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Original Research Article

Biological diversity in protected areas: Not yet known but already threatened

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A B S T R A C T

Maintaining biodiversity and ecosystem function is critical on national and global scales. However, while only a fraction of the global biodiversity is known, its current decline is unprecedented, making biodiversity hotspots a conservation priority. The Sierra Gorda Biodiversity Reserve (SGBR) in Central Mexico is known for its rich biodiversity. It is an example of the juxtaposition between species discovery and extinction: aquatic species richness is mostly unknown as no efforts have investigated aquatic communities so far, but are already anthropogenically stressed. We hypothesized that invasive species are already well established in various protected areas and investigated this by assessing the threat of invasive species that are already established within the SGBR on the native biodiversity. By combining field sampling with peer-reviewed literature and local reports, we identify the presence of various non-native species in SGBR. Among these non-native species identified were opportunistic predatory fish and potentially-pathogen transmitting molluscs, but also, a habitat engineer capable of modifying ecosystem functions. Moreover, we highlight that these species were introduced despite legislation and without any knowledge among authorities. As a result, we underline the necessity to describe native species, control invasive and prevent the introduction of further non-native species. If accelerated action is not taken, we risk losing a considerable amount of described and unknown freshwater biota.

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1. Introduction

Worldwide, approximately 1.2 million species have been described (Mora et al., 2011). While this number appears high, the total number of species on earth that remain unknown is estimated at 7.5 million (Mora et al., 2011). This means that it is difficult to estimate the number of species that go extinct each day, as we have only described 15% of the total species on Earth. Furthermore, evidence shows that species diversity is declining at an alarming rate (Cardinale et al., 2012) and that the current extinction rates are approximately 1000 times higher than the background extinction rate (Pimm et al., 2014). Thus, protecting biodiversity and stopping further losses should be one of the highest priorities.

One tool used to conserve biodiversity and to prevent species extinction is the establishment of 'nature protected areas' (NPAs) (Hoffmann et al., 2018). About 10–15% of the world's land surface is already under protection (Soutullo, 2010) and such areas should be further expanded to effectively protect biodiversity (Planet, 2016). Mexico showed one of the most notable increases in protected areas since 2016 (2.0% increase; update on global statistics from Protected Planet Report 2016). Mexican flora and fauna contribute a considerable degree of biodiversity, which makes conservation of areas in this region particularly pressing. Mexico is located in a transition zone between the Nearctic and Neotropic, and has one of the most diverse biotas among temperate zones (Mastretta-Yanes et al., 2015). Due to geological and climatic changes during the Pliocene-Pleistocene and Neogene, respectively, it is now one of the most diverse ecoregions (Salzmann et al., 2011). In the areas declared as NPAs, sustainable use of natural resources is still legal (category VI; see González et al., 2014). Hence people live in these NPAs, however, the population density is comparatively low compared to non NPA areas. Nonetheless, these NPAs also include so-called "core zones" which are under strict protection, that is to say areas where human impacts are strictly controlled and limited (category I).

One of these complex NPAs with different protection zones is the Sierra Gorda Biosphere Reserve (SGBR), in the Central Plateau of Mexico. Known for its diverse habitats, biotic groups and ecotypes (CONANP, 2019), the total area of 3800 km^2 comprises 11 core zones (Carabias Lillo et al., 1999). The population density of 24.5 per km^2 within the NPA is about half the world's average of 45 per km^2. Therefore, the two biggest drivers of biodiversity loss, 'land use change' and 'direct exploitation' (compare IPBES Report, 2019), should have a lesser impact within the SGBR. However, it remains unclear if, and how, the most important driver for biodiversity loss 'invasive alien species' (Blackburn et al., 2019), adds to a possible species decline in protected areas (such as the SGBR). This question becomes more pressing as it was shown that not much is known about the aquatic fauna within the SGBR (Pino-Del-Carpio et al., 2011), especially as freshwater ecosystems are generally more vulnerable to invasions than marine or terrestrial ecosystems (Strayer, 2012).

Globally, the introduction of non-native aquatic species is often caused by recreational angling (i.e. voluntary introduction of non-native species by anglers); aquaculture (resulting the release of non-native species during flooding events), and releases from the pet-trade (Patoka et al., 2017). In recent years, several aquatic non-native species have been recorded in Mexico. The most well documented examples of detrimental invasive species are the red swamp crayfish *Procambarus clarkii* and the catfish *Ictalurus punctatus* (Mifsut and Jiménez, 2007). Both species were introduced to serve as easily accessible resources (food source; Trujillo-jiménez and Beto, 2007). Such invasive species have often been introduced disregarding environmental consequences (Kettunen et al., 2008), as their effect in protected areas might be substantial (Brown et al., 2019; Lockwood and Burkhalter, 2015). However, recent literature shows that our understanding of the distribution of invasive species within protected areas is scarce and only anecdotal at best (Figueroa and Sánchez-Cordero, 2008).

Since invasive species often have detrimental effects on conservation and management attempts, knowing their distribution (especially with respect to NPAs) is of utmost importance (Norton and Miller, 2000). We hypothesize that biodiversity within protected areas, which in many cases has not been fully assessed yet, is already threatened by invasive species. To contribute knowledge on the presence of potentially harmful non-native species within protected areas, we used SGBR, one of Mexico's largest protected areas, as our case-study (Pino-Del-Carpio et al., 2011). We first present an updated list of aquatic non-native species within Mexico's SGBR, to highlight the need for taxonomic efforts to a) identify native biodiversity and b) to better understand the impacts (e.g. species extinctions and niche shifts, etc.) of non-native species on native biodiversity. Secondarily, we discuss potential implications of non-native species introductions and missing taxonomic lists in regard to conservation efforts on the case-study SGBR.

2. Methods

2.1. Study area

Sierra Gorda is a Biosphere Reserve (SGBR) and Natural Protected Area (NPA) in the Central Plateau of Mexico. It comprises 11 smaller areas which are of raised concern and protected by Mexican Norm (NOM-059-ecol-1994) (Carabias Lillo et al., 1999). The rivers in the SGBR drain into the Gulf of Mexico (Fig. 1) and the Jalpan River flows into a reservoir before joining the Santa María River. Climatically, this zone varies from semi-warm to warm with annual average temperatures above 18 °C. Precipitation averages 313 mm in the dry season and 883 mm in the rainy season between July and October. The vegetation in the Sierra Gorda with 1724 species is one of the most diverse among all the Natural Reserves in Mexico. According to Zamudio et al. (1992) the study area comprises five vegetation types: a) pine forest, b) rain forest, c) oak forest, d) tropical deciduous forest, and e) xerophytic *matorral* (a typical shrubland). Land uses include: crops such as corn, bean, lemon, ornamental plants, and introduced grasses (INEGI, 2010). The high diversity of the region, due to the mixture of rain forests,

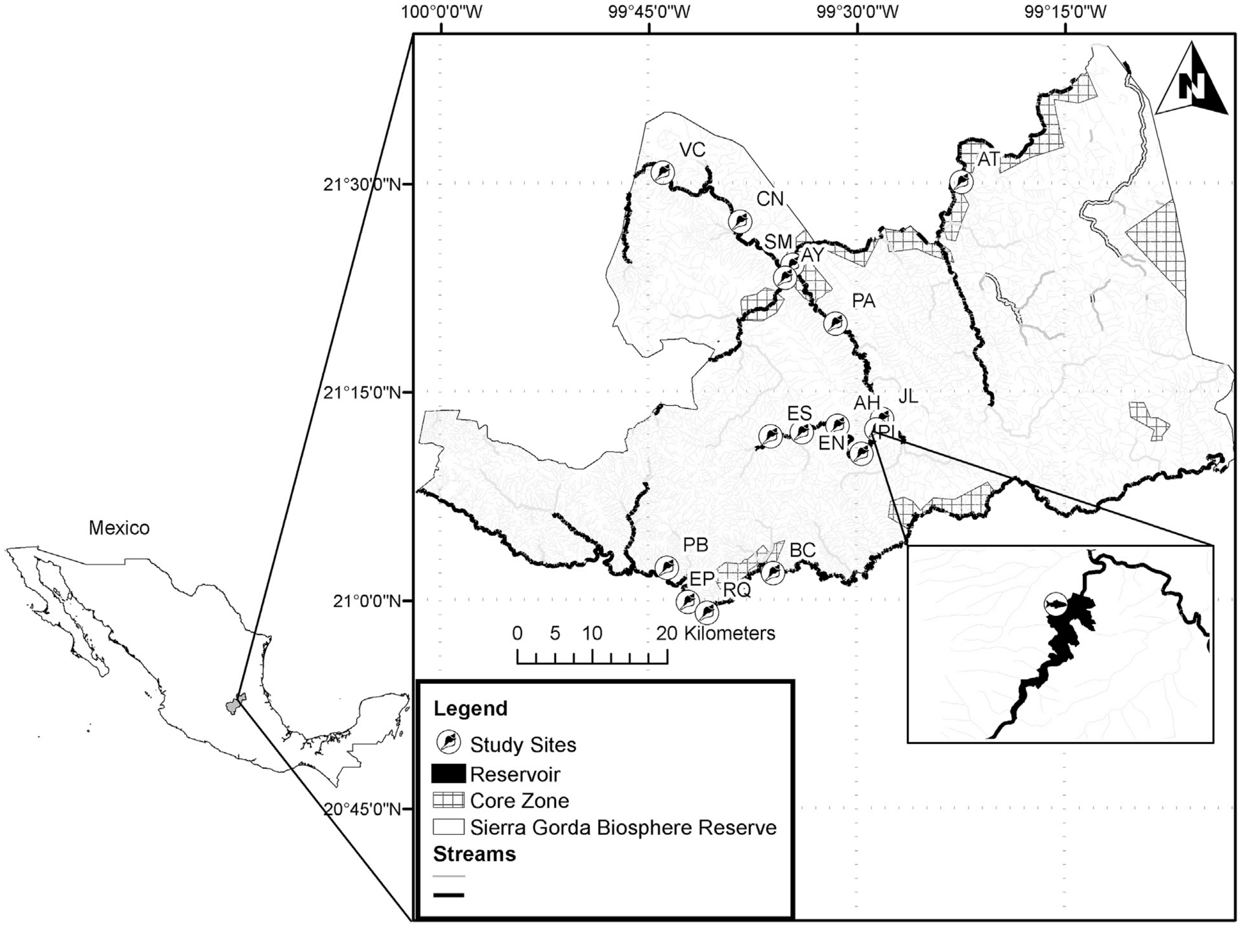

Fig. 1. Biosphere Reserve Sierra Gorda and its hydrologic systems; polygons present priority areas; the Jalpan reservoir at the central area of the SGBR located in Jalpan river is indicated. Acronyms present sampling sites: Extoraz River (sites: EP; RQ; BC); Escanela-Jalpan River (sites: EN; JL; PA); Santa Maria tributaries (sites: VC; CN; AY); Santa Maria River (sites: AT; SM).

xerophytic ecosystems, and the climatic transition in the area (Neotropical and Neartic), make the SGBR a "hotspot" for many rare or endemic species (Carabias Lillo et al., 1999). For instance, records include all six felines recorded in the country (e.g. *Panthera onca*), and many highlighted vertebrates such as American black bear (*Ursus americanus*), American crocodile (*Crocodylus acutus*), peregrine falcon (*Falco peregrinus*), buzzard (*Cathartes aura*), and semi aquatic representatives like otter (*Lutra longicaudis*) (Carabias Lillo et al., 1999). Moreover, the NPA harbors about 35 fish species, where tropical species (51.5%) are overrepresented compared to Neartic species (20%). Amphibians are well represented with about 23 species recognized in the area. Regarding aquatic macroinvertebrates, taxa from 83 families were reported in the Jalpan River, including the presence of the decapod crustaceans *Procambarus* spp., *Atya* spp. and members of the family Pseudothelphusidae (Gutiérrez-Yurrita et al., 2004; Torres-Olvera et al., 2018). Furthermore, a few species/genera such as Lepidoptera (CONABIO, 2019) are well documented in the SGBR, however, there remains insufficient information on aquatic invertebrates and community compositions.

2.2. Data collection

Information on the presence of non-native species was collected from biological monitoring sampling events at 15 study sites (Fig. 1). Sampling was conducted between February and July 2017 using multi-habitat methods from US EPA (United States Environmental Protection Agency; Barbour et al., 2006) and AQEM (European Union; Hering et al., 2004, 2006). At each site, two subsamples were taken in riffle sections using a kick net. Additionally, two subsamples were taken in the most dominant habitat type. For the latter, a spoon net was used. Utilized nets had a mesh size of 500 μm. For each subsample 5 min of sampling time were spent, adding up to a total of 20 min. The sampling material of the four subsamples was combined and preserved in 70% ethanol. The identification of aquatic macroinvertebrates was carried out using specialized literature from Merrit and Cummins (1996) and Thorp and Covich (2009) for North American and Neotropical areas. Taxa were identified to the genus level (Supplement 1). These efforts were part of a biomonitoring action targeting the hydrological systems within the SGBR.

Additionally, a literature review was conducted on https://scholar.google.com/using the key words 'SGBR' or 'Sierra Gorda' with all possible combinations of the keywords 'alien*', 'invas*', 'non-native', and 'introduction' (in both English and Spanish). In total, 1148 potentially suitable articles were identified, from which 12 (Supplement 2) contained valuable information on the SGBR for this study. Despite being known for sport fishing, only one article was identified concerning non-native fish species. Hence, additional information was gathered with the help of local anglers and catches from the "Segundo Torneo de Pesca Recreativa y Deportiva de Lobina 'Bienvenido Paisano" fishing tournaments held on the 23rd of December 2019, as well as local taxonomists. Non-native species identified in the SGBR were confirmed using the REMIB ("Red Mundial de Información sobre Biodiversidad") database from the Mexican manager of biodiversity (CONABIO, 2019) and the GBIF (2013) database.

3. Results

We found 115 macroinvertebrate genera from 89 families, thus confirming the diversity estimates of Torres-Olvera et al. (2018). A detailed list of these macroinvertebrate taxa identified at the 15 sample sites can be found in Supplement 1. Due to taxonomic knowledge gaps in benthic invertebrates from Central America, the identification on genus level was difficult and not possible at species level. Thus, the number of genera at these 15 sites is expected to be higher (e.g. see all genera which were identified as "unknown").

Thirty five fish species have been recorded and described in the literature. From these, five species are under national protection (NOM-059-ECOL-2001), which also includes native species from the genus *Ictalurus* and the Mexican tetra *Astyanax mexicanus* (Gutiérrez Yurrita and Morales Ortiz, 2004).

Overall, nine non-native species were found to be established in the SGBR (Table 1). Five of these are already considered as invasive in Mexico following the definition by Ricciardi et al. (2013). In addition, all species have previously been associated with negative environmental impacts (Mifsut and Jiménez, 2007). The sampling efforts identified invasive molluscs within four of the 11 protected core zones. Non-native and potentially invasive fish species were found only in the Jalpan reservoir (Fig. 1; Table 1). In watersheds directly associated to watersheds within the SGBR, the following eight non-native species were identified (Table 2):

3.1. *Melanoides tuberculatus* (O. F. Müller, 1774)

The red-rimmed melania, *Melanoides tuberculatus*, is a known invader in the tropics that originated from eastern Africa and the Middle East. Due to its wide tolerance towards varied environmental conditions, it successfully invades various habitats, leading to an increased competition for resources. However, its presence has been also associated with positive impacts, as it has reduced populations of the freshwater mollusc *Biomphalaria glabrata*, a host of schistosomiasis. The first record of *M. tuberculatus* was in Coahuila in 1966, followed by a record in Veracruz in 1973 (Contreras-Arquieta et al., 1995). Today, it has been recorded in other regions of Mexico, particularly in lakes and rivers from in the South and East. Currently there is a lack of knowledge about its distribution in North and Central Mexico (López-Altarriba, 2019).

Table 1
List of non-native species occurring in the Sierra Gorda Biosphere Reserve; Extoraz River (sites: EP; RQ; BC); Escanela-Jalpan River (sites: EN; JL; PA); Santa Maria tributaries (sites: VC; CN; AY); Santa Maria River (sites: AT; SM).

Class	Scientific name	Common name	Status in Mexico	Origin	Location (abundance)
Molluscs	*Melanoides tuberculatus*	Malasian snail	invasive	Asia	EP (619); RQ (23); BC (46); EN (1); JL (40): PA (132); VC (309); CN (43); AY (37); AT (3); SM (38)
	Corbicula fluminea	Common Clam	invasive	Asia	JL (16); PA (18); VC (2); CN (3); AY (7); SM (2)
	Tarebia granifera	Melanio snail	invasive	Asia	PA (12)
Fish	*Cyprinus carpio*	Common carp	established	Asia	Jalpan reservoir
	Ictalurus punctatus	Channel catfish	established	North America	
	Oreochromis niloticus	Nile tilapia	invasive	North Africa	
	Micropterus salmoides	Black bass	invasive	North America	
	Herichthys cyanoguttatus	Rio Grande cichlid	established	North America	
	Lepomis macrochirus	Bluegill	unclear	North America	

Table 2
List of non-native species present in watersheds around the Sierra Gorda Biosphere Reserve that are connected to watersheds within the SGBR.

Class	Scientific name	Common name	Status in Mexico	Origin
Crustaceans	*Procambarus clarkii*	Red swamp crayfish	invasive	Asia
Fish	*Carassius auratus*	Goldfish	invasive	Asia
	Ctenopharyngodon idellus	Grass carp	unclear	Asia
	Oreochromis aureus	Blue tilapia	established	North Africa
	Oreochromis mossambicus	Mozambique tilapia	invasive	Africa
	Poecilia reticulata	Guppy	invasive	Caribe and South America
	Oncorhynchus mykiss	Rainbow trout	unclear	North America
	Ameiurus melas	Black bullhead	established	North America

* source: Gutiérrez-Yurrita et al. (2004).

3.2. *Corbicula fluminea (O. F. Müller, 1774)*

The Asian clam, *Corbicula fluminea*, has previously been described as one of the most invasive molluscan pest species due to the various pathways that can lead to its spread, coupled with its high reproduction rate. Its presence has since led to various negative impacts in its introduced range. This Asian bivalve has been recorded in various places in Mexico, from the Pacific coast to the Gulf of Mexico, principally outgoing from North-western and occidental locations (Contreras-Arquieta et al., 1995; Torres-Orozco and Revueltas-Valle, 1996). In the Gulf of México, its presence was recorded in various wetlands and rivers (Tuxpam, Tecolutla, Papaloapan, Grijalva and Usumacinta; Barba-Macías and Trinidad-Ocaña, 2017; López-López et al., 2009).

3.3. *Tarebia granifera (Lamarck, 1816)*

Degradation of terrestrial vegetation may promote introduced invasive species such as *Tarebia granifera*, by altering available resources. In invaded ecosystems, nitrogen cycles are often impacted by snail excretion. Among this and other impacts, its ability to displace other native molluscs by parasite transition has been recognized. The negative effects of *T. granifera* also include being an intermediate in the life cycle of parasites, with final hosts being vertebrates such as fishes and humans (Cowie and Robinson, 2003; Goldsmith and Heyneman, 1995). The first record of *T. granifera* occurred in Chiapas in 1995, but it is further known from Southern an Eastern Mexico. Locally, it has been recorded in lakes and rivers from Tabasco and Veracruz (Barba-Macías and Trinidad-Ocaña, 2017; López-López et al., 2009), but there is scarce information from Central and Northern Mexico (López-Altarriba, 2019).

3.4. *Cyrprinus carpio Linnaeus, 1758*

The common carp, *Cyprinus carpio*, is known for its historical use in aquaculture dating back to approximately 500 BC. As a result, it has been introduced Europe-wide for aquaculture. Moreover nowadays, it is favoured for angling purposes and is considered the most widely distributed freshwater fish. Its impacts on recipient ecosystems are mostly founded in its feeding on zooplankton during juvenile live stages and benthic feeding in the adult life stage, thus often leading to increased turbidity and algal blooms. *Cyprinus carpio* var. *communis* and *C. carpio* var. *specularis* were introduced to Mexico in 1889 and 1956, respectively (Obregón-Fernández, 1961). Currently, both varieties are widely distributed in Mexico. They are cultured in the states of Aguascalientes, Chiapas, Chihuahua, Coahuila, Durango, Guanajuato, Hidalgo, Jalisco, Michoacán, Oaxaca, Puebla, Querétaro, San Luis Potosí, Sonora, and State of Mexico, Tlaxcala and Zacatecas (Cuarenta et al., 2011). It is considered as one of the most important fishes in Mexico, due to its usage as a food source in rural areas and occupying the second place in importance for fisheries and recreational angling since 1985 (CONAPESCA, 2014).

3.5. *Oreochromis niloticus (Linnaeus, 1758)*

As one of the world's most important food fishes, the Nile tilapia, *Orechromis niloticus*, has been introduced in most tropical countries for aquaculture, or to improve natural fisheries and angling. Originally an African freshwater cichlid, it is known for its resilience. As a known "pioneer" species, *O. niloticus* thrives in anthropogenically-disturbed habitats and due to its opportunistic and highly fertile nature, outcompetes native competitors. Several tilapia species were introduced to mainly in the norther states in the 1960s and 1970s and commonly named as 'African tilapia' (Fitzsimmons, 2000). They are reproduced in aquaculture but also locally introduced to increase the productivity of rivers to provide nutrition in rural areas. Records of the introduction of tilapia in Mexico date back to 1883 when Esteban Cházari wrote the first manuscript of the aquatic culture (*Piscicultura en Agua Dulce*).

3.6. *Ictalurus punctatus* (Rafinesque, 1818)

The North American Channel catfish, *Ictalurus punctatus,* is cultured world-wide for aquaculture and increasingly for angling purposes and is native to southern Canada, the eastern US and northern Mexico. It has established self-sustaining populations along a wide climatic gradient, is very resilient towards a variety of environmental conditions and with high reproductive success. Moreover, *I. punctatus* is known for its omnivorous, opportunistic and nest-guarding behaviour. Impacts include detrimental effects on native and endangered species (especially amphibians) and fisheries due to competition for resources (Haubrock et al., 2018, 2019a, 2019b, 2019c). Recently, it was described as one of the fastest expanding invasive fish species. The introduction of *I. punctatus* in Mexico dates back to 1970, where efforts to culture catfish started (CONAPESCA, 2014). The cultures were developed principally in Northern Mexico in ponds under controlled conditions, changing later into lakes or floating cages. The aim of catfish introduction in Mexico was principally to produce fish for human consumption (CONAPESCA, 2017).

3.7. *Micropterus salmoides* Lacépède, 1802

As a major angling species in North America, *Micropterus salmoides* has been introduced globally (Khosa et al., 2020). Due to its aggressive feeding strategy, it is known to rapidly cause declines of native prey fishes (Haubrock et al., 2019a, 2019b, 2019c). Black bass have a great amount of proteins and are consumed by humans in poor areas in Mexico. Principally, it was introduced to Central Mexico in 1929 and 1930 as a food source, but rapidly was cultured to satisfy the demand of anglers and to promote tourism (García de León, 1985).

3.8. *Herichthys cyanoguttatus* Baird & Girard, 1854

Herichthys cyanoguttatus' popularity as an ornamental freshwater fish is based on its wide environmental tolerances. Released into open water, it benefits from its ability to colonize anthropogenically-disturbed habitats, fast growth and parental care. Once established, it competes with native species for resources, expresses a high level of aggressiveness, and predates aquatic invertebrates. In Mexico, *H. cyanoguttatus* has been introduced to the Rio Verde basin (La Media Luna lake region; Kullander, 2003) from where it passively spread.

3.9. *Lepomis macrochirus* Rafinesque, 1810

The bluegill, *Lepomis macrochirus* belongs to the sunfish family (Centrarchidae). When introduced into an ecosystem, it can develop dense populations and lower the growth of native species due to intense competition for resources. It has a high tolerance towards a wide range of environmental parameters (FAO, 1997; Welcomme, 1988). Being native to northern Mexico, it was distributed to southern regions to benefit angling, as it is a common food source for the also introduced black bass *M. salmoides* and as an available food source in rural areas.

4. Discussion

4.1. Impacts of non-native species on native biodiversity

Our results provide evidence of the presence of non-native species in protected, but also remote, areas such as the Sierra Gorda Biosphere Reserve in Mexico. Invasive species are one of the major threats to native biodiversity (IPBES, 2019). Once introduced, they have numerous effects on recipient communities. As such, knowledge about the presence of invasive species is necessary to understand their effects on native biota. A good example is the presence of crustaceans in the SGBR: 67 of 500 species belonging to the family of Pseudothelphusidae are known in Mexico. From these species, 5% are considered non-native (Cumberlidge et al., 2014). However, detailed species-related literature for Mexico is obsolete or poorly detailed, making it difficult to separate native from non-native species. The SGBR has few reports for non-native species have been published, mostly regarding African and Asian mollusks referencing their known adverse effects on ecosystem and native biota (Pino et al., 2010). However, available data from non-native species such as mollusks is fragmented, or not referenced to particular areas like NPAs. We showed the occurrence of different non-native aquatic species within the SGBR, detailing their presence in several core areas (see Fig. 1). These non-native mollusks were likely introduced hitchhikers (Patoka et al., 2017). In addition to previous reports on non-native species in Mexico, *T. granifera* was not mentioned (López-López et al., 2009), but is recorded for the first time within the SGBR. The adverse effects of mollusks like *T. granifera* are very similar to those from *C. fluminea* and *M. tuberculatus*, which can cause native macroinvertebrate extinctions due to the introduction of parasites (Pino et al., 2010). Hence, the development of better biosecurity protocols for such "hitchhikers", to reduce secondary spread in waters, is pertinent (Bradbeer et al., 2020).

Many global fish introductions have occurred due to accidental aquaculture releases or the voluntary release of a species as an accessible food source (Nuñez et al., 2012). Several non-native fish species were introduced for the purpose of being an accessible food source (e.g. *I. punctatus*, *O. nilocticus*) in the SGBR. In contrast, others (*C. carpio, M. salmoides*) were introduced into the SGBR for recreational angling. A further case is rural aquaculture, as for instance pre-Hispanic cultures maintained fish for “ritual and religious” purposes, while nowadays, many species are introduced for production in aquaculture (Fitzsimmons, 2000). Indeed, the use of aquatic species as source of animal protein is relatively important in rural areas of Mexico with increasing demand (Silva et al., 2009). The culture surrounding *Oreochromis* ssp. is an ancient tradition and was one of the earliest human mediated species introductions in Mexico. However, *Oreochromis* ssp. introduction caused extinctions of native poecillid species (Trujillo-jiménez and Beto, 2007). As a result, the culture of non-native fish in or near NPAs can be a risk for protected habitats, biodiversity and ecosystem functioning.

We emphasize the presence of the non-native species *I. punctatus*, which is well known for its negative impacts on recipient ecosystems (Haubrock et al., 2019a, 2019b). *Ictalurus punctatus* is physiologically tolerant towards extreme conditions, omnivorous, opportunistic feeder, and a large species, which promotes cascading effects (Matsuzaki et al., 2011). While there is an urgent need for further studies concerning potential impacts, the recorded non-native fish species were mostly found in the Jalpan reservoir but spread in and along associated streams is deemed possible. Furthermore, in the case of *C. carpio*, impacts on water quality are driven by sediment resuspension as well as increased turbidity, but also predation on native benthic species can be expected (Mifsut and Jiménez, 2007).

4.2. Implications of non-native species introductions and missing taxonomic lists in regard to conservation efforts

Within the SGRB, three catchments join and drain into the Gulf of Mexico, forming a complex drainage system that is born from steep and isolated Mountain ranges (Carabias Lillo et al., 1999). Steep mountains are a barrier on the edge of the SGBR which represents a filter that invasive species must successfully overcome (Havel et al., 2015). However, invasive aquatic species often overcome such barriers due to anthropogenic facilitation (Gallardo and Aldridge, 2018). Therefore, locations with invasive species in direct proximity to the SGRB present a direct threat to protected biodiversity. Settlements, aquaculture and subsequently, the presence of non-native species within the close Zimapan reservoir and San Juan River might prove to be effective pathways and vectors (Gutiérrez Yurrita and Morales Ortiz, 2004), particularly as a linkage between catchments is possible due to the connection of river tributaries (Lajtner and Crnčan, 2011). In regions surrounding the SGBR, Contreras-MacBeath et al. (2014) recorded 25 invasive species. From these, we identified 8 to be present in watersheds that are connected with rivers within the SGBR (Table 2).

Due to the diverse impacts that invasive species can exert, there is an urgent need to know how many and which non-native species might become invasive, as in the case of *T. granifera*, *M. tuberculatus* and *C. fluminea,* or could invade the SGBR, such as *P. clarkii*. The effects of various invasive species on native biota will likely increase in the future, potentially causing irreversible damage to the ecosystem and its biodiversity (Strayer, 2012). Recently, a hybridization phenomenon between *O. nilocticus* and *O. aureus* species at Zimapan reservoir has already been reported (Gómez-Ponce et al., 2014). This example highlights the diverse risks for native species in protected areas. Such impacts may cause a cascade effect on native species by parasite transmission (Havel et al., 2015; Pino et al., 2010). Our study reports the presence of invasive mollusks within four of the 11 highly protected core zones, highlighting the imminent threat to biodiversity as postulated by López-Altarriba (2019). Hence, considerable effort is needed to not only identify native biodiversity, but to also establish an effective framework of measures to mitigate the introduction and spread of non-native species into, but also within protected areas.

5. Conclusion

The SGBR, with its protected “core zones”, is an example of how good intentions to protect native biodiversity fail when implemented without further control and monitoring. It is alarming to see that the vast majority of native species in the SGBR are not yet described. Further studies will be needed to identify the aquatic macroinvertebrate biodiversity to species level. Therefore, despite being only one case study, the SGBR could be symbolic for various protected areas globally: Aquatic biodiversity is often not properly assessed, specifically at species level, while several invasive species are already established. Without taxonomists and ongoing efforts to identify species native to varying climatic or biogeographic regions as in the diverse SGBR, biodiversity loss can occur without notice. However, due scarce information on native species within NPAs, our results cannot identify which species are most threatened by invasion of non-native animals. Given the intrinsic connectivity and less perceived fauna of aquatic habitats in comparison to terrestrial environments, a recorder bias in the results, owing to an absence of records for non-native aquatic taxa that are e.g. smaller and more difficult to detect, must be deemed possible (Selge et al., 2011). As a result, the presented list of native genera as well as non-native macroinvertebrate species must be considered as very conservative. In our study, the SGBR served as a case study, but the situation in other protected areas of the world might indeed be similar or even worse (see Spear et al., 2013). Moreover, the presence of invasive species in protected areas limits the ability to control and eradicate these species as only manual, non-chemical approaches can be used due to the threat of negatively affecting native species. As such, efforts to sustain protected biodiversity should not stop at the confinement of special areas. Rather, we need to consider ongoing monitoring to recognize invasions in the early phases to prevent establishment and conserve the biodiversity present in these hotspots. Economically, costs associated to invasive species (Kettunen et al., 2008; Pimentel, 2000) are far higher than costs for active prevention. In South Africa, chemical treatments such as rotenone have been used to eradicate invaders, with native species recovering shortly thereafter (Bellingan et al., 2019). However, whether using toxic substances to get rid of non-native species as a good approach, is questionable.

Concluding, we highlight the need for standardized sampling efforts combined with efforts to identify species, rather than genera and families, as without these, biodiversity losses are impossible to notice.

Declaration of competing interest

No conflict of interest has to be declared.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2020.e01006.

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