp	NCP4	High	Lusk et al., 2010
Hypophthalmichthys nobilis	Bighead carp	NCP4	High	Moreau & Costa-Pierce, 1997
Hypophthalmichthys nobilis	Bighead carp	NCP2	High	Perdikaris et al., 2010
Hypophthalmichthys nobilis	Bighead carp	NCP4	High	Molnár et al., 2021

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Hypophthalmichthys nobilis	Bighead carp	NCP4	High	Singh et al., 2013
Hypophthalmichthys nobilis	Bighead carp	NCP4	High	Salehi, 2009
Hypophthalmichthys nobilis	Bighead carp	NCP4	High	De Silva et al., 2006
Hypophthalmichthys nobilis	Bighead carp	NCP3	Medium	Chapman et al., 2021
Hypophthalmichthys nobilis	Bighead carp	NCP3	Potential	Datta & Jana, 1998
Hypophthalmichthys nobilis	Bighead carp	NCP4	High	Garvey et al., 2010
Hypophthalmichthys nobilis	Bighead carp	NCP4	Medium	Butler et al., 2019
Hypophthalmichthys nobilis	Bighead carp	NCP4	High	Bouska et al., 2020
Hypophthalmichthys nobilis	Bighead carp	NCP4	Medium	Hoover et al., 2015
Hypophthalmichthys nobilis	Bighead carp	NCP3	Medium	Lieberman, 1996
Hypophthalmichthys nobilis	Bighead carp	NCP4	High	Phan & De Silva, 2000
Ictalurus furcatus	Blue catfish	NCP4	High	Bonvechio et al., 2012
Ictalurus furcatus	Blue catfish	NCP6	High	Bonvechio et al., 2012
Ictalurus furcatus	Blue catfish	NCP6	High	Schmitt et al., 2019
Ictalurus furcatus	Blue catfish	NCP6	High	Fabrizio et al., 2021
Ictalurus furcatus	Blue catfish	NCP6	High	Bonvechio et al., 2012
Ictalurus furcatus	Blue catfish	NCP6	High	Nepal et al., 2020
Ictalurus furcatus	Blue catfish	NCP6	High	Aguilar et al., 2017
Ictalurus furcatus	Blue catfish	NCP6	High	Orth et al., 2020
Ictalurus furcatus	Blue catfish	NCP6	High	Hilling et al., 2021

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Ictalurus furcatus	Blue catfish	NCP6	High	Nepal & Fabrizio, 2019
Ictalurus furcatus	Blue catfish	NCP6	High	Nepal & Fabrizio, 2021
Ictalurus furcatus	Blue catfish	NCP6	High	Bunch et al., 2018
Ictalurus furcatus	Blue catfish	NCP6	High	Tuckey et al., 2017
Ictalurus furcatus	Blue catfish	NCP6	High	Moran et al., 2016
Ictalurus furcatus	Blue catfish	NCP6	High	Belkoski et al., 2021
Ictiobus cyprinellus	Bigmouth buffalo	NCP4	Medium	Kalous et al., 2018
Ictiobus cyprinellus	Bigmouth buffalo	NCP6	Medium	Fuller & Sturtevant, 2023
Kobus leche	Southern lechwe	NCP6	Medium	Moshobane et al., 2020
Labeo rohita	Rohu	NCP4	Medium	Moreau & Costa-Pierce, 1997
Labeo rohita	Rohu	NCP4	High	Phan & De Silva, 2000
Lates calcarifer	Barramundi	NCP4	High	Le Moullac et al., 2003
Lates calcarifer	Barramundi	NCP4	High	Stern & Rothman, 2021
Lates niloticus	Nile perch	NCP4	High	Riedmiller, 1994
Lates niloticus	Nile perch	NCP4	High	Marshall, 2022
Lates niloticus	Nile perch	NCP4	High	Kitchell et al., 1997
Lates niloticus	Nile perch	NCP4	High	Balirwa et al., 2003
Lates niloticus	Nile perch	NCP4	High	Balirwa, 2007
Lates niloticus	Nile perch	NCP4	High	Johnson, 2010
Lates niloticus	Nile perch	NCP4	High	Van der Knaap, 2013

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Lates niloticus	Nile perch	NCP4	High	Aloo et al., 2017
Macrochelys temminckii	Alligator snapping turtle	NCP5	Medium	Esposito et al., 2022
Macrochelys temminckii	Alligator snapping turtle	NCP5	Medium	Koo et al., 2021
Mecistops cataphractus	African slender-snouted crocodile	NCP5	Medium	Roberto et al., 2021
Morone saxatilis	Striped bass	NCP4	Medium	Bariche et al., 2020
Morone saxatilis	Striped bass	NCP6	High	Shelton & Rothbard, 2006
Morone saxatilis	Striped bass	NCP6	High	Stevens et al., 1985
Morone saxatilis	Striped bass	NCP4	High	Stevens et al., 1985
Morone saxatilis	Striped bass	NCP4	High	Le Doux-Bloom et al., 2022
Morone saxatilis	Striped bass	NCP4	High	Boughton, 2020
Morone saxatilis	Striped bass	NCP3	High	Churchill et al., 2002
Morone saxatilis	Striped bass	NCP6	High	Taylor et al., 2013
Mylopharyngodon piceus	Black carp	NCP3	Potential	Ben-Ami & Heller, 2001
Mylopharyngodon piceus	Black carp	NCP3	Potential	Hunter & Nico, 2015
Mylopharyngodon piceus	Black carp	NCP4	Medium	Chapman et al., 2021
Mylopharyngodon piceus	Black carp	NCP3	Medium	Papoulias et al., 2011
Mylopharyngodon piceus	Black carp	NCP3	Medium	Nico et al., 2011
Mylopharyngodon piceus	Black carp	NCP4	High	Nico et al., 2011
Mylopharyngodon piceus	Black carp	NCP4	High	Whitledge et al., 2022

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Mylopharyngodon piceus	Black carp	NCP3	Medium	Ledford & Kelly, 2006
Mylopharyngodon piceus	Bighead carp	NCP5	Medium	Dickey et al., 2023
Myxocyprinus asiaticus	Chinese high-fin banded shark	NCP5	Medium	Dickey et al., 2023
Oncorhynchus tshawytscha	Chinook salmon	NCP6	High	Di Prinzio & Pascual, 2008
Oncorhynchus tshawytscha	Chinook salmon	NCP6	High	Hunt et al., 2017
Oncorhynchus tshawytscha	Chinook salmon	NCP4	High	Araya et al., 2014
Oncorhynchus tshawytscha	Chinook salmon	NCP4	High	Pascual et al., 2009
Oncorhynchus tshawytscha	Chinook salmon	NCP6	High	Arismendi et al., 2014
Oncorhynchus tshawytscha	Chinook salmon	NCP6	High	Cid-Aguayo et al., 2021
Oncorhynchus tshawytscha	Chinook salmon	NCP4	High	Cid-Aguayo et al., 2021
Oncorhynchus tshawytscha	Chinook salmon	NCP4	Medium	Sepúlveda et al., 2013
Oncorhynchus tshawytscha	Chinook salmon	NCP4	High	Johnston et al., 2021
Oncorhynchus tshawytscha	Chinook salmon	NCP6	High	Ivanova et al., 2022
Oncorhynchus tshawytscha	Chinook salmon	NCP3	Medium	Ivanova et al., 2022
Oncorhynchus tshawytscha	Chinook salmon	NCP6	High	Scott et al., 2003
Oncorhynchus tshawytscha	Chinook salmon	NCP3	Medium	Kornis et al., 2019
Oncorhynchus tshawytscha	Chinook salmon	NCP3	Medium	Stewart et al., 1991
Oncorhynchus tshawytscha	Chinook salmon	NCP4	High	Kornis et al., 2020
Oncorhynchus tshawytscha	Chinook salmon	NCP6	High	Simpson et al., 2016
Oncorhynchus tshawytscha	Chinook salmon	NCP6	High	Raynor & Phaneuf, 2020

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Oncorhynchus tshawytscha	Chinook salmon	NCP4	High	Unwin & James, 1998
Paleosuchus palpebrosus	Dwarf caiman	NCP5	Medium	Roberto et al., 2021
Paleosuchus trigonatus	Smooth-fronted caiman	NCP5	Medium	Roberto et al., 2021
Pangasianodon hypophthalmus	Striped catfish	NCP4	High	Garcia et al., 2018
Pangasianodon hypophthalmus	Striped catfish	NCP5	High	Garcia et al., 2018
Pangasianodon hypophthalmus	Striped catfish	NCP4	Medium	Lianthuamluaia et al., 2019
Pangasianodon hypophthalmus	Striped catfish	NCP4	High	Tarkan et al., 2020
Pangasianodon hypophthalmus	Striped catfish	NCP5	Medium	Dickey et al., 2023
Pangasius sanitwongsei	Giant pangasius	NCP5	Medium	Makinen et al., 2013
Pangasius sanitwongsei	Giant pangasius	NCP5	Medium	Yoğurtçuoğlu, 2018
Phractocephalus hemioliopterus	Redtail catfish	NCP5	Medium	Dickey et al., 2023
Polyodon spathula	Paddlefish	NCP4	Medium	Arndt et al., 2002
Polyodon spathula	Paddlefish	NCP4	High	Paschos et al., 2008
Polyodon spathula	Paddlefish	NCP4	High	Jarić et al., 2019
Polyodon spathula	Paddlefish	NCP5	Medium	Dickey et al., 2023
Potamotrygon motoro	Ocellate river stingray	NCP5	Medium	Ng et al., 2018
Potamotrygon motoro	Ocellate river stingray	NCP5	Medium	Brisset et al., 2006
Potamotrygon motoro	Ocellate river stingray	NCP5	High	Jerikho et al., 2023
Potamotrygon motoro	Ocellate river stingray	NCP5	Medium	Ng et al., 2010
Potamotrygon motoro	Ocellate river stingray	NCP5	Medium	Dickey et al., 2023

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Pylodictis olivaris	Flathead catfish	NCP6	High	Belkoski et al., 2021
Pylodictis olivaris	Flathead catfish	NCP5	High	Grabowski et al., 2004
Salminus brasiliensis	Dorado	NCP6	Medium	Gubiani et al., 2010
Salminus brasiliensis	Dorado	NCP6	Medium	Ribeiro et al., 2017
Salminus brasiliensis	Dorado	NCP6	Medium	Vitule et al., 2014
Salminus brasiliensis	Dorado	NCP6	Medium	Daga et al., 2016
Salminus brasiliensis	Dorado	NCP6	Medium	Geller et al., 2021
Salmo salar	Atlantic salmon	NCP6	High	Hunt et al., 2017
Salmo salar	Atlantic salmon	NCP4	High	Abrantes et al., 2011
Salmo salar	Atlantic salmon	NCP4	High	Crawford, 2003
Salmo salar	Atlantic salmon	NCP4	High	Fisher et al., 2014
Salmo salar	Atlantic salmon	NCP4	High	Piccolo et al., 2012
Salmo salar	Atlantic salmon	NCP4	High	Shelton & Rothbard, 2006
Salmo salar	Atlantic Salmon	NCP4	High	Araya et al., 2014
Salmo salar	Atlantic salmon	NCP4	High	Pascual et al., 2009
Salmo salar	Atlantic salmon	NCP6	High	Arismendi et al., 2014
Salmo salar	Atlantic salmon	NCP4	High	Arismendi et al., 2014
Salmo salar	Atlantic salmon	NCP4	High	Marín-Nahuelpi et al., 2022
Salmo salar	Atlantic salmon	NCP4	High	Valiente et al., 2010
Salmo salar	Atlantic salmon	NCP4	High	Schröder & Garcia de Leaniz, 2011

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Salmo salar	Atlantic salmon	NCP4	High	Shelton & Rothbard, 2006
Salmo salar	Atlantic salmon	NCP4	High	Soto et al., 2023
Salmo salar	Atlantic salmon	NCP4	High	Soto et al., 2001
Salmo salar	Atlantic salmon	NCP4	High	Sepúlveda et al., 2013
Salmo salar	Atlantic salmon	NCP4	High	Quiñones et al., 2019
Salmo salar	Atlantic salmon	NCP4	Medium	Perdikaris et al., 2010
Salmo salar	Atlantic salmon	NCP4	Medium	Dugenci & Candan, 2003
Salmo salar	Atlantic salmon	NCP6	Medium	Gerig et al., 2019
Salmo trutta	Brown trout	NCP6	High	Jackson et al., 2004
Salmo trutta	Brown trout	NCP6	High	Hunt et al., 2017
Salmo trutta	Brown trout	NCP6	High	Arismendi et al., 2014
Salmo trutta	Brown trout	NCP4	High	Arismendi et al., 2014
Salmo trutta	Brown trout	NCP4	High	Kang et al., 2023
Salmo trutta	Brown trout	NCP4	Medium	Perdikaris et al., 2010
Salmo trutta	Brown trout	NCP6	High	Lorenzoni et al., 2018
Salmo trutta	Brown trout	NCP4	Medium	Orrù et al., 2010
Salmo trutta	Brown trout	NCP6	High	Orrù et al., 2010
Salmo trutta	Brown trout	NCP6	High	Shelton & Rothbard, 2006
Salmo trutta	Brown trout	NCP6	High	Kornis et al., 2020
Salmo trutta	Brown trout	NCP6	High	Simpson et al., 2016

Binomial name	Common name	NCP (+) category	NCP (+) magnitude	Reference
Salmo trutta	Brown trout	NCP6	High	Griffin & Fayram, 2007
Salmo trutta	Brown trout	NCP6	High	Jones & Closs, 2017
Salvelinus namaycush	Lake trout	NCP6	High	Crossman, 1995
Salvelinus namaycush	Lake trout	NCP4	Medium	Crossman, 1995
Salvelinus namaycush	Lake trout	NCP4	High	Martinez et al., 2009
Salvelinus namaycush	Lake trout	NCP6	High	Martinez et al., 2009
Silurus asotus	Amur catfish	NCP7	Medium	Huang, 2018
Silurus glanis	Wels catfish	NCP4	High	Antognazza et al., 2022
Silurus glanis	Wels catfish	NCP6	High	Rodrı´guez-Labajos, 2014
Silurus glanis	Wels catfish	NCP6	Medium	Moreno-Valcárcel et al., 2013
Silurus glanis	Wels catfish	NCP5	Medium	Maceda-Veiga et al., 2013
Silurus glanis	Wels catfish	NCP6	Medium	Britton et al., 2007
Silurus glanis	Wels catfish	NCP6	Medium	Rees et al., 2017
Tragelaphus spekii	Sitatunga	NCP6	Medium	Diaz-Delgado et al., 2021

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