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Prediction of the potential Brazilian distribution for invasive mollusc *Melanoides tuberculata* (Müller, 1774), including a new record from Northern Coastal Region

Predição da potencial distribuição brasileira do molusco invasor *Melanoides tuberculata* (Müller,1774), incluindo um novo registro para o Litoral Norte

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The freshwater snail *Melanoides tuberculata* (Müller, 1774) native from Africa and Asia, recently spreads out over the world. Records of invasive species are extremely important, because it helps in future invasions mitigation. Here, we report for the first time the occurrence of *M. tuberculata* in a protected area of Northern Brazilian Coast and use predictive distribution modeling to know the potential Brazilian distribution for this species. The gastropod *M. tuberculata* were collected in the municipalities of Tutóia and Santo Amaro - Maranhão State. According to the results of the predictive map distribution for Brazil, the regions with the highest susceptibility are the northeast, southeast and midwest. Preciptation of month and Isothermalithy were de variables that most contribute to the species' potential distribution. This species presented high to medium suitability of occurrence in 32 national protected areas. Futher studies are recommended to monitor the growth and dispersion, in order to determine its real impact.
Keywords: freshwater snail, invasive species, protected areas.

O caramujo de água doce *Melanoides tuberculata* (Müller, 1774), nativo da África e da Ásia, recentemente se espalhou pelo mundo. Registros de espécies invasoras são extremamente importantes, pois auxiliam na mitigação de futuras invasões. Nesse trabalho, relatamos pela primeira vez a ocorrência de *M. tuberculata* em uma área protegida da costa norte do Brasil e utilizamos modelagem de distribuição preditiva para conhecer a distribuição potencial brasileira para esta espécie. Os gastrópodes *M. tuberculata* foram coletados nos municípios de Tutóia e Santo Amaro - Maranhão. De acordo com os resultados da distribuição do mapa preditivo para o Brasil, as regiões com maior suscetibilidade são Nordeste, Sudeste e Centro-Oeste. A precipitação mensal e a isotermalidade foram as variáveis que mais contribuíram para a distribuição potencial da espécie. Esta espécie apresentou aptidão de ocorrência alta a média em 32 unidades nacionais de conservação. Recomendam-se mais estudos para monitorar o crescimento e a dispersão, a fim de determinar o seu real impacto.
Palavras-chave: caramujo de água doce, espécies invasoras, áreas protegidas.

1. INTRODUCTION

The introduction of invasive species into the environment can often put ecosystem functionality and biodiversity at risk [1, 2] threatening the livelihoods, human and animal health [3-5] affecting not only environment, but also the local economy [6-8]. The establishment of these species and environmental changes are two of the main causes of the loss of biodiversity of molluscs aquatics and lands [9-13] and also considered the first cause of the loss of biodiversity in protected areas [14-16].

The gastropod *Melanoides tuberculata* (Müller, 1774) is native from the Afrotropical and Paleartic regions, but have been expanding worldwide [17] with high adaptability in new freshwater environments [18-21]. Its first occurrence in South America was registered in Southeast coast of Brazil, in the city of Santos, São Paulo state [22]. Since that, the species were recorded in 20 Brazilian states and in the Federal District [23].

It is important to emphasize that the invasion of *M. tuberculata* can result in environmental and economic damage and impacts on public health [24]. Therefore, it is necessary to carry out research that can monitor aquatic environments, predict species with invasive tendencies and areas vulnerable to invasion.

Malacological surveys based on manual snail collection are simple but the logistics for conducting these studies are time consuming. An alternative to overcoming these challenges is to determine the factors that regulate the abundance of snails, and to use this information to predict their presence in unstudied areas [25-27]. In this way the use of modeling approaches based on relationships between known occurrences of species and features of the ecological and environmental landscape, is an important tool [28-32].

Distribution models and ecological niche models are used to understand the ecological needs of species, aspects of biogeography, predict the existence of unknown populations and species in an area, select areas for conservation, predict the effects of environmental change [28] The predictive distribution modeling maps developed by spatial technologies and species distribution models (SDMs) can be used to assess potential geographic distributions of invasive species when a good database is available and provide adequate distribution of various species. Such maps are useful in the management of invasive species [25, 31, 32]. Therefore, the objective of the present study is to report the occurrence of *M. tuberculata* in a protected area in Maranhão state, in the Northern Coast of Brazil, and use predictive distribution modeling to know the potential Brazilian distribution of this species, including the possibility of the invasion of another protected area.

2. MATERIALS AND METHODS

2.1 Study area

The study area is located in the region of Lençóis Maranhenses National Park and Protected Area of Delta do Parnaiba, in Maranhão, Brazil. The reservoirs studied are in the municipality of Santo Amaro, with an area of 1.601,18 km², and Tutóia, with an area of 1.651,649 km², respectively. Both located in a touristic area [33]. The climate in this region is sub-humid, with an average annual temperature of 26 °C. The rainfall regime has two defined seasons: rainy (January to July) and dry (August to December). Annual rainfall during the rainy season ranges from 1200 to 2000 mm [34].

This area is characterized by the presence of bays, rivers, lagoons, coastal scrublands, floodplains, dunes fields, and mangroves [35]. Consequently, the Lençóis Maranhenses Microregion is considered a major tourist attraction, drawing thousands of visitors from around the world to experience its natural beauty.

2.2 Sampling and identification

The gastropod *M. tuberculata* were collected in environment lentic and lotic in the municipalities of Tutóia and Santo Amaro. Samplings was conducted from June 2016 to November 2019, once a year (a total of four campaigns), always at the beginning of the rainy season. These survey points were chosen due to the massive presence of *M. tuberculata* and their accessibility to the local human population and tourists.

The *M. tuberculata* specimens were collected using the Olivier and Schneiderman (1956) [36] capture method. All collection points were georeferenced with GPS. The specimens were fixed using the Niku-Niku technique [37] and subsequently de deposited in the Coleção de Tecidos e DNA da Fauna Maranhense – CoFauMA, Universidade Estadual do Maranhão. The snail collections were authorized by the Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis - IBAMA, License nº 53224.

2.3 Predictive distribution modeling

To compose the distribution matrix for *M. tuberculata* in Brazil, we used the records available in Coelho et al. (2018) [23]. This study provided data from 1987 to 2017, supplemented by information from biological collections housed in Brazilian museums, including the Museu de Zoologia da Universidade de São Paulo (MZUSP), the Museu Nacional do Rio de Janeiro (MNRJ), and the Coleção de Moluscos do Instituto Oswaldo Cruz (CMIOC). Additionally, new records of the occurrence of *M. tuberculata* published after the review by Coelho et al. (2018) [23] were added: da Silva et al. (2019) [38], Silva et al. (2020) [39], Barros et al. (2020) [18] and Barros et al. (2020) [19]. Furthermore, we incorporated data on the occurrence of *M. tuberculata* in Maranhão obtained during our research group's field collections, carried out between 2016 and 2019. The shape file used was the one provided by the IBGE website for Brazil [40].

Duplicate occurrence data were identified based on the collector's name (e.g., Silva, M. S.), collection number, and collection date (day/month/year), when possible. After verification, duplicates were removed and records with valid coordinates were checked at different levels according to administrative units (municipality, state, and country). All these steps were performed using R 4.0.2 software with the sp, rgdal, and maps packages [41]. Coordinates were assigned to all records that did not have coordinate data based on the location information found on the labels. First, we used the geoLoc tool from the speciesLink database [42] to assign coordinates. Some records that geoLoc could not assign coordinates to were manually georeferenced using Google Earth [43], but records that did not have adequate information for precise georeferencing were excluded.

For the construction of the predictive distribution model, information on the occurrence of *M. tuberculata* in 845 GPS coordinates of collection where the species were identified was considered. The result of the predictive distribution modeling was used to perform the suitability analysis using shapes from federated conservation units by the program R version 4.0.2.

The choice of environmental layers is suggested by Chapman et al. (2005) [44] and Giannini et al. (2012) [45], the use of layers with 30 seconds of arc, for local analysis and for analysis on a continental scale it is recommended the use of 2.5 or 5 minutes arcs. It is important to define the resolutions of the layers to ensure the quality of the final model [45]. From public databases such as Worldclim (http://worldclim.org/) or CHELSA (http://chelsa-climate.org/) we can obtain layers of bioclimatic variables in different spatial resolutions, from 30 seconds (~ 1 km^2) to 10 minutes (~ 340 km^2). In this work we use the environmental layers with 30-second arcs.

The environmental data were obtained through the Wordclim database (https://worldclim.org/) which has 19 bioclimatic variables and one altitude that are usually used in species distribution models. We made an assessment of environmental variables to avoid redundant variables, where a correlation analysis was performed organizing a matrix with the values of the Spearman coefficients [32] for each pair of variables, pairs above 0.75 were considered highly correlated [46] and were discarded from the model [28, 47] making a pre-selection of bioclimatic variables (Figure 1), by means of program R version 4.0.2.

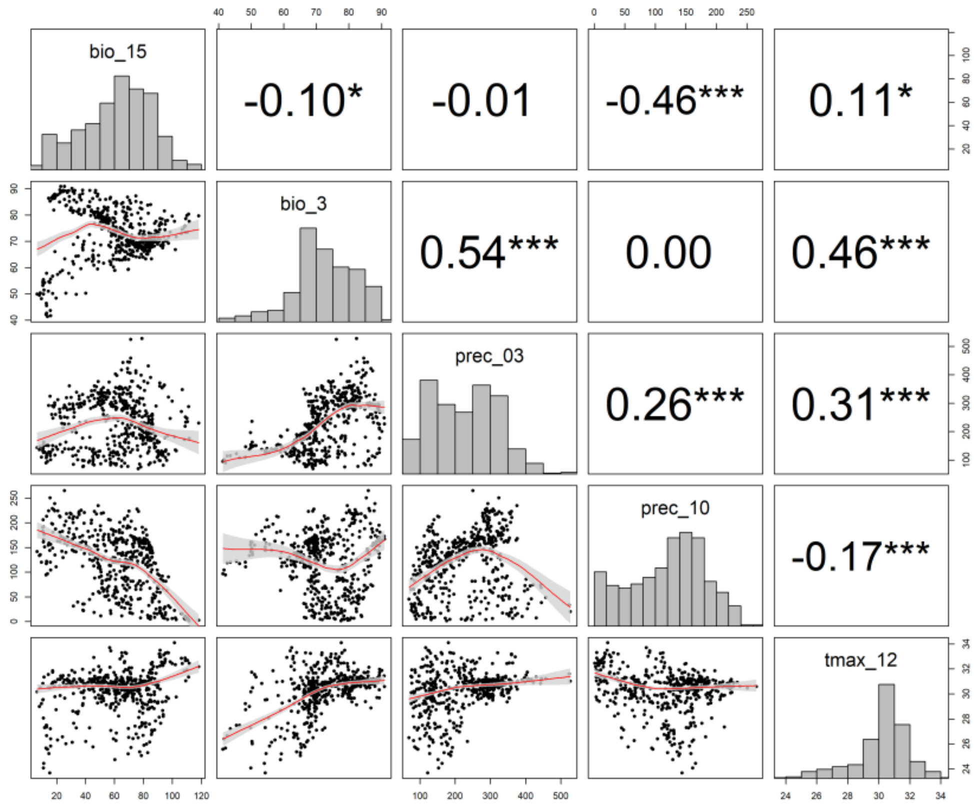

Figure 1: Selection of bioclimatis variables.

We elaborate the models of climate suitability based on the algorithms: Generalized Linear Models (GLM), Vector Machines and Support (SVM), Bioclimatic Envelope (BIOCLIM), DOMAIN, MaxEnt and RandomForest. We calibrate the models in 70% of the data for training and 30% for testing. Each algorithm performed 10 repetitions. Minimum cut limits were established, 30% and 50%.

To evaluate the accuracy of the model we use the area over the curve (Area Under the Curve-AUC), obtained from the curve ROC (Receiver Operating Characteristics), where AUC ranges from zero to one, where values close to 1 show high model performance and values close to 0.5 indicate low model performance [48, 49] and through the True Skill Statistic (TSS). We select only those models indicative of "good" performance with TSS higher than 0.7 and AUC higher than 0.8.

The bioclimatic data with the presence records of the species were handled in the software R 4.0.2 to generate maps of potential distribution of the species under study, using the ensemble (set of forecasts of potential areas in common between the algorithms) of all algorithms in the construction of the final map of potential distribution of molluscs, to reduce the uncertainties of the forecasts [50].

3. RESULTS

A total of 1,158 *M. tuberculata* were collected in the municipality of Santo Amaro and Tutóia from June 2016 to November 2019. These specimens have a turriform shell, with spiral lines with thorn or nodules, horny armpit and opening of the shell facing the right side (dextrogira) (Figure 2). The shells of our specimens correspond to the descriptions of Silva et al. (2019) [38], das Chagas et al. (2018) [51], Quirós-Rodríguez (2018) [52], Santos et al. (2012) [53], Ohlweiler et al. (2010) [54] and Simone (2006) [55].

Figure 2: Melanoides tuberculata (Müller, 1774) collected at Tutóia, Maranhão, Brazil. Scale: 5mm.

The Figure 3 shows the mean AUC and TSS values for model predictions from the *M. tuberculata* occurrence data, in Brazil. For each modeling algorithm, AUC and TSS values used always higher 0.75 for good model performance. SVM, RandomForest and MaxEnt models showed the highest AUC values (> 0, 75), while TSS showed the lowest.

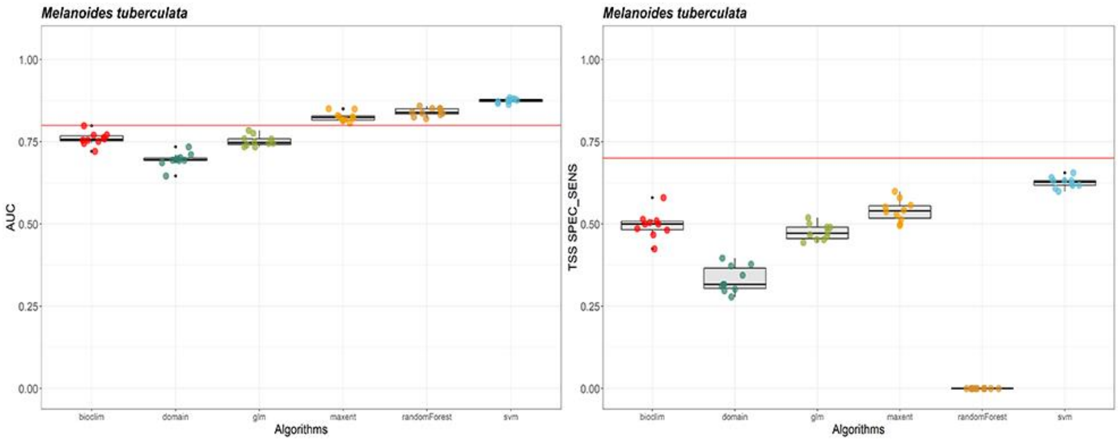

Figure 3: Algorithms performance AUC and TSS.

The environmental variables that contributed most to these models were: precipitation of month 3 (prec 3) that contributed with 36,8%, followed by Isothermality (bio 03) with 32,20% and precipitation of month 10 (prec 10) with 22%. These variables have a direct effect on the distribution and density of the snail populations. Our review of the distribution of *M. tuberculata* (literature and field collection) presents records of these snails in 353 municipalities, 21 Brazilian states and the Distrito Federal.

According to the predictive distribution map for Brazil, the regions with the highest susceptibility to the expansion of the range of this species are the northeast (Ceará, Piauí, Rio Grande do Norte, Pernambuco, Paraíba, Alagoas, Sergipe, Bahia states), southeast (Minas Gerais; São Paulo; Espírito Santo, Rio Janeiro) and Midwest (Goiás and Mato Grosso do Sul states) (Figure 4). The Tocantins state, in the central Brazilian lands presents high susceptibility as well as.

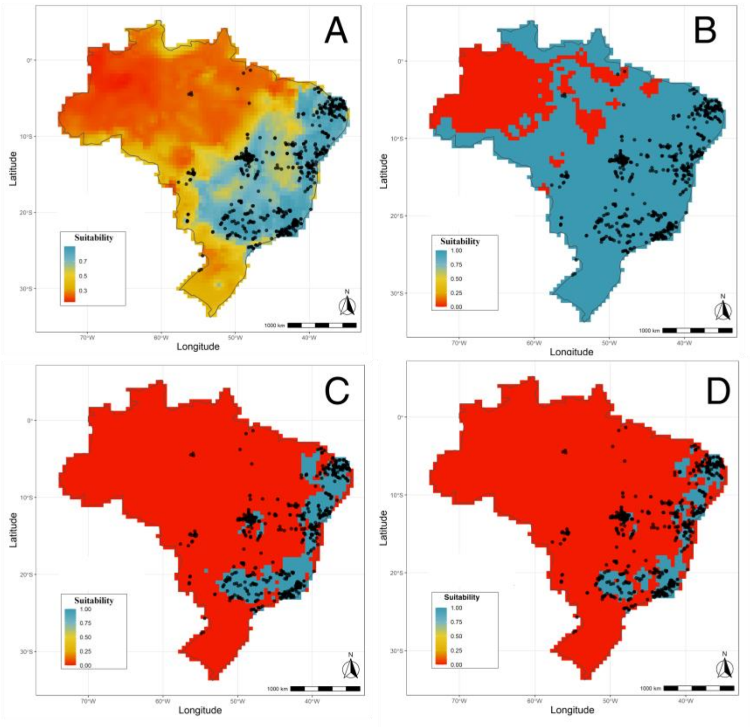

Figure 4: Predictive distribution models for Melanoides tuberculata (Müller, 1774) from the Lençois Maranhenses Microregion. A- medium consensus; B- medium consensus with minimum cut-off threshold; C- medium consensus with 30% cut-off limit; D- medium consensus with 50% cut-off limit. ● Occurrence.

This species presented high to medium suitability of occurrence in 32 national protected areas, included in three categories: Biological Reserve, Ecological Station and National Park (Figure 5; Table 1).

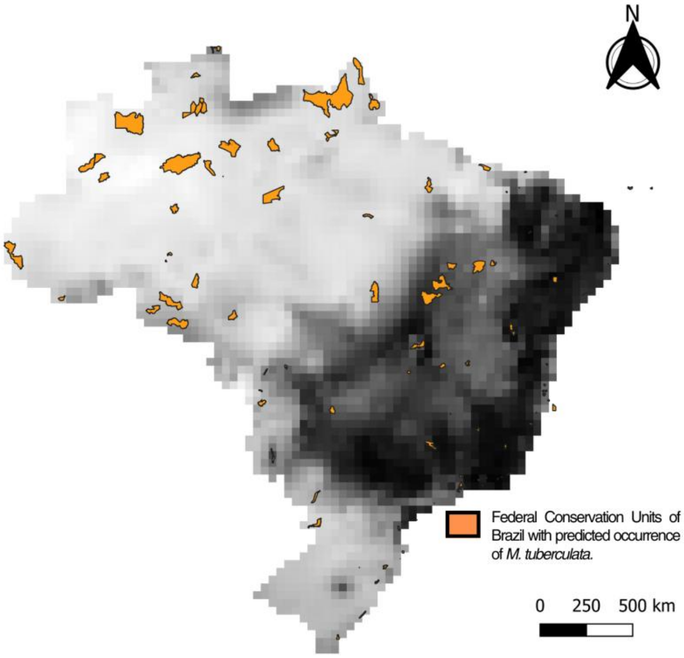

Figure 5: Map of Melanoides tuberculata (Müller, 1774) prediction in Federal protected areas in Brazil.

Table 1: Adequacy of prediction of occurrence of Melanoides tuberculata (Müller, 1774) in Federal protected areas in Brazil.

Conservation Unit	Suitability
National Park of Monte Roraima	0.621272872
National Park of Ubajara	0.6323729941
Ecological Station of Seridó	**0.9161934137**
Ecological Station of Aiuaba	**0.9776507995**
Biological Reserve of Guaribas	**0.8851234435**
National Park of Serra das Confusões	0.6656628162
Ecological Station of Uruçui - Una	**0.7241146747**
Biological Reserve of Serra Negra	**0.9102745378**
Biological Reserve of Saltinho	**0.7923192527**
Biological Reserve of Pedra Talhada	**0.8942888712**
Ecological Station Raso da Catarina	**0.9518978902**
Biological Reserve of Santa Isabel	**0.8374720928**
National Park of Chapada Diamantina	**0.9219387015**
National Park of Cavernas do Peruaçu	0.6563737429
National Park Grande Sertão Veredas	**0.7872663716**
Biological Reserve of Una	**0.7412822198**
National Park Chapada dos Guimarães	0.6327918441
National Park of Brasília	**0.7728071489**
National Park of Pau Brasil	0.6693051401
National Park of Monte Pascoal	0.6531241738
National Park of Descobrimento	0.6531241738
National Park of Emas	**0.7538597233**
Biological Reserve Córrego Grande	**0.7267962498**
Biological Reserve Córrego do Veado	**0.8853746474**
Ecological Station of Pirapitinga	**0.7627825017**
Biological Reserve of Sooretama	**0.8890870671**
National Park of Serra do Cipó	**0.9334481805**
Biological Reserve of Comboios	**0.8600795818**
Biological Reserve of Augusto Ruschi	**0.8469409148**
National Park of Serra da Canastra	**0.912860552**
National Park of Caparaó	**0.9543010056**
National Park of Serra da Bodoquena	0.6862134903
National Park Restinga de Jurubatiba	**0.9407860412**
National Park of Itatiaia	**0.8387620328**
Biological Reserve União	**0.9794009705**
National Park of Serra dos Orgãos	**0.9455478296**
Biological Reserve of Tinguá	**0.9477862831**
Biological Reserve of Poço das Antas	**0.9794009705**
National Park of Serra da Bocaina	**0.7192477649**
National Park of Tijuca	**0.9261719382**
Ecological Station of Tamoios	**0.9252411972**
Ecological Station of Tupinambás	0.6585567565
Ecological Station of Tupiniquins	**0.8957517294**
National Park of Superagui	**0.8453026516**
Ecological Station of Guaraqueçaba	**0.8373722214**
National Park of Uperagui	**0.8532330818**
Ecological Station of Castanhão	**0.7968124403**
Ecological Station of Murici	**0.8788310113**
National Park Saint-Hilaire / Lange	**0.7057769889**
National Park Chapada dos Veadeiros	**0.7356739336**
Ecological Station Serra Geral of Tocantins	**0.8411599093**
National Park Nascentes of Parnaíba	**0.799136209**

4. DISCUSSION

This work registered for the first time the presence of *M. tuberculata* in the state of Maranhão expanding further north the records of the species in Brazil. The specimens were found in the municipalities of Tutóia and Santo Amaro, confirming the hypothesis suggested by Coelho et al. (2018) [23] of the probable establishment of this species in the state of Maranhão.

Predictive distribution modeling is becoming a powerful tool to assess geographic distributions of species in regions with poorly samples [56]. In the present study, the model was applied to identify *M. tuberculata* potential distribution range based on occurrence data of the species. The wide distribution and areas with great susceptibility of occurrence of these Thiaridae is worrying, because it is an intermediate host of several larval forms of trematodes of medical and veterinary importance [23, 57] as *Paragonimus westermani* (Kebert, 1878), *Clonorchis sinensis* (Cobbold, 1875) e *Centrocestus formosanus* (Nishigori, 1924) responsible, respectively, for the transmission of paragonomiasis, clonorchiasis and centrocestiasis in humans and animals. In Brazil, natural infection by *C. formosanus* was already verified in Minas Gerais [58] and in Rio de Janeiro [59].

When modelling the distribution of *M. tuberculata* based on environmental characteristics, precipitation and isothermality were the characteristics that most contribute in predition of analysis. Analyzing the global distribution of native and introduced populations of *Biomphalaria straminea* (Dunker, 1848) in the Americas and China, Yang et al. (2018) [2] observed that isothermality was one of the most important climatic characteristics for the occurrence of *B. straminea*.

The high suitability of this species in protected areas is dangerous, due to the unknow impacts on native species. The occurrence of invasive exotic species in protected areas, created to ensure the preservation of natural resources and biodiversity of species, is still little studied in Brazil [60]. The National System of Nature Conservation Units (SNUC) prohibits the introduction of exotic species into these units. However, a survey of exotic species in the federal protected areas found 144 species. Thus, the impacts of these species are only verified on large scale, due to negligence in the initial detection of the introduction of these species the environment [61].

The specimens found in this study were collected in Lençóis Maranhenses National Park and Protected Area of Delta do Parnaíba. This specie has already been verified in other preservation areas by Ximenes et al. (2017) [59] in Ilha Grande, Rio de Janeiro and Sousa-Souto et al. (2011) [62] in Monumento Natural Grota do Angico and environmental Protection Area of Litoral Sul, in Sergipe.

In a recent survey of invasive species in Brazilian reservoirs conducted by Miyahira et al. (2020) [9], found that *M. tuberculata* was the species with the most records of occurrence in reservoirs in all Brazilian basins. This species was also among the three invasive species of freshwater molluscs responsible for most of the impacts on Brazilian reservoirs [53, 63-70].

The presence of exotic species in the environment is associated with negative impacts, as these species can compete with native species for essential resources, exerting predatory pressure on the species of native [9, 71-82]. This issue is even more worrying in environmental protection areas, as the loss of biodiversity can compromise ecosystem functionality, make it less resilient and more vulnerable to threats, and cause the extinction of endemic or threatened species that are not found elsewhere [83]. In this context, the presence of an invasive species represents an additional challenge for the management of Conservation Units, reinforcing the need for more research focused on the management of biological invasions [84].

Some studies already point *M. tuberculata* as responsible for the decrease of native species population. As decline of a population of *Pomacea lineata* (Spix 1827) [85] total replacement of a natural population of *Aylacostoma tenuilabris* (Reeve 1860) (Thiaridae) after the introduction of *M. tuberculata* [38, 64].

This invasive exotic species of afrosiatica origin reproduces parthenogenetically [86] and is able to tolerate various environmental stressors [87]. Besides being extremely resistant to salinity variation, desiccation and temperature [38, 88-92]. As *M. tuberculata* can reach high population levels, in some extreme cases these high populations can cause die-offs leading to hypoxia and increased concentrations of toxic ammonia due to the decomposition of dead animals [93]. These characteristics favor a greater abundance of this species and explains the ability to colonize and dominate freshwater environments in tropical and subtropical regions [63, 94].

Melanoides tuberculata is often found in fresh or brackish water, such as streams, rivers, wetlands, springs and coastal lakes [95, 96]. The specimens collected in Tutóia and Santo Amaro were verified in lentic environments (lagoons on the dunes) and in lotic (rivers). The introduction of *M. tuberculata* in Maranhão is unknown, but possible hypotheses can be raised, such as the introduction by means of some fishing materials where these individuals could be fixed or even the transport by hunting grounds and/or small boats.

Although some surveys of freshwater gastropods have already been conducted in Maranhão, this is the first record of the occurrence of *M. tuberculata* in this Brazilian state. Due to the biological characteristics of the species and its environmental adaptability, we believe that the distribution of *M. tuberculata* is not confined to the area investigated in this study. For this reason, we reaffirm the importance of conducting further studies in freshwater environments in the state of Maranhão to assess the occurrence and monitor the presence of snails.

The model performed here contributes to developing approaches that will inform and guide the study of the poorly known distribution of *M. tuberculata* in Brazil. We compared six distinct modeling algorithms in predicting the geographic distribution of the *M. tuberculata*. The lower predictive power of the BIOCLIM algorithm compared to other algorithms was also observed by Elith et al. (2006) [48], Tsoar et al. (2007) [97] and Giovanelli et al. (2009) [98]. The SMV and MAXENT method was one of the most precise methods for ecological niche modeling of anuric amphibians that have a distribution restricted to the Atlantic Forest domain [98] and also had good performance modeling of virulent pathogen distribution (*Phytophthora ramorum*) in Califórnia [99] and *B. straminea* in the Americas and China [2].

5. CONCLUSION

The first record of *M. tuberculata* for the state of Maranhão and the suitability of occurrence of this gastropod in Brazilian conservation units provide a basis for decision-making regarding the management and control of this invasive snail. It is possible to identify regions where *M. tuberculata* is most prevalent and those that are at risk of invasion. These data assist in evaluating which local ecosystems are most susceptible to the alterations caused by the presence of the snail, such as competition with native species and the alteration of aquatic ecosystems.

Furthermore, our results indicate certain environmental conditions that favor the survival and dispersal of *M. tuberculata*. Based on this, it is possible to identify areas with similar characteristics that have not yet been invaded by this snail but that may be potentially vulnerable in the future.

About public health perspective, the predictive analysis of *M. tuberculata* distribution can assist managers in planning control measures in areas with a higher risk of the snail's occurrence. It is important to remember that the dispersal of an invasive species facilitates the introduction of new parasites, and *M. tuberculata* is a vector for trematodes that have medical and veterinary importance.

Considering these aspects, this research highlights the need to prioritize management and control actions for *M. tuberculata*, directing efforts to critical areas and enabling the implementation of preventive and corrective measures to protect local ecosystems and biodiversity. Long-term malacological surveys to monitor the dispersal of this snail will also contribute to a better understanding of the environmental and economic impacts caused by *M. tuberculata*.

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