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Recent decline and potential distribution in the last remnant area of the microendemic Mexican axolotl (*Ambystoma mexicanum*)

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ABSTRACT

Native populations of the axolotl (*Ambystoma mexicanum*), a microendemic salamander from Central Mexico, have seen alarming decline in the last decades owing to habitat loss caused by urban growth. The last remnant of its distribution is in a highly heterogeneous urban–rural water system in the Xochimilco region, at the southern edge of Mexico City. We developed a model of the species local distribution based on its ecological niche, using occurrence data and *ad hoc* limnetic variables via the Genetic Algorithm for Rule-set Production (GARP), to identify suitable areas for the species and prioritize conservation efforts. Results indicated that potential distribution of the axolotl in Xochimilco is limited to 11 sites in six reduced, isolated, and scattered areas, located mostly in zones where traditional agriculture (*chinampas*) is the primary land use. Recent surveys found only a single organism in the whole study region, in one of the predicted sites, suggesting a critical situation for the long-term survival of the axolotl in the wild, and demanding urgent actions toward habitat and population restoration. This study also illustrates the utility of niche modeling approaches for aquatic systems at a fine scale.

1. Introduction

In recent years, amphibian populations and species have suffered dramatic declines caused directly and indirectly by human activities (Beebee and Griffiths, 2005; Pounds, 2001). Amphibians are particularly sensitive to environmental change, so habitat alteration is likely to be a major direct cause for their decline (i.e., pollution and eutrophication of waterbodies; Collins and Storfer, 2003). Climate change has also been identified as an important indirect threat for amphibian populations in recent decades (Blaustein and Kiesecker, 2002; Pounds et al., 2006).

The axolotl (*Ambystoma mexicanum*), a neotenic salamander microendemic to the Mexican Central Valley (MCV), is among the species that have seen a dramatic population reduction due to habitat transformation (Zambrano et al., 2007). Originally, the whole MCV was occupied by a series of lakes and wetlands holding populations of this species. As Mexico City expanded throughout the valley, the axolotl distribution contracted down to its current last remnant in the Xochimilco area, in the southeastern portion of the MCV.

Xochimilco is a complex water system of $\approx$40 km^2 of artificial channels, small lakes and temporary wetlands between rural and urban areas (Zambrano et al., 2009). This system plays a key role in the hydrological dynamics (water provision and sewage) of Mexico City – *a* > 18 million people megalopolis. Most of the water of Xochimilco comes from treated water, whereas a much smaller amount comes from rainfall and springs. This area supports a diversity of activities and processes that directly impact water quality, such as traditional agriculture (*chinampas*), greenhouses, tourism, and urban development. This highly complex and dynamic water network produces a heterogeneous landscape, which directly impacts the habitat availability for the axolotl.

The current distribution of axolotls within Xochimilco is barely known, but direct and indirect evidence indicates that populations have been declining alarmingly in recent decades (Graue, 1998; Zambrano et al., 2007). Due to its low population numbers, *A. mexicanum* is in the IUCN Red List categorized as critically endangered, and is declared under special protection by the Mexican law (NOM-059-SEMARNAT-2001). It becomes urgent, thus, to identify those areas where axolotl populations still exist in order to carry out *in situ* conservation and restoration actions. As such, we present a spatial analysis for this salamander based on an ecological niche model to produce a predictive map, aiming to identify specific areas for searches for as-yet unknown populations (García, 2006; Guisan et al., 2006; Pawar et al., 2007; Raxworthy et al., 2003) and prioritize conservation efforts.

2. Methods

The ecological niche model for the axolotl was built with the Genetic Algorithm for Rule-set Production (GARP) system

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(Stockwell and Noble, 1992), using the desktop version 1.1.6 (http://www.nhm.ku.edu/desktopgarp/). In general, this algorithm detects non-random relationships between two sets of data: (a) georeferenced occurrence records of the species, and (b) a set of digital raster data layers representing environmental variables potentially relevant to determining the species' geographic distribution at that particular scale of analysis (Pearson and Dawson, 2003).

Traditionally, niche modeling in freshwater systems has been limited because raster data layers directly relevant to this realm are very scarce or non-existent for most regions in the world (Chen et al., 2007; McNyset, 2005; Wiley et al., 2003). Previous studies have had to rely on variables derived from terrestrial measurements as surrogates for aquatic dimensions (e.g., surface temperature and precipitation, Domínguez-Domínguez et al., 2006; Iguchi et al., 2004; Zambrano et al., 2006). In this study, such limitations were overcome by generating the environmental variables directly from field sampling.

2.1. Sources of data

2.1.1. Occurrence data

Axolotls were sampled with a cast net or "atarraya" (5.8 m diameter and 1/2-in. mesh size) from September 2002 to November 2003. Within this period of time, we performed 27 field trips, having at least one field trip per month. The survey was performed on seven channels, by casting at least 40 nets along each of the channels. In total, 1821 cast net throws were carried out. Each axolotl captured was weighed, measured, and released. Each site where the amphibian was captured was georeferenced.

2.1.2. Environmental layers

From June to September of 2004, eleven water physicochemical variables were measured, including: depth, temperature, pH, conductivity, salinity, turbidity, dissolved oxygen, percentage of oxygen saturation, nitrate, ammonium, and phosphate. The environmental variables chosen to build this GARP model are normally considered relevant for a good number of aquatic species (Wetzel, 1983) and particularly for amphibians. Some of these variables such as temperature, pH, oxygen, nitrates and ammonium are relevant in axolotls living in colonies (Kiesecker, 1996; Schrode, 1972).

Sampling site selection for environmental variables was based on finding those places suitable to generate an interpolation map. Therefore, sampled channels were selected using the following criteria: (1) channels with lengths over 500 m, (2) these channels were interconnected, and (3) channels with any length but in which axolotls were detected in the 2003 survey. With these criteria, a total of 59 points were selected across 40 channels and eight lakes. Sampling points were georeferenced with a portable GPS (Garmin III plus). The total length surveyed was 31,521 m, with an average channel size of 900 m (s.d. = 623).

A raster map was built for each environmental variable using the Inverse Distance Weighted (IDW) interpolation technique using the ArcMap 8.0 geographic information system (GIS; ESRI, 1999–2001), masking the analysis only to waterbodies. Final resolution (pixel size) of all raster layers was 1 m^2 (Zambrano et al., 2009).

2.2. Ecological niche modeling

The general procedure using GARP algorithm to build the niche model and projected map follows the next series of steps. First, input presence records are re-sampled to reach 1250 observations, and an equal number of points are selected randomly from pixels not holding presence records (pseudo-absences). These 2500 points are randomly divided in two equal groups, one for model training and the other one for model testing. Next, training data are used to generate a series of seed models via four different methods: a logistic regression and three environmental envelope rules. Seed models take the form of if-then statements ('environmental rules'), which are then evaluated using the testing dataset. After that, seed rules are perturbed mimicking chromosomal evolution (i.e., mutations, insertions, deletions) and evaluated again, if a daughter rule performs better than the seed rule, the former is retained in a population of rules. This process is repeated until a fixed number of iterations (1000 in this case) or until convergence (i.e., when model does not improve for more than 1% from one iteration to the next). Finally, the niche model is projected onto a geographic scenario to produce a binary map representing suitable (1) or unsuitable (0) environmental conditions for the species. A detailed description of GARP can be found elsewhere (Stockwell and Peters, 1999; Stockwell and Noble, 1992). In previous studies, GARP has proven reliable for predicting the geographic distribution of aquatic species (Domínguez-Domínguez et al., 2006; Iguchi et al., 2004; McNyset, 2005; Wiley et al., 2003; Zambrano et al., 2006).

Because GARP produces somehow different results from one run to the next using the same input dataset due to all the randomization involved in the process, we developed 100 independent prediction models for our analysis, from which we selected a subset of 10 best models based on two criteria: (1) A first set of 20 models with <10% omission error was selected. (2) From them, we selected the 10 models closest to the median in the area where the species was predicted as present (Anderson et al., 2003). These 10 models were then summed in a GIS, generating a consensus map with pixel values ranging from 0 to 10, where 0 represents areas in which all models predicted absence of the species and 10 represents areas where all models agree on predicting the species' presence. Finally, the consensus map was reclassified to build a presence/absence map, using as a threshold the minimum value in which all training occurrences were predicted (Lowest Presence Threshold or LPT).

Our final model was statistically validated using a jackknife method especially designed for low occurrence numbers (Pearson et al., 2007). In this procedure, each locality is removed once from the totality of occurrences and a model is built; predictive ability is then tested with the excluded locality. The same steps are repeated for each one of the localities of the whole set, which in our case were five. The number of predictive successes and failures are used to calculate a test criterion (D) and a p-value, which reflects the probability that observed success is better than random expectations. This test requires a threshold value for deciding the area predicted as present in each independent model, which in this case was established as the LPT, being the most conservative criterion (Pearson et al., 2007).

Once the predictive distribution map was built, verification surveys were carried out through 37 field trips from October 2005 to January 2006. Channel selection was based on 11 sites where the species was predicted to be present (five of them with prediction values above three in the GARP outputs) and 13 channels where axolotl was predicted as absent. All channels were distributed across the complete study area. Axolotl sampling methods were identical as in the previous survey, but with a total of 668 nets casted and at least 17 throws per channel.

3. Results

In the 2002–2003 surveys, 23 axolotls were found in only four sites, with a sampling effort of 0.013 organisms per throw. Channels and lakes where axolotls were found were scattered and separated by 1.5–4.0 km (Fig. 1).