

Predicting the potential distribution of the alien invasive American bullfrog (*Lithobates catesbeianus*) in Brazil

João G. R. Giovanelli · Célio F. B. Haddad ·
João Alexandrino

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Abstract The non-native invasive anuran *Lithobates catesbeianus* is presently distributed in Brazil, especially in the Atlantic Rainforest biodiversity hotspot. Here, we use a maximum entropy ecological niche modeling algorithm (i) to model the North American native geographic distribution of this species and (ii) to project that model onto the whole of Brazil. After applying a threshold value that balances commission and omission errors, the projection results suggested high probabilities of occurrence mostly in southern and southeastern Brazil. We also present the first report on the species known distribution in Brazil, showing good agreement with model predictions. If the predictive map is interpreted as depicting invasiveness potential of *L. catesbeianus*, strategies to prevent further invasion in Brazil should be focused especially in the Atlantic Rainforest biodiversity hotspot.

Keywords Ecological modeling · Exotic species · Maxent · Bioclim · Anura · American bullfrog

Introduction

The American bullfrog (*Lithobates catesbeianus* Shaw 1802) has been considered one of the most harmful invasive species (Lowe et al. 2000). Native to eastern North America, from southern USA up to southern Canada, it was introduced, accidentally or intentionally, into southern Europe, Asia and South America (Bruening 2002). In Brazil, introductions have occurred since the 1930's in association with aquaculture (Fontanello and Ferreira 2007). Presently the species is usually recorded in the field across several southern and southeastern localities (Borges-Martins et al. 2002), mostly in the Brazilian Atlantic Rainforest (Dixo and Verdade 2006; Conte and Rossa-Feres 2006). Whether this invasive species is or not contributing to population losses in some Brazilian native amphibians is unfortunately still a matter of speculation (Young et al. 2001; Silvano and Segalla 2005).

Ecological niche-modeling is a good tool to assess potential geographic distributions of species (Guisan and Thuiller 2005; Elith et al. 2006), providing in some cases additional information for conservation planning strategies and selection of protection areas (Jeganathan et al. 2004; Young 2007). Ecological niche modeling has also been applied to the prediction of the invasive potential of non-native species (Peterson and Vieglais 2001; Peterson et al. 2003; Papes and Peterson 2003; Ficetola et al. 2007).

J. G. R. Giovanelli · C. F. B. Haddad ·
J. Alexandrino (✉)
Herpetology Lab, Department of Zoology, UNESP-Rio
Claro, 13506-900, P.O. Box 199, Rio Claro, SP, Brazil
e-mail: jalex@rc.unesp.br

The potential global distribution of *L. catesbeianus* was recently predicted by Ficetola et al. (2007) but their work was mostly aimed at predicting the outcome of American bullfrog introductions (invasive or non-invasive) for well studied European non-native populations. We here wish to contrast their example with the rather poorly known non-native populations of *L. catesbeianus* in Brazil, which especially occur in the Atlantic Rainforest biodiversity hotspot. We use recently described ecological niche modeling methods to generate a predictive map for the distribution of *L. catesbeianus* in Brazil and compare our results with the available information for the actual Brazilian distribution of this frog.

Materials and methods

To produce an ecological niche model for the native distribution of *L. catesbeianus* we took 784 georeferenced occurrence points in North America from the Global Biodiversity Information Facility (2007) and HerpNet (2007) databases, including occurrences in Mexico, USA, and Canada (Fig. 1A). The data was checked in the DIVA-GIS software (Hijmans et al. 2002) for bias and errors.

We used 19 bioclimatic and 1 topographic layers as predictors. The bioclimatic variables result from global land area interpolation of climate point data (1950 – 2000 period) at a spatial resolution of 2.5 arc-min (Hijmans et al. 2005; available at <http://www.worldclim.org>). The altitude variable was derived from the U.S. Geological Survey's Hydro-K data set, at the same spatial resolution.

The realized ecological niche was modeled using the Maxent software for species habitat modeling (MAXENT; Phillips et al. 2006, software available at <http://www.cs.princeton.edu/~schapire/maxent>). It has been developed within the machine learning community and it implements a general purpose algorithm for making predictions and inferences from incomplete information. The MAXENT algorithm estimates geographic distributions of species from locality point data by finding the maximum entropy distribution (Phillips et al. 2006). MAXENT was ranked among the most effective methods for species distribution modeling from presence-only data in a recent comprehensive model comparison study (Elith et al. 2006).

The model was developed for occurrences within the native distribution in North America and run over the area represented by the inset in Fig. 1. Occurrence data were divided into training data, the 75% of occurrence point data that was used for model prediction, and test data, the 25% of occurrence point data that was used for model validation. The resulting model was evaluated with the Receiver Operating Characteristics Curve (ROC) calculating the area under the curve (AUC), a threshold independent index widely used in ecological studies. A ROC plot is created by plotting the sensitivity values, the true-positive fraction against 1-specificity, and the false positive fraction for all available probability thresholds (further reading: Fielding and Bell 1997, Manel et al. 2001). The AUC is a measure of the area under the ROC ranging from 0.5 (random accuracy) to a maximum value of 1.0 (perfect discrimination).

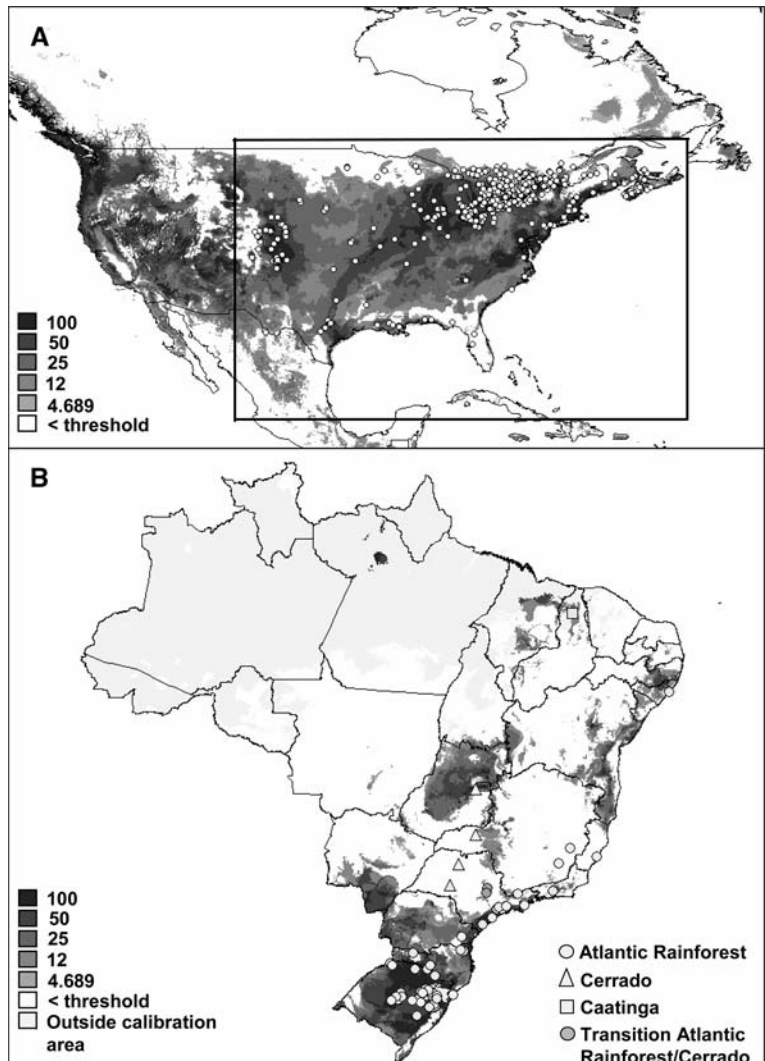
The output of MAXENT is a continuous map which allows fine distinctions to be made between the modeled suitability of different areas. To generate a binary (presence/absence) prediction map we used a cumulative threshold value that balances training omission, predicted area, and threshold value, i.e., balancing commission and omission errors (Phillips et al. 2006).

The resulting model was projected onto both North America and Brazil to assess the potential geographic distribution of *L. catesbeianus*. Probabilities below the threshold value were transformed to zero. Projection results for Brazil were validated only in areas where environmental conditions fall within the range of the calibration area, to avoid spurious projections (for details see Thuiller et al. 2004). Finally, we plotted the actual species occurrence points in Brazil (Appendix 1) on the predicted Brazilian distribution map.

Results and discussion

Invasive species are one of the most important threats to native communities (Begon et al. 1996). The occurrence of *Lithobates catesbeianus* in areas of the Brazilian Atlantic Rainforest is specially concerning because this biome is a biodiversity hotspot (Myers et al. 2000). It is likely that *L. catesbeianus* has deleterious effects to populations of native amphibians and other organisms through competition

Fig. 1 (A) Predicted potential geographic distribution for *Lithobates catesbeianus* in North America resulting from Maxent climatic modeling using occurrence records within the species native range. The inset is the area of environmental calibration for the purpose of projecting the habitat suitability model (see text for details); (B) Projection map for the potential distribution of *L. catesbeianus* in Brazil. Real occurrence localities of the species in distinct Brazilian biomes are represented by distinct polygon shapes or shading (see legend in the figure)



and predation (Moyle 1973; Kiesecker and Blaustein, 1998; Lowe et al. 2000).

Maxent modeling of 588 training and 196 testing presence records, within the native range of *L. catesbeianus*, yielded an AUC of 0.917 and 0.960, respectively for the training and the test data, suggesting high predictive power of the model. Model probabilities below the threshold value of 4.689 were classified as predicted absence and transformed to null values. The model projection predicting occurrence in North America showed a good agreement with both the species native distribution and the occurrence in non-native western North America (Fig. 1A). The environmental variables that most influenced the predictions were, mean

diurnal range temperature, annual mean temperature and precipitation of the driest quarter (results not shown).

The projection of the native range distribution model onto Brazil showed that predicted occurrence included the actual distribution of *L. catesbeianus* in southern and southeastern coastal areas of the Atlantic Rainforest, but also suggested that areas in central and northeastern Brazil could be colonized by the species (Fig. 1B). Most of the Amazonian environments were outside the model calibration range for the species native distribution, albeit above the model threshold value. Real occurrence is in good agreement with the predicted Brazilian distribution map with the few occurrences not predicted by the

model located in the Cerrado biome (Fig. 1B and Appendix 1). Anecdotal information of failed *L. catesbeianus* colonization exists for one of these localities (Brandão and Rossa-Feres, personal communication; see Appendix 1 and Fig. 1B) but no studies have ever examined the status of any introduced Brazilian population. Bioclimatic factors such as low dry-season precipitation could be limiting the species ability of invading areas away from the sites of introduction in the Cerrado, but we cannot rule out that other ecological factors (e.g. biotic interactions) would concur for restricted or failed colonization. We expect that the predicted distribution presented here provides an hypothetical framework from which to derive comparative investigations of population dynamics in areas of occurrence predicted by the model and areas of occurrence not predicted by the model.

If we conservatively assume that the predicted distribution map presented here is a proxy for invasion potential, southern and southeastern Brazil must be considered especially sensitive because this part of the Atlantic Rainforest is where bullfrog aquaculture has been traditionally more widespread.

Appendix 1 Occurrence points of *Lithobates catesbeianus* in Brazil based on field work, the literature, museum collections and personal communications (CFBH—Coleção de Anuros

The understanding that both habitat suitability and likelihood of human introduction for the invasive American bullfrog coincide with areas hosting the most diverse anuran communities in the planet should urge both researchers and planners to act. Research is needed to start understanding the dynamics of American bullfrog populations in Brazil, while planning should focus on the eradication of invasive populations and aquaculture farming control. The production of bullfrog meat in aquaculture farms is a profitable economic activity in Brazil (Feix et al. 2006) that will not be easily eradicated, but it should be strictly regulated and monitored by the Brazilian government to avoid further accidental introductions, especially in areas more suitable for invasion.

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Célio F. B. Haddad, Unesp, Rio Claro, SP, Brazil; DZSJRP—Coleção do Departamento de Zoologia de São José do Rio Preto, Unesp, São José do Rio Preto, SP, Brazil)

Municipality	State	Biome	Longitude	Latitude	Source
Duque de Caxias	Rio de Janeiro	Atlantic Rainforest	-43.30446°	-22.58242°	Instituto Hórus (2007)
Cocal de Telha	Piauí	Caatinga	-41.98333°	-4.53333°	Instituto Hórus (2007)
Santo Antônio do Descoberto	Goiás	Cerrado	-48.26030°	-15.96968°	Brandão (pers. comm.)
Maceió	Alagoas	Atlantic Rainforest	-35.74513°	-9.62554°	Instituto Hórus (2007)
Vitória	Espírito Santo	Atlantic Rainforest	-40.41272°	-20.33107°	Instituto Hórus (2007)
Caratinga	Minas Gerais	Atlantic Rainforest	-42.14000°	-19.79000°	Instituto Hórus (2007)
Uberlândia	Minas Gerais	Cerrado	-48.27997°	-18.90001°	Instituto Hórus (2007)
Viçosa	Minas Gerais	Atlantic Rainforest	-42.88000°	-20.76000°	Instituto Hórus (2007)
Agudo	Rio Grande do Sul	Atlantic Rainforest	-53.24992°	-29.64157°	Instituto Hórus (2007)
Arroio do Tigre	Rio Grande do Sul	Atlantic Rainforest	-53.09613°	-29.33865°	Instituto Hórus (2007)
Barão	Rio Grande do Sul	Atlantic Rainforest	-51.53456°	-29.37932°	Borges-Martins et al. (2002)
Barracão	Rio Grande do Sul	Atlantic Rainforest	-51.45442°	-27.67698°	Instituto Hórus (2007)
Caxias do Sul	Rio Grande do Sul	Atlantic Rainforest	-51.16754°	-29.17837°	Borges-Martins et al. (2002)
Canela	Rio Grande do Sul	Atlantic Rainforest	-50.80187°	-29.35992°	Instituto Hórus (2007)
Derrubadas	Rio Grande do Sul	Atlantic Rainforest	-53.85530°	-27.26627°	Borges-Martins et al. (2002)
Dom Feliciano	Rio Grande do Sul	Atlantic Rainforest	-52.11066°	-30.69785°	Instituto Hórus (2007)
Dona Francisca	Rio Grande do Sul	Atlantic Rainforest	-53.35898°	-29.62626°	Instituto Hórus (2007)
Encantado	Rio Grande do Sul	Atlantic Rainforest	-51.87989°	-29.23984°	Instituto Hórus (2007)

Appendix 1 continued

Municipality	State	Biome	Longitude	Latitude	Source
Estrela	Rio Grande do Sul	Atlantic Rainforest	-50.98002°	-28.10002°	Instituto Hórus (2007)
Estrela Velha	Rio Grande do Sul	Atlantic Rainforest	-53.15368°	-29.17225°	Instituto Hórus (2007)
Erechim	Rio Grande do Sul	Atlantic Rainforest	-52.26892°	-27.62956°	Borges-Martins et al. (2002)
Gravataí	Rio Grande do Sul	Atlantic Rainforest	-50.99000°	-29.95000°	Borges-Martins et al. (2002)
Guaíba	Rio Grande do Sul	Atlantic Rainforest	-51.32000°	-30.11000°	Instituto Hórus (2007)
Ibarama	Rio Grande do Sul	Atlantic Rainforest	-53.12692°	-29.42114°	Instituto Hórus (2007)
Lajeado	Rio Grande do Sul	Atlantic Rainforest	-51.95792°	-29.44716°	Instituto Hórus (2007)
Muçum	Rio Grande do Sul	Atlantic Rainforest	-51.86931°	-29.16500°	Instituto Hórus (2007)
Nova Palma	Rio Grande do Sul	Atlantic Rainforest	-53.47223°	-29.47145°	Instituto Hórus (2007)
Nova Petrópolis	Rio Grande do Sul	Atlantic Rainforest	-51.14000°	-29.36000°	Borges-Martins et al. (2002)
Nova Roma do Sul	Rio Grande do Sul	Atlantic Rainforest	-51.40667°	-28.99972°	Instituto Hórus (2007)
Porto Alegre	Rio Grande do Sul	Atlantic Rainforest	-51.22000°	-30.04000°	Borges-Martins et al. (2002)
Santa Cruz do Sul	Rio Grande do Sul	Atlantic Rainforest	-52.43371°	-29.71577°	Instituto Hórus (2007)
Santa Maria	Rio Grande do Sul	Atlantic Rainforest	-53.82853°	-29.69524°	Instituto Hórus (2007)
Santa Tereza	Rio Grande do Sul	Atlantic Rainforest	-51.74586°	-29.16881°	Instituto Hórus (2007)
Taquari	Rio Grande do Sul	Atlantic Rainforest	-51.86026°	-29.80109°	Instituto Hórus (2007)
Tenente Portela	Rio Grande do Sul	Atlantic Rainforest	-53.76015°	-27.37591°	Borges-Martins et al. (2002)
Torres	Rio Grande do Sul	Atlantic Rainforest	-49.75560°	-29.34821°	Instituto Hórus (2007)
Veranópolis	Rio Grande do Sul	Atlantic Rainforest	-51.56000°	-28.94000°	Borges-Martins et al. (2002)
Viamão	Rio Grande do Sul	Atlantic Rainforest	-50.98000°	-30.09000°	Borges-Martins et al. (2002)
Campos Novos	Santa Catarina	Atlantic Rainforest	-51.24860°	-27.38399°	Present study (CFBH 13260)
Corupá	Santa Catarina	Atlantic Rainforest	-49.28181°	-26.43266°	Present study
Igrejinha	Santa Catarina	Atlantic Rainforest	-50.80000°	-29.58000°	Present study
Ipuaçú	Santa Catarina	Atlantic Rainforest	-52.40806°	-26.57067°	Present study (CFBH 7303)
Jaraguá do Sul	Santa Catarina	Atlantic Rainforest	-49.10000°	-26.48000°	Borges-Martins et al. (2002)
Campos do Jordão	São Paulo	Atlantic Rainforest	-45.58008°	-22.73046°	Instituto Hórus (2007)
Cotia	São Paulo	Atlantic Rainforest	-46.95245°	-23.74414°	Dixo and Verdade (2006)
Embu	São Paulo	Atlantic Rainforest	-46.83191°	-23.63990°	Present study (CFBH 11628)
Marília	São Paulo	Cerrado	-49.94580°	-22.21390°	Present study (DZSJRP 2644–45)
Pariquera-Açu	São Paulo	Atlantic Rainforest	-47.88330°	-24.71670°	Present study (DZSJRP 4961)
Pedro de Toledo	São Paulo	Atlantic Rainforest	-47.23137°	-24.28726°	Present study (CFBH 12711)
Piracicaba	São Paulo	Transition Atlantic Rainforest/Cerrado	-47.64000°	-22.71000°	Instituto Hórus (2007)
Rio Claro	São Paulo	Transition Atlantic Rainforest/Cerrado	-47.57117°	-22.35471°	Present study
São José dos Pinhais	Paraná	Atlantic Rainforest	-49.20640°	-25.53470°	Present study (DZSJRP 6226)
São José do Rio Preto	São Paulo	Cerrado	-49.37940°	-20.81970°	Present study (DZSJRP 1806)
São Luís do Paraitinga	São Paulo	Atlantic Rainforest	-45.13300°	-23.34600°	Present study (CFBH 12159)
São Paulo	São Paulo	Atlantic Rainforest	-46.64290°	-23.77614°	Present study (CFBH 10155)
Suzano	São Paulo	Atlantic Rainforest	-46.29992°	-23.56980°	Present study (CFBH 5626)
Ubatuba	São Paulo	Atlantic Rainforest	-45.13253°	-23.49728°	Present study (CFBH 13375)

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