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New Distribution Records and Potentially Suitable Areas for the Threatened Snake-Necked Turtle *Hydromedusa maximiliani* (Testudines: Chelidae)

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Abstract. – *Hydromedusa maximiliani* is a freshwater turtle endemic to the Atlantic Forest of eastern and southeastern Brazil and threatened by extinction. Here, we add 15 new locality records for this species based on photographs of specimens encountered in the field and examination of museum collections. We also used ecological niche modeling tools of 3 different algorithms (GARP, SVM, and Maxent) to suggest potential suitable areas for the occurrence of the species. Models predict 53,679–263,844 km^2 of suitable habitat for *H. maximiliani,* with 8396–31,758 km^2 inside protected areas. Besides being useful in a reassessment of the species' conservation status, our results contribute to the knowledge of distribution patterns of *H. maximiliani* and highlight potential areas to drive future field surveys.

Key Words. – Reptilia; biogeography; conservation; ecological niche; freshwater turtle; geographic distribution; species distribution model

Hydromedusa maximiliani (Mikan 1825) is a small freshwater turtle species endemic to the Atlantic Forest of eastern and southeastern Brazil (Iverson 1992; Souza and Martins 2009). Individuals inhabit clear and cold-water streams with sandy and rocky bottoms (Souza and Martins 2006, 2009), from coastal rivers below 100 m to water bodies above 600 m elevation (Souza 2005; Souza and Martins 2009).

Anthropogenic threats, including habitat loss and water pollution, are the main factors affecting populations of *H. maximiliani* (Souza and Martins 2009). This species is considered Vulnerable by the International Union for Conservation of Nature Red List, although its evaluation needs updating (Tortoise & Freshwater Turtle Specialist Group 1996). It is not included in the Brazilian Red List (Ministério do Meio Ambiente 2014), but is considered locally threatened in the states of Espírito Santo (Secretaria de Estado de Meio Ambiente e Recursos Hídricos [SEAMA] 2005; Almeida et al. 2007) and Minas Gerais (Conselho de Política Ambiental [COPAM] 2010). In the first edition of the List of Endangered Species of the state of Minas Gerais, *H. maximiliani* was considered Critically Endangered (COPAM 1995; Moreira 1998). Following the latest review of that list, the species' conservation status was changed to Vulnerable on account of its discovery in previously unknown localities (Fundação Biodiversitas 2007).

We present new locality records for *H. maximiliani* and use ecological niche modeling tools to predict additional areas with suitable habitats for its occurrence. These new data may be useful to better understand the species' distribution pattern and to guide a more realistic evaluation in future reviews of its conservation status.

METHODS

In order to update the information on its geographic distribution, we gathered records of *H. maximiliani* from the following sources: 1) literature records; 2) photographs of unvouchered field specimens taken by us and other colleagues allowing unambiguous identification of the species; and 3) voucher specimens in herpetological collections (Table 1). We do not consider a record from EmySystem (2010) based on a specimen from the British Museum of Natural History, London (BMNH 1965.823), because of uncertainty of sampling locality (C. McCarthy, *in litt.*, January 2011).

Additionally, we used ecological niche modeling tools to suggest potential suitable areas for the occurrence of *H. maximiliani* (Guisan and Thuiller 2005). The study area was delimited by a buffer of 500 km around known occurrences, in order to reduce the area where background points (pseudo-absence) could be generated in the modeling process, being closer to species' known occurrences. This method is more reliable because the species' absence in places too far from its known occurrence is more likely to be influenced by another factor such as geographic isolation, than by environmental variables.

To generate the models, environmental layers were obtained from WorldClim (www.worldclim.org) for bioclimatic variables and EROS Data Center (eros.usgs.gov) for digital elevation model (DEM). Slope layer was derived from DEM considering differences in altitude between cells of a raster map. Using 19 bioclimatic layers and 2 aspect layers, a correlation analysis was carried to choose the variables to be used in the distribution modeling, excluding variables with correlation value below 0.8 to avoid model overfitting (Jiménez-Valverde et al. 2011). An analysis of correlation using Moran's *I* index was also conducted to evaluate the spatial autocorrelation of the records used.

The species' records were combined with 8 environmental layers (annual mean temperature, mean diurnal range, temperature seasonality, temperature annual range, annual precipitation, precipitation seasonality, altitude, and slope) from current climate data in 0.04° resolution (Hijmans et al. 2005) using 3 algorithms: Genetic Algorithm for Rule-set Production (GARP), support vector machine (SVM), and Maximum Entropy Modeling (Maxent). GARP and SVM models were generated in OpenModeller software (http://openmodeller.cria.org.br/) and Maxent in Maxent software (http://www.cs.princeton.edu/~schapire/maxent/). The choice of an ensemble approach was to reduce the uncertainties of models, by selecting as potential distribution only the areas shared by all algorithms.

When working with a map in a grid of 0.04°, some records were in the same cell and thus were excluded because they were considered similar records for having all the same environmental characteristics. When doing the distribution models, we were not considering each record as a sample, but the cells where the species is present. So, 36 of 48 records were used, divided between 75% used as training data (27 records) and 25% used as testing data (9 records). Algorithms (GARP, SVM, and Maxent) were used to calculate the similarity between localities with known occurrence of the species and other places in the study area (Li and Wang 2013).

Accuracy of the models was evaluated using cross-validation analysis and a partial-area receiver operating characteristic (ROC) approach (Peterson et al. 2008). This method does not directly compare the area-under-the-curve values, which would drive to an erroneous analysis because different algorithms were used. In partial ROC analysis, 3 different omission error percentages were considered: 0%, 5%, and 20%. After these analyses, a ''lowest presence'' value was used as a threshold in order to obtain a binary map of presence and absence (Liu et al. 2005). An ensemble of binary maps from the 3 algorithms was made and only areas identified by all 3 were considered to be potentially suitable for the species' occurrence (Araújo and New 2006).

Available data indicate that *H. maximiliani* populations depend on forest remnants for survival (e.g., Souza 2005). Thus, the final distribution map was superimposed onto a map of vegetation remnants (http://siscom.ibama.gov.br/monitorabiomas/) to better estimate where the species would be able to occur, considering 2 hypothetical scenarios: one where suitable areas cannot be > 0.5 km from a stream margin, and the other where the distance cannot exceed 1.5 km. These results were superimposed on a map of Brazilian protected areas to estimate the range of the species within conservation units.

RESULTS

The search for new specimens of *H. maximiliani* led us to add 15 new localities where the species occurs, all in the state of Minas Gerais. The historical distribution of this species is now composed of 48 localities: 5 in the state of Bahia, 2 in the state of Espírito Santo, 21 in the state of Minas Gerais, 10 in the state of Rio de Janeiro, and 10 in the state of São Paulo (Fig. 1; Table 1). Presently, *H. maximiliani* is known to occur in small rivers belonging to 1) the Catolé, Cachoeira, Contas, Jiquiriçá and Pardo river basins (Atlantic Eastern basin); 2) the Baixada Santista, Doce, Jequitinhonha, and Paraíba do Sul river basins (Atlantic Southeastern Basin); 3) the Paraopeba River basin (São Francisco basin); and 4) the Paranapanema River basin (Paraná basin).

Variables that influenced species distribution the most were annual mean temperature and mean diurnal range, with 34.3% and 24.9% contribution to model prediction, respectively. Moran's *I* index of spatial autocorrelation showed clustered distribution of records in relation to almost all environmental variables. The only variable with values randomly distributed with respect to presence records was slope. This pattern of clustered distribution was shown even when subsamples of presence records were analyzed.

All algorithms used to model the species' geographical distribution showed an accuracy rate of 100% in cross-validation analysis. In partial-area ROC analysis, the SVM algorithm was slightly better than GARP and Maxent, with greater values of partial-area ROC in situations of lower percentages of omission errors (SVM: 5.69 [0%], 3.09 [5%], 1.64 [20%]; GARP: 1.75 [0%], 2.45 [5%], 2.17 [20%]; Maxent: 1.83 [0%], 1.83 [5%], 1.81 [20%]). Also, the consensus map was influenced mainly by SVM, the most restricted model. The total area predicted to be occupied by *H. maximiliani,* considering only areas having vegetation remnants, is 263,844 km^2 (Fig. 1A), with 31,758 km^2 inserted in 93 protected areas. This

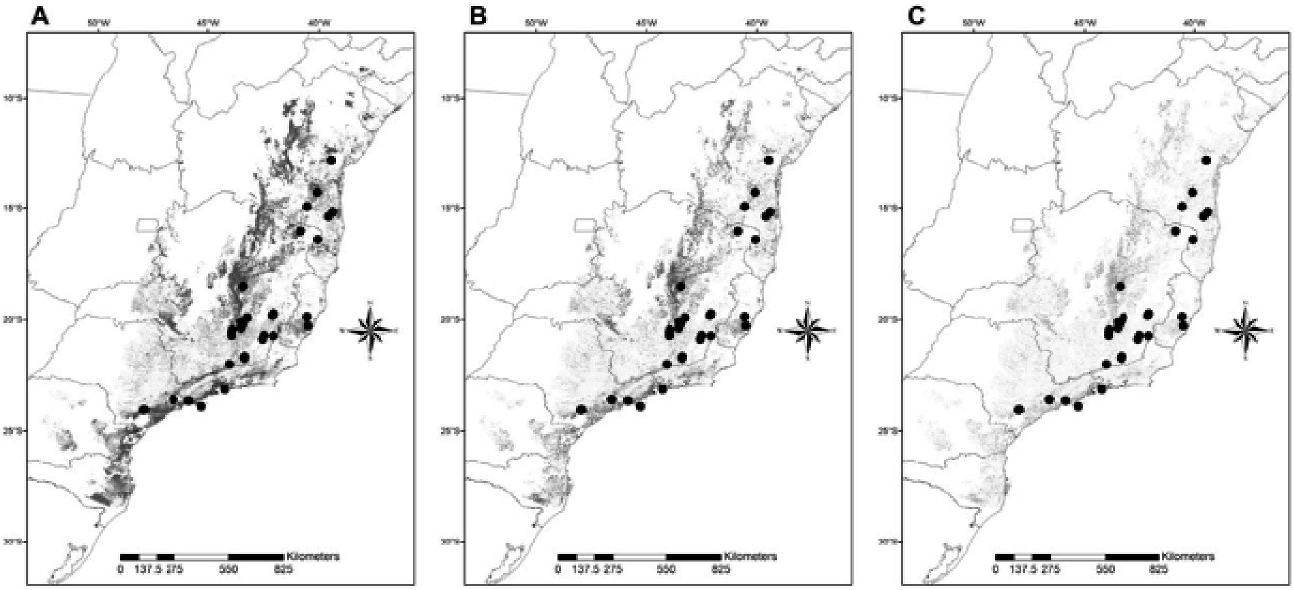

Figure 1. Binary distribution models generated by an ensemble of GARP, SVM, and MaxEnt algorithms, using the known records of *Hydromedusa maximiliani* in southeastern and eastern Brazil, to predict suitable areas for occurrence of the species. (A) Predictions at broader scale; (B) predictions considering that suitable areas cannot be > 1.5 km from a stream margin; (C) predictions considering that suitable areas cannot be > 0.5 km from a stream margin (see ''Methods'' for detailed information). Black dots represent localities where the species was recorded (see Table 1 for detailed information).

corresponds to 12% of suitable habitats for *H. maximiliani* being under protection by governmental laws.

However, the proximity to streams is an important factor for the maintenance of populations of this species. It is unknown how far from streams these turtles can survive; therefore, 2 scenarios were used: the first considering that suitable habitats could not exceed 0.5 km from streams, and a second one where this distance could not exceed 1.5 km. The first scenario resulted in an area of 146,639 km^2 (Fig. 1B), with 23,730 km^2 (16%) in protected areas; the second scenario estimates 53,679 km^2 of suitable areas (Fig. 1C), with 8396 km^2 (16%) in protected areas.

DISCUSSION

The new distribution records of *H. maximiliani* presented here greatly increase the known geographic range of this species, from 33 to 48 records, previously located mainly in the states of São Paulo and Rio de Janeiro. Most new records are in the Espinhaço Mountain Range, a Precambrian orogenic belt extending from 1000 km north to south in the states of Bahia and Minas Gerais (Leite et al. 2008; United Nations Educational, Scientific and Cultural Organization [UNESCO] 2011). With elevations up to 2000 m, the Espinhaço Range bears a mosaic of phytophysiognomies related to the Atlantic Forest, Cerrado, Caatinga, and even particular types of vegetation on iron-rich rock outcrops (Gontijo 2008), making this distinct massif an important Brazilian center of endemism (Silva et al. 2008). The Espinhaço was predicted to harboring much suitable habitat for *H. maximiliani* (Fig. 1), which may be explained by the presence of many streams and springs inside forest areas throughout the massif's range (Silva et al. 2008). The predictions also include the Espinhaço region in Bahia state, where there is no available record of *H. maximiliani.* This region is still poorly surveyed for reptiles, especially turtles (Juncá 2005). Future surveys there to search for *H. maximiliani* populations are essential, mainly because the forest areas (suitable habitats for the occurrence of the species) are among the habitat types most affected by human activities there (Juncá 2005).

Models indicated some small suitable areas for *H. maximiliani* in Pernambuco, Alagoas, and Sergipe states in northeastern Brazil, and larger areas in Paraná and Santa Catarina states, in the southeast. No record exists for the species in any of these states (especially as far north as Pernambuco, Alagoas, and Sergipe), a result that may have been caused by overprediction (commission error; Guisan and Thuiller 2005). It is also possible that *H. maximiliani* occurs in the 3 northeastern states as sink populations (Pulliam 2000). On the other side, Paraná and Santa Catarina have large areas (mainly in coastal region) predicted to be suitable for *H. maximiliani.* However, at least in some of them, the congeneric *Hydromedusa tectifera* has been recorded (Iverson 1992); thus, a case of niche conservatism may exist between these species. Usually, *H. maximiliani* is absent from elevations below 600 m when occurring in sympatry with *H. tectifera* (Souza and Martins 2009). For this reason, it is also possible that some suitable predicted areas in southern Brazilian states lie within the species' Grinellian niche, but outside its realized niche (Soberon 2007).

There are predicted suitable areas in western Minas Gerais state and a few in eastern Goiás state. Although

Table 1. Known distribution records of *Hydromedusa maximiliani* (Mikan 1825). Locality names are written as *Specific locality* (when available), County (*município*). * = new localities; # = protected areas. Specimens listed are housed in the following collections: Coleção Herpetológica da Universidade Federal de Minas Gerais (UFMG); Museu de Ciências Naturais, Pontifícia Universidade Católica de Minas Gerais (MCN); Laboratório de Zoologia dos Vertebrados, Universidade Federal de Ouro Preto (LZV-UFOP); Museu de Zoologia João Moojen, Universidade Federal de Viçosa (MZUFV); Museu Nacional, Universidade Federal do Rio de Janeiro (MNRJ).

Locality name	Latitude	Longitude	Reference
Bahia state			
Reserva Jequitibá, Elísio Medrado#	−12.866	−39.466	Argôlo and Freitas 2002
Fazenda Boa Esperança, Boa Nova	−14.316	−40.083	Argôlo and Freitas 2002
Fazenda Recanto da Adriana, Barra do Choça	−14.950	−40.550	Argôlo and Freitas 2002
Fazenda São José, Jussari	−15.183	−39.400	Argôlo and Freitas 2002
Fazenda Pratinha, Pau Brasil	−15.383	−39.583	Argôlo and Freitas 2002
Espírito Santo state			
Reserva Biológica Nova Lombardia (*Augusto Ruschi*), Santa Teresa#	−19.890	−40.549	Emysystem 2010
Santa Teresa	−19.916	−40.600	Emysystem 2010
Reserva Biológica Duas Bocas, Cariacica#	−20.283	−40.503	Tonini et al. 2010
Minas Gerais state			
Fazenda Limoeiro, Almenara*	−16.050	−40.850	MZUFV 030
Fazenda Duas Barras (current *Parque Estadual Alto Cariri*), Santa Maria do Salto*,#	−16.429	−40.055	MCNR 1346
Mina do Serro, Serro*	−18.609	−43.391	MCNR 3403
Piedade de Caratinga*	−19.756	−42.050	Photographed by Harley Coelho
Parque Municipal de Caratinga, Unidade IV, Caratinga*,#	−19.833	−42.100	MZUFV 053
Piracicaba river, Água Limpa mines, Mariana*	−19.929	−43.226	MCNR 4111
Reserva Particular do Patrimônio Natural Serra do Caraça, Catas Atlas#	−20.083	−43.466	Souza 2004; MCNR 669
Mariana*	−20.178	−43.481	UFMG 831
Tributary of the Piracicaba river, Mariana*	−20.200	−43.417	MZUFV 003; MZUFV 004
Vicinities of the São Francisco de Paula church, Ouro Preto*	−20.382	−43.508	LZV-UFOP 1078S
Parque Estadual do Itacolomi, Ouro Preto#	−20.439	−43.514	Fundação Biodiversitas 2007
Serra da Moeda, Congonhas*	−20.464	−43.885	Photographed by Felipe S.F. Leite
Parque Estadual da Serra do Brigadeiro, Araponga#	−20.721	−42.479	Fundação Biodiversitas 2007
Reserva Particular do Patrimônio Natural Jurema, Queluzito*,#	−20.729	−43.929	MCNR 2205
Fazenda Santa Rita, Carangola	−20.737	−42.060	Fundação Biodiversitas 2007
Viçosa	−20.799	−42.859	Pereira and Cuocolo 1940
Coimbra*	−20.850	−42.791	MZUFV 029
Brejo do Joaquim de Paula, near the *Parque Estadual da Serra do Brigadeiro*, Muriaé*	−20.904	−42.545	MZUFV 055
Reserva Biológica Municipal Santa Cândida, Juiz de Fora#	−21.688	−43.344	Fundação Biodiversitas 2007
Lake of Mariano Procópio Museum, Juiz de Fora	−21.746	−43.359	Vieira et al. 2008
Além Paraíba*	−21.864	−42.669	MNRJ 2410
Reserva Particular do Patrimônio Natural Ovídio Antônio Pires 3, Bom Jardim de Minas*,#	−22.016	−44.033	MCNR 3642
Rio de Janeiro state			
Nova Friburgo	−22.317	−42.033	Souza et al. 2003
Teresópolis	−22.450	−42.467	Souza et al. 2003
Resende	−22.463	−44.456	Pereira and Cuocolo 1940
Petrópolis	−22.517	−43.167	Emysystem 2010
Parque Nacional da Serra dos Órgãos, Guapimirim#	−22.526	−43.013	Levandeira-Gonçalves et al. 2007
Mendes	−22.526	−43.728	Emysystem 2010
Itatiaia	−22.583	−44.567	Emysystem 2010
Duque de Caxias	−22.652	−43.358	Salles and Silva-Soares 2010
Ilha Grande, Angra dos Reis	−23.133	−44.233	Souza and Martins 2009
Paraty	−23.250	−44.700	Emysystem 2010
São Paulo state			
Piquete	−22.600	−45.183	Emysystem 2010
Porto Feliz	−23.217	−47.533	Emysystem 2010
Vila Prudente, São Paulo	−23.591	−46.579	Luderwalt 1926
Ipiranga, São Paulo	−23.591	−46.608	Luderwalt 1926
Estação Biológica de Boracéia, Salesópolis#	−23.650	−45.870	Emysystem 2010
Serra do Mar, entre Pai Matias e Evangelista de Souza	−23.700	−46.600	Emysystem 2010
Paranapiacaba	−23.783	−46.317	Emysystem 2010
Ilhabela	−23.900	−45.300	Luderwalt 1926; Souza and Martins 2009
Parque Estadual da Serra do Mar#	−23.900	−46.517	Famelli et al. 2011
Parque Estadual Carlos Botelho, São Miguel Arcanjo#,[a]	−24.050	−47.983	Souza and Abe 1997; Souza et al. 2002a, 2002b; Souza and Martins 2006; Martins and Souza 2009

[a] There is > 1 collection site in this locality.

this result may have been caused by commission errors, it indicates the potential occurrence of *H. maximiliani* in the Cerrado. These areas may be inside gallery forests, well-known as habitat for some Amazonian and Atlantic Forest species whose range reaches the Cerrado (e.g., Silva et al. 2013).

The conservation status of *H. maximiliani* in the state of Espírito Santo is ''Vulnerable'' (Almeida et al. 2007). Confirmed records are from the southeastern region of the state, where most forest fragments are located (Fundação SOS Mata Atlântica and INPE 2013). Besides this region, model predictions include 2 important protected areas in Espírito Santo: Parque Nacional do Caparaó (boundaries with Minas Gerais) and Reserva Natural Vale (at the state's northeast). Therefore, priority should be given to these 2 areas in future surveys for *H. maximiliani* in Espírito Santo state.

According to the models results, annual mean temperature and mean diurnal range (i.e., mean of monthly maximum temperature minus minimum temperature) are the variables that most influence the distribution of *H. maximiliani*. This pattern may be explained by the species' thermoconformity strategy and its dependence on cold-water streams with constant year-round temperatures, even during the summer (Souza and Martins 2006, 2009). The spatial autocorrelation found by Moran's *I* index could also be explained by the ecological features of *H. maximiliani,* a small freshwater turtle species with limited dispersal capabilities (Souza et al. 2002b), living in streams with relatively low water temperatures (18°C; Souza and Martins 2006) inside forest areas with dense canopy, mainly in mountainous regions above 600 m elevation (Souza and Martins 2009).

Although the present study suggests a potential extension in the distribution range of *H. maximiliani,* all drainage basins where the species is found are subject to dam construction, discharge of chemicals, sewage, agricultural, and industrial effluents, and mining (e.g., Azevedo et al. 2004; Marques et al. 2004). As a consequence, erosion, silting, and habitat loss occur (Marques et al. 2004).

In recent years, species distribution models have been applied to different taxonomic groups (e.g., Marini et al. 2010; Ferraz et al. 2012; Silva et al. 2013). Some studies have been conducted with Testudines (e.g., Rödder et al. 2009; Stephens and Wiens 2009; Forero-Medina et al. 2012), but we are unaware of published records concerning Brazilian freshwater turtles. The present study contributes to the knowledge of distribution patterns of *H. maximiliani,* highlighting potential areas to conduct field surveys, especially along the Espinhaço Range and in eastern Brazil. Our analyses may decrease costs and improve the efficiency of future searches (Marini et al. 2010).

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