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DISREGARDED DIVERSITY AND ECOLOGICAL POTENTIALS

Potential distribution of *Batrachochytrium dendrobatidis* in Argentina: implications in amphibian conservation

R. Ghirardi · M. G. Perotti · M. M. Steciow · M. L. Arellano · G. S. Natale

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Abstract Within the last two decades *Batrachochytrium dendrobatidis* (*B.d.*), the causative agent of chytridiomycosis, seems to have become a pandemic parasite, and is proposed as one of the more important causes of amphibian declines worldwide. In Argentina, the first report was in 2002 in *Leptodactylus ocellatus*. Since then, the fungus has expanded through different environments and species. In this study, we predict *B.d.* distribution in Argentina applying niche modelling based on reports of infected amphibians and environmental variables. The distribution hypothesis showed regions with highest suitability for *B.d.* including habitat types with (1) the most diverse amphibian fauna in Argentina such as the Paraná River Basin, (2) endangered species, such as north Patagonia and northwest Andean highlands, and (3) wide range of optimum precipitation and temperatures allowing development of *B.d.*

Keywords Chytridiomycosis · Ecological niche · Amphibian · Argentina

The chytrid fungus *Batrachochytrium dendrobatidis* (*B.d*) (Longcore et al., 1999) is the causative agent of the amphibians emerging infectious disease chytridiomycosis and is distributed worldwide. The earliest infection was identified in 1938 in a *Xenopus laevis* specimen from South Africa (Weldon et al., 2004) and since then *B.d.* has been recorded worldwide in a broad range of habitats (Mutschmann et al., 2000; Bradley et al., 2002; Weldon et al., 2004). Factors such as temperature (Woodhams et al., 2003; Piotrowski et al., 2004) and moisture (Johnson & Speare,

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R. Ghirardi (✉) · M. M. Steciow · M. L. Arellano
Instituto de Botánica Spegazzini, Facultad de Ciencias Naturales y Museo (UNLP), Calle 53 No 477, 1900 La Plata, Buenos Aires, Argentina
e-mail: romighirardi@yahoo.com.ar

R. Ghirardi
Instituto Nacional de Limnología (INALI-UNL-CONICET), Ciudad Universitaria, Paraje El Pozo, 3000 Santa Fe, Santa Fe, Argentina

M. G. Perotti
Laboratorio de Fotobiología, INIBIOMA (UNCOMA-CONICET), Quintral 1250, 8400, San Carlos de Bariloche, Río Negro, Argentina

M. M. Steciow · M. L. Arellano
Facultad de Ciencias Naturales y Museo (FCNyM-UNLP), Av. 60 y 122, 1900, La Plata, Buenos Aires, Argentina

G. S. Natale
Departamento de Química, Facultad de Ciencias Exactas (FCE-UNLP), Centro de Investigaciones y Medio Ambiente (CIMA), Calle 115 esquina 47, 1900 La Plata, Buenos Aires, Argentina

2003) have been suggested to be the most important environmental factors influencing growth and survival of *B.d.* under laboratory conditions and possibly control the prevalence of the pathogen and the timing of chytridiomycosis outbreaks in the field (Berger et al., 2004; McDonald et al., 2005; Woodhams & Alford, 2005; Kriger & Hero, 2006).

Recently, researchers have developed some techniques to predict ecologically suitable areas for the establishment of species in regions where they have not being found yet (Peterson & Vieglais, 2001; Peterson, 2003). This methodology builds an ecological niche model based on the values of environmental variables (niche dimensions) at known localities for the target species. Some global predictive models for the potential distribution of *B.d.* have been proposed (Ron, 2005; Puschendorf et al., 2009; Rödder et al., 2009). Ron (2005) described specific regions in South America such as the Brazilian Atlantic forest, the temperate forest in Chile and western Argentina (south to 30° S), northeastern Argentina, Uruguay and Paraguay. Later findings of the fungus in native and exotic species of nine countries in and around these regions support the hypothesis (i.e., Ron & Merino, 2000; Mazzoni et al., 2003; Seimon et al., 2005; Barrionuevo & Mangione, 2006; Carnaval et al., 2006; Fox et al., 2006; Barrionuevo et al., 2008; Ruiz & Rueda-Almonacid, 2008; Arellano et al., 2009; Borteiro et al., 2009; Ghirardi et al., 2009; Solis et al., 2009). In Argentina, the earliest evidence of this fungus dates from 2002 (Herrera et al., 2005), and since then new reports have expanded the extent of *B.d.* distribution to a wide range of environments in the country (Arellano et al., 2006, 2009; Barrionuevo & Mangione, 2006; Fox et al., 2006; Ghirardi et al., 2009).

Any attempt to limit further spread of the pathogen requires extensive knowledge of the current distribution of *B.d.* (Rödder et al., 2009). Therefore, our study in Argentina was focused on prediction of *B.d.* distribution through niche modeling based on reports of infected amphibians at different localities and by the use of environmental variables. Understanding the range of environmental factors favouring growth of this fungus will help us to promote conservation tools for more susceptible amphibian species in Argentina, expanding the monitored areas and focusing on species at risk.

For identifying potential areas of distribution of *B.d.* in Argentina, we elaborated prediction maps using the Genetic Algorithm for Rule-Set Prediction model (Desktop GARP v. 1.1.4) (Scachetti-Pereira, 2001). The GARP uses presence data of the target species and environmental variables, then to run the model we used localities of *B.d.* presence infecting amphibians in Argentina from published data (Herrera et al., 2005; Barrionuevo & Mangione, 2006; Fox et al., 2006; Arellano et al., 2006, 2009; Ghirardi et al., 2009) and 15 climatic variables extracted from the World Clim interpolated map database (30 s; ~1 km resolution) (Hijmans et al., 2005).

We generated 100 models (iterations) and choose the 20 most robust (Peterson, 2001; Ron, 2005). The resulting geographic predictions in the output maps were exported to ESRI ArcView (version 3.2) with the Spatial Analyst extension and were overlapped to obtain one definitive map of potential niche distribution for *B.d.* The suitable regions for *B.d.* in Argentina were classified with an Overlap Index (OI) from 0 to 1. To describe the areas we used the phytogeographical division of Argentina proposed by Cabrera (1976).

In the localities with positive *B.d.*, we used the zonal statistic routine to extract from the digital maps the environmental variables values from each point (ArcView 3.2, Spatial Analyst). These values were also used to run Principal Component Analysis (PCA; implemented in XLSTAT v.3.0) to visualize the degree of clustering in environmental space among Argentinean localities where *B.d.* was found.

We identified nine localities of known occurrence of *B.d.* infecting six amphibians' species (Herrera et al., 2005; Barrionuevo & Mangione, 2006; Fox et al., 2006; Arellano et al., 2006; 2009; Ghirardi et al., 2009).

Final map resulted with areas highly suitable for the presence of *B.d.* (OI > 0.7) dispersed irregularly over all country (Fig. 1). There are localities with highly suitable for the fungus in central and north regions of Phytogeographic Provinces (P.P.) of Yungas and Prepuneña (northwest of Argentina). Also, there is a highly suitable region in southern of Chaqueña P.P., a big portion of Espinal P.P., almost all Pampeana P.P., and a portion of Paranaense P.P. (northeast and central east Argentina) (Fig. 1). On the west of Argentina, there is also high probability of *B.d.* occurrence in some zones of Puneña P.P. and Monte P.P. Finally a huge extension of Patagonica P.P., and some isolates patches of Altoandina P.P. (Fig. 1).

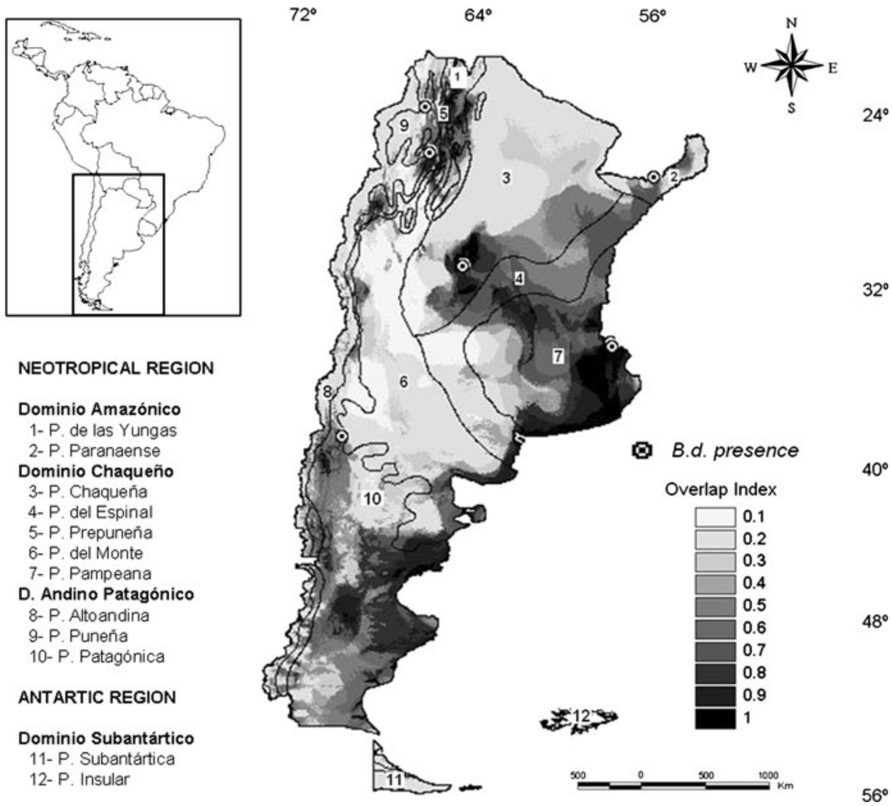

Fig. 1 Predicted distribution for *B.d.* presence in Argentina. *Circles* represent localities of known presence of *B.d.* used to construct the model

We found that OI varied among regions and was represented by different percentages of covered surface. Areas with OI = 1 (highest suitability for chytrid development) covered only 3.06 % of the total surface. Areas with $1 < \mathrm{OI} \geq 0.7$ covered 24.58 % of the country while areas with $7 < \mathrm{OI} > 0$ covered 66.86 %. Areas with OI = 0 (no probability of *B.d.* development) covered only 8.56 % of the total surface of Argentina (Fig. 1).

The environmental variables in the localities where *B.d.* was found show that suitable locations for the fungus are possible across a wide range of habitats (Table 1). In the localities with known presence of the fungus, the annual mean temperature ranged from 5°C (Prepuneña P.P.) to 21.4°C (Paranaense P.P.), moreover in areas where the OI = 1, the annual mean temperature ranged from 16.2°C to 17.2°C. Also our analysis shows that the presence of the fungus in Argentina is related to precipitations between 142 mm (Patagonica P.P.) and 1799 mm (Paranaense P.P.).

With eigenvalues >1, Principal Component I was positively correlated with (1) mean annual temperature, (2) minimum temperature in the coldest month, (3) annual precipitation, (4) precipitation of wettest month and (5) precipitation of coldest quarter, explaining 63.6% of the variance of the system. Principal Component II explained 19.0% and was highly positively correlated only with seasonal temperature, while Principal Component III explained 9.0% and was positively correlated with (1) mean diurnal range of temperature and (2) annual temperature range.

The large surface area of Argentina and its variable topography provide a unique and wide array of climates, vegetation patterns and aquatic environments. In this study, regions with highest incidence of *B.d.* include the habitats with the most diverse amphibian fauna in Argentina [*E. bicolor* from the Atlantic Forest (Paranaense P. P.), inhabit in one of the five biodiversity hotspots of South America (Myers et al., 2000; Conservation International 2005)] and some of them have endemic and endangered species [*T. atacamensis*: categorized as in critical danger of extinction, *T. pisanoi*: endangered and *A. patagonicus*: endangered (International Union for Conservation of Nature and Natural Resources (IUCN) 2007)].

Table 1 Environmental global conditions at all localities of known occurrence of *B.d.* in Argentina

Variable	Min	Max	Mean	SD
Mean annual temperature	5.0	21.4	14.7	4.8
Mean diurnal range	9.4	15.2	12.5	2.3
Isothermally	0.4	0.6	0.5	0.1
Temperature seasonality	33.2	54.2	44.5	6.1
Maximum temperature of warmest month	15.5	32.6	26.9	5.0
Minimum temperature of coldest month	−9.2	10.3	2.3	5.9
Annual temperature range	22.0	28.0	24.6	2.4
Mean temperature of wettest quarter	4.0	23.2	17.9	7.0
Mean temperature of driest quarter	0.3	17.1	10.1	4.5
Annual precipitation	142.0	1799.0	808.2	508.2
Precipitation of driest month	25.0	174.0	98.9	43.1
Precipitation of wettest month	0.0	95.0	31.6	33.8
Precipitation seasonality	14.0	102.0	48.8	35.2
Precipitation of warmest quarter	18.0	438.0	240.8	117.1
Precipitation of coldest quarter.	2.0	329.0	108.9	110.6

Values are estimated with random point generator (ArcView 3.2) from digital maps. Temperatures are in °C and precipitations in mm

The high risk areas emerged from our hypothesis are ecologically similar to those where the fungus has already been found in other parts of the world. However it is important to remember that these extrapolation algorithms only find regions that "resemble", in terms of the layers provided, those where occurrence points are located. Then, the rest of the process is an interpretation of results (Soberon & Peterson, 2005).

Ron (2005) predicted suitability regions for *B.d.* in the Brazilian Atlantic Forest, where declines in amphibians populations have been already reported (Heyer et al., 1988), although this declining has not been confirmed as a consequence of chytridiomycosis. In the present study, we report suitable areas for *B.d.* occurrence in some portions of Paranaense P.P., limited by the Brazilian Atlantic Forest to the east and north. Also, in the Pampas's plain (Pampeana P.P.) there is a high suitability predicted area, limited on the southwest by Uruguay, where there is a record of a captive population of *L. catesbeianus* crashed by chytridiomycosis (Mazzoni et al., 2003).

While there have been no reports of large scale mortality rates in Argentina yet, it seems very urgent to learn more about the dispersion and host range of *B.d.* to be more confident of finding useful information to generate conservation tools to protect native amphibians from a sudden outbreak of this disease.

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