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At the doors of the Amazonian region: occurrence of *Limnoperna fortunei* (Dunker, 1857) (Mollusca, Bivalvia, Mytilidae) in the Tocantins River

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Abstract. The Tocantins river basin was one of the few regions in Brazil considered free of Golden Mussel, *Limnoperna fortunei* (Dunker, 1857). This is an invasive species that has been dispersing throughout South America since 1990. We report the first record of this species in the state of Tocantins. Its presence there represents a problem in the region and a major alert for the Amazon Basin. The Tocantins river basin constitutes one of the gateways to the Amazon Basin.

Key words. Environmental impact, Golden Mussel, invasive species, Luis Eduardo Magalhães Reservoir, Tocantins-Araguaia Basin

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INTRODUCTION

Golden Mussel, *Limnoperna fortunei* (Dunker, 1857) (Bivalvia, Mytilidae), was first recorded in South America in 1990, in the estuary of the Río de La Plata. This species is native to Southeast Asia and was probably introduced into South America in ballast water of ships (Darrigran and Pastorino 1995). It quickly spread to Argentina, Bolivia, Brazil, Paraguay, and Uruguay (e.g. Oliveira et al. 2015; Miyahira et al. 2024). In Brazil, the Amazon, Tocantins-Araguaia, and Parnaíba basins, as well as some coastal regions, have been considered free of this invasive species (Barbosa et al. 2016; Miyahira et al. 2024).

The state of Tocantins, located in the central region of Brazil, has great potential for agribusiness and presents rapid growth in this sector. The state is considered the newest agricultural frontier in Brazil (Sano 2019). This potential also has drawbacks, such as a rapid habitat modification of habitats and increased flow of people and goods, which increase the probability of introducing invasive species (Darrigran et al. 2020; Miyahira et al. 2020).

The Tocantins River crosses the central part of Tocantins and is economically and environmentally important. The headwater of the Tocantins River is in the state of Goiás between the municipalities of Ouro Verde de Goiás and Petrolina de Goiás. This river flows through the states of Tocantins, Maranhão, and Pará. Near the border with Pará, it receives its main tributary: the Araguaia River. The mount of the Tocantins River is Marapatá Bay, an inlet of the Amazon River estuary near Belém, Pará. The Tocantins–Araguaia basin is included in the Amazon region and directly connected to the Amazon Basin (Venticinque et al. 2016). The Tocantins River is approximately 2,400 km long and has seven large hydroelectric plants (Serra da Mesa, Cana Brava, São Salvador, Peixe Angical, Lajeado, Estreito, and Tucuruí; Figure 1) with a large energy generation potential (ANA 2024).

The Lajeado hydroelectric power plant and reservoir is located approximately 60 km downstream from Palmas, the capital of Tocantins. The reservoir, which was filled in 2001–2002, has an average flow of 2,532 m^3/s and is among the largest in Brazil (Investco 2024). The city of Palmas was planned to be located on the banks of the reservoir and currently has approximately 302,692 inhabitants (IBGE 2022). The formation of the reservoir provided to the local population multiple uses of water, such as leisure, sport fishing, and as a source of water supply for humans, irrigation, and fish farming (IIE 2003). Thus, the reservoir has great economic and social importance for the local population and the country.

Although fish farming is an old activity in Tocantins, only in 2013 did this sector become more extensive. At that time, a license was granted for the implementation of aquaculture parks in the Lajeado Reservoir (CO-

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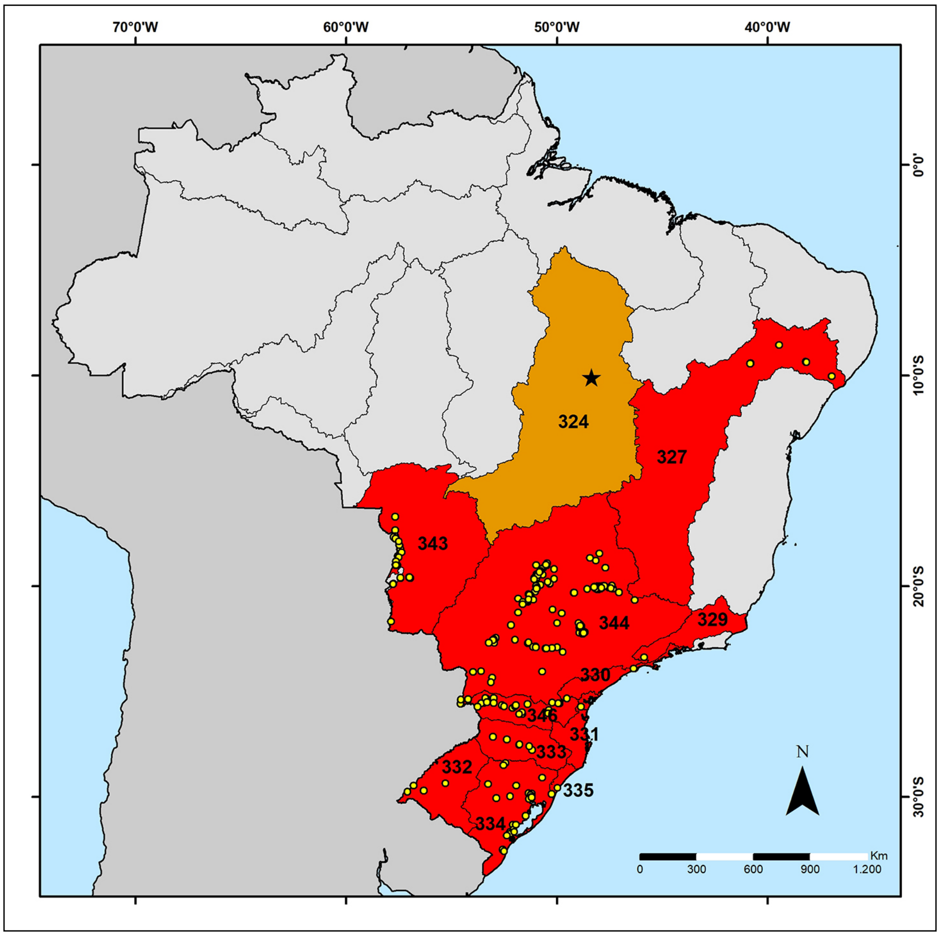

Figure 1. Black star shows the area of occurrence of the Golden Mussel (*L. fortunei*) in the northern region of Brazil. The ecoregions in red are previously colonized by the *L. fortunei*, in orange the recently colonized ecoregion. The codes of the freshwater ecoregions, following Abell et al. (2008), are 324 (Tocantins-Araguaia), 327 (São Francisco), 329 (Paraíba do Sul), 330 (Ribeira de Iguape), 331 (Southeastern Mata Atlantica), 332 (Lower Uruguay), 333 (Upper Uruguay), 334 (Laguna dos Patos), 335 (Tramandaí-Mampituba), 343 (Paraguay), 344 (Upper Paraná) and 346 (Iguassu). Based on Oliveira et al. (2015), Barbosa et al. (2016), Senske et al. (2019), Santos et al. (2022), Miyahira et al. (2024) and CBEIH database (https://base.cbeih.org/).

NAMA 2013a, 2013b; Naturatins 2013; COEMA 2018a), and permission for the rearing of Nile Tilapia, *Oreochromis niloticus* (Linnaeus, 1758) was granted in 2018 in these aquaculture parks (COEMA 2018b). *Oreochromis niloticus* is an African fish which is now dispersed throughout Brazil and is raised especially in the Paraná river basin (Peixe BR 2022). Currently, there are five authorizations for aquaculture parks in the Lajeado Reservoir, but only three are in operation: Miracema/Lajeado Aquaculture Park, Sucupira Aquaculture Park, and Brejinho II Aquaculture Park. It is estimated that the reservoir may produce 89,238 t of fish/year (MAPA 2020). In Sucupira Aquaculture Park, which is in the municipality of Palmas, three fish species are farmed: Tambaqui, *Colossoma macropomum* (Cuvier, 1818); Caranha, *Piaractus brachypomus* (Cuvier, 1818); and *O. niloticus*.

We report the first record of *L. fortunei* in the Tocantins river basin, in the municipality of Palmas, thus characterizing the introduction of this species in another watershed of Brazil.

METHODS

Limnoperna fortunei were collected by hand from net cages (3 m × 3m × 3 m) of the Sucupira Aquaculture Park in August 2024. This time of year, corresponds to the dry season. The specimens fixed in 70% alcohol. The molluscs were living in dense agglomerations. We identified the species using the current literature (e.g. Mansur 2012). Voucher specimens were deposited in the Museum of Biological Diversity of the University of Campinas (UNICAMP).

The map was created and edited using QGIS v. 3.34 (QGIS 2024). The geographic coordinates of previously published records were obtained from the literature (Oliveira et al. 2015; Barbosa et al. 2016; Senske et al. 2019; Santos et al. 2022; Miyahira et al. 2024) and from the CBEIH database (https://base.cbeih.org/).

RESULTS

***Limnoperna fortunei* (Dunker, 1857)**

Figures 1, 2

New record. BRAZIL – TOCANTINS • municipality of Palmas, Sucupira Aquaculture Park, attached to net cages; 10°05′07.6″S, 048°22′00.1″W; 16.VIII.2024; RT Honda leg.; ca. 500 specimens, ZUEC-BIV-5246.

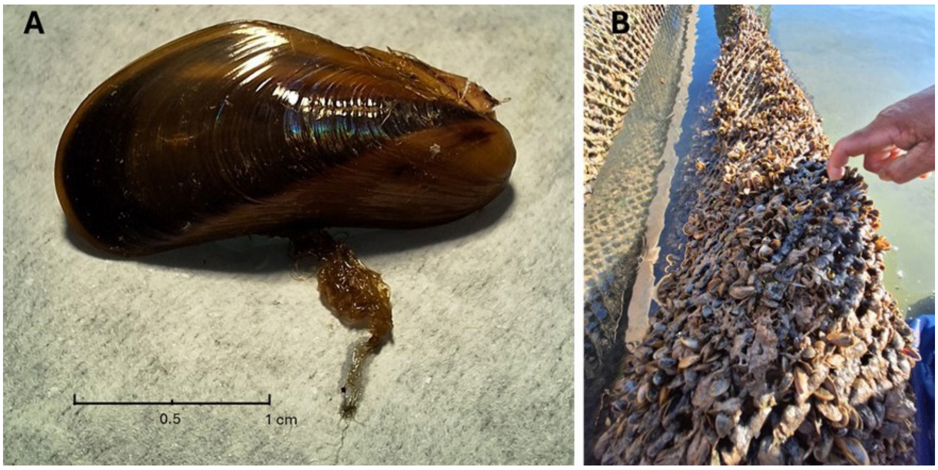

Figure 2. *Limnoperna fortunei.* **A.** Collected from the Lajeado-Tocantins Aquaculture Park located in Lajeado Reservoir (Palmas, Tocantins). **B.** Colonies on the net cages.

Identification. The valves are 2.5–3.0 cm long, equal, triangular in outline, with an elongate base, and with subterminal umbones. The periostracum is smooth, thin, glossy, and slightly yellowish or light brown. The hinge ligament is simple (Mansur 2012).

DISCUSSION

Limnoperna fortunei appeared in the Tocantins River approximately 34 years after it arrived in South America and 22 years after the filling of the Lajeado Reservoir. In June 2024, producers in Sucupira Aquaculture Park reported the presence of *L. fortunei* in their net cages where tilapia were raised. However, this species' occurrence was confirmed only in August 2024 with the collection of live specimens from net cages (Figure 2). According to the local producers, *L. fortunei* was first observed in net cages in the first half of 2023, approximately one year after they acquired tilapia fingerlings from other states. Until then, tilapia fingerlings were acquired from local producers. In 2022, the local production of fingerlings was insufficient to supply the local demand, which is why the change to other suppliers. The mean time for *L. fortunei* to become a large adult (3 cm) is about 3 years (Ayroza et al. 2021; Liu et al. 2024) and considering the historical background described above, *L. fortunei* probably arrived in the Tocantins River in 2021 or 2022. There were no reports of mussels with the fingerlings at the time of the release of the fish into the tanks. Mussels are currently present in all net cages of the Aquaculture Park and are more numerous at the bottoms of the cages (at a depth of ca. 2 m), with their numbers gradually decreasing along the sides of the cages towards the water surface.

Aquaculture is one of the main forms of dispersion of invasive molluscs in South America (Lima Junior et al. 2018; Darrigran et al. 2023). In Brazil, although the license for the practice of fish farming demands that invasive species be monitored, in practice this measure is ineffective (CONAMA 2013b). Although ballast water has been identified as the main source of long-distance introduction of *L. fortunei*, fish farming has been an extremely effective vector of local dispersion (Darrigran et al. 2023). Miyahira et al. (2024) traced the introduction of *L. fortunei* into the Paraíba do Sul river basin in southeastern Brazil to the trade of fingerlings and fish farming. The mussels and their larvae can be transferred to other regions in water and with fish fingerlings. Fish farming is advancing rapidly in Brazil and will continue to be a strong vector of dispersion of this species. Thus, secondary introduction (local/regional) is a major factor in the dispersion of this species in Brazil. Boltovskoy et al. (2006) indicated that *L. fortunei* arrived in the Amazon Basin via oceanic vessels that frequently navigate the river, but the introduction of this species in Tocantins Basin points to a downstream dispersion or a secondary local introduction. Moreover, the constant use of infected waters for leisure or fishing can promote the dispersion of *L. fortunei* by the transport of water with larvae and contamined fishing gear or other goods.

The presence of *L. fortunei* in the Tocantins river basin is noteworthy because the density of this mollusc can reach 290,000 individuals·m^{-2}, which can have a strong adverse effects on the trophic structure of native aquatic organisms (Sylvester et al. 2007), and according to the review by Darrigran and Damborenea (2011), mussels can make changes in the ecosystem. However, a better understanding of the potential impacts of *L. fortunei* on the environment is achieved when spatial and temporal variables are considered. For example, shortly after the mussel's arrival, changes in the benthic community and predator populations are commonly observed, and the macroinvertebrate community is significantly affected. Simultaneously, changes in water transparency are also frequently noted due to the high capacity for this species to filter water. Population densities of *L. fortunei* reach their highest levels in the early stages of invasion, but then fluctuate, and eventually stabilize at smaller population levels approximately 10 years later. Thus, the introduction of *L. fortunei* into the Tocantins River is probably now at its initial stage and is expected some increase in population size and sightings in the following years. The density of the populations found at Tocantins River was not quantitatively measured, but we believe it to be a dense population (Figure 2B). The species appears to be spreading in the reservoir, and were found in more places than initially seen.

The fish community may be affected by *L. fortunei*, as mussels and their debris can introduce a new element into the diet of some fish species. *Leporinus obtusidens*, *Prochilodus lineatus*, among others cited by Darrigran and Damborenea (2011), have incorporated mussels into their diet. In this context, changes are expected in the population structure of both prey species that existed prior to the introduction of the mussel and fish species that, within a short period, have been exposed to an overabundant food supply (García and Protogino 2005).

After habitat modification, the introduction of species is the greatest environmental impact related to a decrease in biodiversity (Ricciardi 1998; Allendorf and Lundquist 2003; Miyahira et al. 2022). The complex biotic and abiotic relationships that the invasive species establishes in the new environment make the measurement of the real impacts of this invasive species extremely difficult. There are native bivalve species in the Tocantins–Araguaia river basin, as well as in the Amazon Basin, which attach to hard surfaces via a byssus; these include *Anticorbula fluviatilis* (Adams, 1860) and *Rheodreissena* spp. (Simone 1999; Mansur et al. 2019; Cuezzo et al. 2020), the former being endemic to the Amazon and the latter found throughout the Amazon and Orinoco basins. The effects of *L. fortunei* on native bivalves in the Tocantins River are unknown, but in other regions, native mussels and other macroinvertebrates have been found to be negatively affected (Mansur et al. 2003; Silva et al. 2021). Another aggravating factor is that the distance from the Lajeado Reservoir to the mouth of the Tocantins River is approximately 1900 km, which ensures a long distance downstream for dispersal of *L. fortunei*.

The introduction of *L. fortunei* can also cause economic losses, as large numbers of individuals may clog of filters, pipes, and net tank screens used in fish farming; they may obstruct the entry of water into hydroelectric and thermoelectric plants, demanding high maintenance cost (Allendorf and Lundquist 2003). The United States is estimated to spend approximately $78.5 billion per year on losses caused by invasive species. In Brazil, this estimate is approximately US$42.6 billion (Pimentel et al. 2001). Ludwig et al. (2021) estimated that shutting down the Itaipu Reservoir for three days for cleaning may cost US$750,000. There are no such estimates available for the Lajeado Reservoir, but a similar cost can be assumed. Until now, there has been no report of economic losses caused by *L. fortunei* in the reservoirs of the Tocantins river basin. However, there are a series of reservoirs that could be colonized by *L. fortunei* in the future. The two reservoirs located downstream of Lajeado could be quickly colonized by the drifting larvae.

Another worrying aspect of the occurrence of *L. fortunei* in Tocantins is that the state is part of the Legal Amazon, which has the largest biome in Brazil (Amazon Rain Forest) with the greatest biodiversity, including several freshwater species (e.g. Brosse et al. 2013; Tisseuil et al. 2013; Miyahira et al. 2022). There are 2,257 fish species described from Amazonas Basin, of which 1,248 are endemic, which corresponds to 15% of the freshwater fish species in the world (Tedesco et al. 2017; Oberdorff et al. 2019). The molluscan fauna of the Amazon Basin is largely unknown (Miyahira et al. 2022), and new species have recently been described from this biome (Mansur and Pimpão 2008; Mansur et al. 2019). The introduction of *L. fortunei* into the basin represents a major threat to the biodiversity of aquatic organisms and may cause impacts to a greater or lesser extent depending on the affected region because the diversity also follows an unexpected gradient of distribution intensity in basin (e.g. Oberdorff et al. 2019). The freshwaters are hot throughout the year (24–27 °C in running water and 30°C in stagnant water; Walker and Henderson 1996), which greatly favors *L. fortunei* (Oliveira et al. 2010a; Liu et al. 2024), although adult *L. fortunei* have been found at lower temperatures (5–10 °C; Karatayev et al. 2007; Liu et al. 2024) and this species can reproduce at 35°C (Perepelizin and Boltovskoy 2007). Apparently higher temperatures for a longer period of time seem to contribute to the production of larvae. In the Paraná River, for example, the water temperature varies between 18 and 30 °C, and under these conditions larvae are produced for 9 or 10 months each year. In Korea (0–30 °C), reproduction occurs over approximately 20 days, and in Japan (ca. 7–25 °C), spawning occurs for 1 or 2 months (Karatayev et al. 2007). We expect that larval production may occur for several months or even throughout the year in the Tocantins Basin. However, multiple factors must be considered, including time, area, population origin, temperature, and other factors, that act in various ways to prevent the identification of a defined pattern in the reproductive cycle of this invasive species (Giglio et al. 2016).

Limnological information about the Lajeado Reservoir is poor, but Rosanova et al. (2019) provided data for the months between January and April: temperature, 30.46 ± 0.321 °C; pH, 7.51 ± 0.163; conductivity, 0.0645 ± 0.0085 mS/cm; turbidity, 5.00 ± 0.555 NTU; dissolved oxygen, 5.315 ± 0.501 mg/L; and total dissolved solids, 0.0438 ± 0.006 g/L. These values fit in the ranges given by Liu et al. (2024) for this species. In the upper Paraguay River, *L. fortunei* was found in water with a pH of ca. 6.0 and low calcium concentrations (0–6.0 $mg \cdot L^{-1}$) (Oliveira et al. 2010b), the lowest values ever recorded in Brazil this species. Regions with less than 1.0 $mg \cdot L^{-1}$ calcium is considered at low risk for the occurrence of *L. fortunei* (Oliveira et al. 2010b). Thus, with few exceptions in the Amazon Basin, most Brazilian river systems have a moderate to high probability of invasion based on the availability of calcium in the water (Oliveira et al. 2010a). Although the combination of high concentrations of suspended sediments, low food availability, and high velocity of water may negatively influence the occurrence of *L. fortunei* (Oliveira et al. 2010a), these conditions are not predominant in the Tocantins River, making the region extremely favorable for *L. fortunei*.

We emphasize that fish farming has important economic and social aspects. However, implementing aquaculture parks in which tilapia is reared without proper control and monitoring has contributed to the dispersion of *L. fortunei* in Brazil (CONAMA 2013b; Naturatins 2013; Miyahira et al. 2024). Notably, mussels have microscopic and free-swimming larvae, and at this stage of the life cycle, *L. fortunei* is difficult to identify and control. The dense populations of *L. fortunei* cause economic losses even to fish farms, blocking the screens of the fish nets cages. The large number of mussels make the water exchange more difficult and cages heavier, increasing coasts with cleaning and maintenance (Godoy et al. 2018; Ayroza et al. 2021). Thus, effective control of *L. fortunei* and good management policies are beneficial for all.

As possible management practices, we suggest that fingerlings are purchased from a trusted source and that the fingerlings be kept in quarantine for a period and water from quarantine tanks be isolated to reduce the spread of mussels.

The occurrence of *L. fortunei* in the Tocantins river basin deserves special attention because it is a doorway to the Amazon River. In addition to the known problems in the basin, like deforestation and large-scale fires, the arrival of *L. fortunei* will further amplify the ongoing economic, social, and environmental damage to the Legal Amazon.

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ADDITIONAL INFORMATION

Conflict of interest

The authors declare that no competing interests exist.

Ethical statement

No ethical statement is reported.

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Author contributions

Conceptualization: FDP, ICM, RTH. Investigation: ICM, RTH. Methodology: RTH. Supervision: FDP, ICM. Writing – original draft: RTH. Visualization: ICM, RTH. Writing – review and editing: FDP, ICM, RTH.

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