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RESEARCH ARTICLE

Buying environmental problems: The invasive potential of imported freshwater turtles in Argentina

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Abstract

1. In recent years, decision-makers in Argentina have allowed the legal import of thousands of specimens of freshwater turtles. Given their invasive potential, many of the imported species have become established and have spread to other countries.
2. The three most commonly imported species recently have been *Graptemys pseudogeographica*, *Trachemys scripta*, and *Pseudemys nelsoni*, all of them native to North America.
3. This study assessed the invasive potential of these species in Argentina based on (i) bioclimatic envelope models, (ii) distribution of water bodies, (iii) location of the most populated cities, (iv) comparisons between their alien and native climatic niches, and (v) the main ecological traits of those species.
4. The results showed that these species are able to establish viable populations in Argentina, especially *T. scripta* and *G. pseudogeographica*. This is because the country offers a large amount of suitable climatic space for these species, in which there are large areas with rivers and other water bodies. The situation is especially problematic in freshwater ecosystems of the north east, as well as in the most populated portion of the country.
5. A range of regulatory policies are suggested, which could help to reduce biodiversity loss and economic impacts in the future.

KEYWORDS

alien species, conservation policy, niche overlap, species distribution modelling, *Trachemys scripta*

1 | INTRODUCTION

Biological invasions are one of the major causes of species extinctions worldwide (Gurevitch & Padilla, 2004; Lowe, Browne, Boudjelas, & De Porter, 2004). Furthermore, their impact on human activities generates huge economic losses every year (Charles & Dukes, 2007; Pimentel, Zuniga, & Morrison, 2005; Simberloff et al., 2013). The establishment of several alien species is associated with food production and the development of regional economies (Pimentel et al., 2005). However, for amphibians and reptiles, recreational activities such as collecting and the pet trade are the most significant reason for the establishment of alien species (Kraus, 2009). Among reptiles, freshwater turtles are probably the favourite species that are kept as pets (Bush, Baker, & Macdonald, 2014). As a result, many of these species have become established and dispersed outside their native range, generating multiple conservation problems in freshwater ecosystems (Cadi & Joly, 2004; Cadi et al., 2004; Ceballos & Fitzgerald, 2004). For example, alien species of freshwater turtles (e.g. the slider turtle *Trachemys scripta*) cause significant increases in the mortality of native species by competitive displacement (Cadi & Joly, 2004; Lever, 2003). In addition, some species of freshwater turtles can hybridize with related native species, generating offspring with a low fitness owing to the introgression of less adapted alleles, introducing strong genetic pollution and the potential loss of native genotypes (Figuereido, 2014; Parham et al., 2013). Another reported conservation problem is the disruption in the food-webs of aquatic ecosystems, associated with high population densities and the generalist feeding habits of these alien species (Ficetola, Rödder, & Padoa-Schioppa, 2012; Kikillus, Hare, & Hartley, 2010; Prévot-Julliard, Gousset, Cadi, Archinard, & Girondot, 2007), or

an adverse impact on bird life induced, for example, by basking activities of alien species in water-bird nesting sites (Lowe et al., 2004).

When several introductions take place under suitable climatic conditions, the probability of success of a new biological invasion is large (Bomford, Kraus, Barry, & Lawrence, 2009). Once established, invasive species generate complications with enormous ecological and economic costs, and eradication and habitat restoration becomes extremely difficult and expensive. Preventing the establishment is still the best and cheapest way to confront biological invasions (Simberloff et al., 2013). Recently, efficient methods and step-by-step approaches have been developed for assessing, over broad geographical scales, the invasive potential of alien species or 'potential invaders', and the likelihood of establishment on the basis of climatic tolerances (Broennimann et al., 2012; Gallagher, Beaumont, Hughes, & Leishman, 2010; Guisan, Petitpierre, Broennimann, Daehler, & Kueffer, 2014). The application of these advances through the interaction of science and policy could significantly reduce these problems.

Only one species of amphibian or reptile in Argentina – the American bullfrog – has invaded extensively (Akmentins & Cardozo, 2009; Nori, Akmentins, Ghirardi, Frutos, & Leynaud, 2011). To date there are only a few isolated records of non-native species of reptiles, mainly associated with urban centres, which apparently have not yet become established or dispersed within natural areas of the country (e.g. *Hemidactylus mabouia* and *Tarentola mauritanica*: Baldo, Borteiro, Brusquetti, García, & Prigioni, 2008). Nevertheless, it is worrying that one of the world's most invasive turtles, *T. scripta* (Lowe et al., 2004), never found before in Argentina, has now been recorded repeatedly in the last three years (Alcalde, Derocco, Rosset, & Williams, 2012; Prado et al., 2012; Quiroga, Gonzáles, & Akmentins, 2015).

The situation in Argentina is now alarming, as every year authorities allow the legal import and trade of thousands of individuals belonging to several species of freshwater turtles (Ministerio de ambiente y desarrollo sustentable de Argentina (Ministry of Environment of Argentina; Walter Prado, pers. comm.)), many of which hold great invasive potential (Masin, Bonardi, Padoa-Schioppa, Bottoni, & Ficetola, 2014). To make things worse, nothing is known about the potential of these massively imported species to establish and generate ecological problems and biodiversity losses in the country. The most densely populated areas of the country, and especially those large cities that receive international imports, are highly vulnerable to the arrival (and potential further establishment) of alien species. Moreover, the country harbours large and very diverse freshwater ecosystems, such as the Argentinian Litoral, which contains the Parana river basin, one of the most important worldwide (Bonetto, Neiff, & Di Persia, 1986; Olson et al., 2001). These kinds of ecosystems are also likely to be strongly affected by these potential new threats. Given this picture, studies on the distribution, trends and invasive risk of the freshwater turtles most widely imported can inform and guide conservation policies.

The main goals of this study were (1) to determine the invasive potential of the most widely imported freshwater turtles in Argentina, (2) to map places that are particularly vulnerable to species invasion, and (3) to suggest regulatory policies for controlling this situation. By offering this information to decision-makers, it should be possible to strengthen control of possession, trade and breeding of imported turtles in Argentina.

2 | MATERIALS AND METHODS

2.1 | Species records

Species were selected based on the list of imported freshwater turtles in Argentina from 2000 to 2012, kindly provided by the Ministry of Environment of Argentina. All species with more than 1000 legally imported individuals in the country during this period were selected: *Graptemys pseudogeographica* (2600 individuals), *Pseudemys nelsoni* (1875 individuals) and *T. scripta* (1185 individuals).

A database containing occurrence records from both the native (North America) and non-native (worldwide) geographical ranges of these species was compiled and organized. Relevant literature was searched (Bugter, Ottburg, Roessink, Grift, & Griffioen, 2011; Kikillus et al., 2010; Masin et al., 2014) and some native records, from the Global Biodiversity Information Facility (GBIF; www.gbif.org) were included. GBIF data have a certain degree of error, therefore only records derived from preserved specimens and deposited at scientific institutions located in the country of origin of the species were considered (following Maldonado et al., 2015). In addition, records were considered as native if they fell within the distributional ranges of each species published by the International Union for the Conservation of Nature (IUCN, 2015). For non-native ranges, only records of populations for which establishment has been explicitly confirmed were considered. Confirmation was obtained from various sources such as Alarcos, del Cueto, Rodríguez-Pereira, & Avia (2010), Bugter et al. (2011), Kikillus et al. (2010), Masin et al. (2014); unpublished information from Ravon Fundation (http://www.ravon.nl), United States Geological Survey (http://www.usgs.gov), and Rob Bugter, pers. comm.). The final database contained 446 individual records (222 records for *T. scripta*, 164 records of *G. pseudogeographica* and 60 records for *P. nelsoni*) (Figure S1 and Appendix S1 in Supplementary Material).

2.2 | Climatic variables

Pearson's correlation was run for 19 bioclimatic variables at a spatial resolution of 10 km, retrieved from WorldClim (www.worldclim.org; Hijmans, Cameron, Parra, Jones, & Jarvis, 2005) and five variables were selected based on their limited collinearity (<0.75). Selected variables were chosen with reference to the natural history and physiological limits of the species studied (Rödder, Schmidtlein, Veith, & Lötters, 2009). These species depend heavily on the availability of water bodies for survival, therefore annual precipitation and precipitation in the driest quarter were included in the models for determining availability of water for the species. Turtles are ectothermic, oviparous and mainly diurnal, so reproduction, activity periods, feeding and survival are all strongly related to the availability of thermal energy (Buckley, Hurlbert, & Jetz, 2012). Thus, the annual mean temperature (in accordance with an energy balance throughout the year; Rödder et al., 2009) and the mean diurnal range of temperatures were included as variables in the models. Since freshwater turtles are also influenced by vegetation cover and topography having specific characteristics (Ficetola et al., 2004), the mean average vegetation fraction 2000–2012 (Broxton, Zeng, Scheftic, & Troch, 2014) and the elevation (available from the WorldClim database) were included as additional variables.

2.3 | Bioclimatic envelope models

Bioclimatic envelope models (BEMs) were built to estimate climatically suitable places for the selected species in Argentina. There are many alternative BEM algorithms, with different levels of accuracy under different circumstances (Diniz-Filho et al., 2009). A proposed solution to take this variability into account is to combine different algorithms into ensembles in order to find 'areas of consensus' (as suggested by Araújo & New, 2007). Here, ensembles of different modelling techniques in the R package (R Core Team, 2014) biomod2 (Thuiller, Georges, & Engler, 2014) were generated. The ensemble included six different modelling methods: generalized additive models (GAMs), Classification Tree Analysis (CTA), multiple adaptive regression splines (MARS), random forest models (RFs), generalized linear models (GLMs) and generalized boosting models (GBMs). Models were calibrated using a subset of 70% of the records of each species, including records from both the native and the invasive range of the species (as suggested by Gallagher et al., 2010). Pseudo-absences were defined for model calibration as twice the number of presences.

The definition of the model training region has important implications for model outcome and evaluation (Barve et al., 2011; Lobo, Jiménez-Valverde, & Real, 2008), even for studies on invasive species (Nori, Urbina-Cardona, Loyola, Lescano, & Leynaud, 2011; Rodda, Jarnevich, & Reed, 2011), in which training areas must consider native but also invasive ranges (Gallagher et al., 2010). Here, the training regions were defined as a buffer surrounding the presences in order to avoid (a) including pseudo-absences in potential suitable places for the species where it has not been introduced (see Rodda et al., 2011), and (b) generating pseudo-absence in areas where dispersal of the species is impossible (Godsoe, 2010). Given the importance of considering the dispersal ability of the species in the definition of the training area (Barve et al., 2011), the buffer area was defined using the maximum distance between a population and its nearest population for each species. This could be interpreted as an extreme measure of the ability of the species to colonize far places.

Models were projected into limits of Argentina to map climatically suitable areas for the species. The maximum value of suitability without omission errors was used as a threshold value (as suggested by Rodda et al., 2011 for alien species). For model evaluation, the remaining 30% of the data were used to calculate the True Skill Statistics (TSS, Liu, White, & Newell, 2011) and the receiver operating characteristic area under curve (AUC, Fielding & Bell, 1997). This analysis was repeated five times, thus providing a five-fold internal cross-validation of models. True Skill Statistics values vary from −1 to +1, so values equal to or lower than zero imply a statistical fit that is no better than those generated at random. AUC values vary from 0 to 1, values higher than 0.5 being better than random. Final ensembles included only those projections with TSS higher than 0.4 and AUC higher than 0.7. Ensembles were calculated as an average of all these projections, weighted by their AUC values. Final maps show ensembles along water bodies and urban centres.

2.4 | Complementary analyses

To obtain additional measures of the invasive potential of species (in particular, to determine whether turtles shift their realized climatic niche during the invasion process), the overlap between native and non-native climatic niches of each species was compared and estimated using a niche overlap and similarity analysis based on Broennimann et al. (2012), available in the 'ecospat' package (Broennimann et al., 2012) of R (R Core Team, 2014). This analysis determines statistically whether a species is invading areas other than those climatically similar to their native range, which would indicate an even greater potential to spread in the non-native area than that predicted with BEMs.

These analyses were run only for *T. scripta* and *G. pseudogeographica*, because the database used does not contain alien populations of *P. nelsoni*. For each species, the non-native niche was characterized on the basis of alien records and the native niche on the basis of native records. For these analyses, exactly the same background zone (i.e. training area) was used. However, in order to obtain a more complete characterization of the environmental niches (as suggested by Broennimann et al., 2012), 19 bioclimatic variables available in WorldClim were used. Information on the main characteristics of habitat, diet and reproduction behaviour of each of the species was obtained from the literature (Table S1, Supplementary Material).

3 | RESULTS

Projections of BEMs for the three species performed well (see values of AUC and TSS in Figure 1). The resulting BEMs showed that Argentina offers large areas of suitable climatic space for *G. pseudogeographica* and *T. scripta*. In addition, in both cases, these climatically suitable regions contain a large area of rivers and other water bodies. Considering the 'suitability without omission' threshold, 1 341 570 km^2 would be suitable for *G. pseudogeographica* and 1 815 207 km^2 for *T. scripta*. Suitable areas were considerably smaller for *P. nelsoni* (79 530 km^2). The north-eastern region of the country would be the most climatically suitable for all species (Figure 1).

The analysis of niche overlap between native and invasive populations showed that the proportion of variance explained by the first two principal component analysis (PCA) axes was high for both species: 80.3% for *G. pseudogeographica* and 81.2% for *T. scripta*. Niche overlap between native and alien niches was low for both species 0.08 for *T. scripta*, and 0.25 for *G. pseudogeographica*. Niche equivalency was rejected for both species, i.e. niche equivalency tests confirmed that niches from the two species in the invaded regions are not identical to the native ones. The niche similarity tests indicate that the niche was more conserved than would be expected at random for *G. pseudogeographica* only (D = 0.25, similarity test invaded - > native: P = 0.009). In contrast, *T. scripta* does not show niche conservatism (D = 0.08, similarity test invaded - > native: P = 0.7). All species are generalists, i.e. they are found in a variety of habitats, have a non-specific diet and lay between 20 and 30 eggs in coastal sand banks (Table S1, Supplementary Material).

4 | DISCUSSION

It is not by chance that in the last three years the first feral specimens of *T. scripta* have been reported in Argentina (Alcalde et al., 2012;

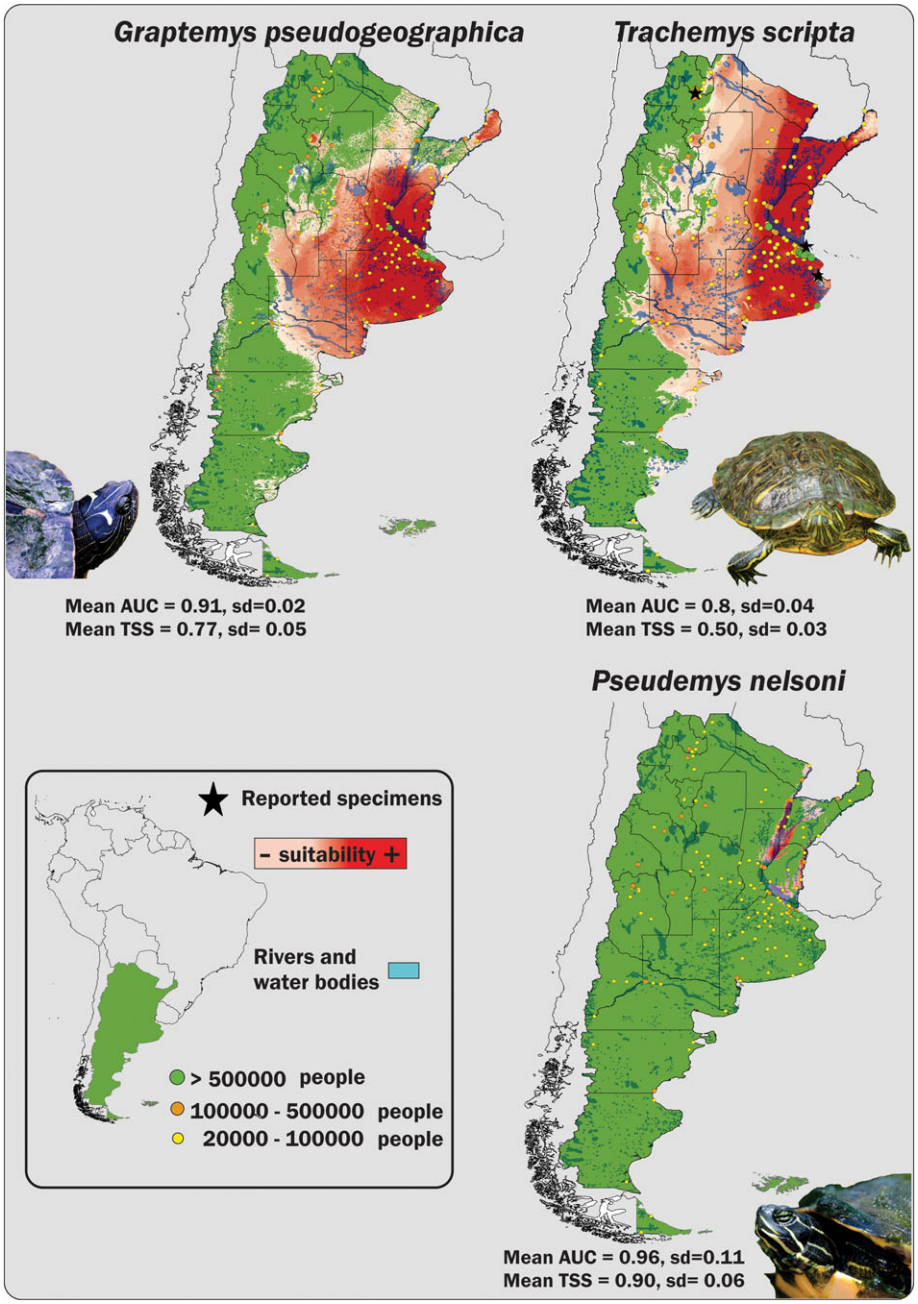

FIGURE 1 Maps showing final projections of the ensembles for each species in Argentina. Red gradient represents the climatic suitability of each pixel. Circles represent urban centres. Rivers and other water bodies are represented by light blue polygons

Prado et al., 2012; Quiroga et al., 2015). Argentinian decision-makers are walking a tightrope: if regulatory policies for the trade and holding of these freshwater turtles are not enforced urgently, new biological invasions may become established in the country soon. This is because two of the turtles most widely imported (*G. pseudographica* and *T. scripta*) have large areas that are climatically suitable, containing many water bodies in which the main ecological resources for the species would be available (both are quite generalist in relation to their diet, reproduction and breeding sites). These areas overlap with important urban centres in the country, which could act as sources of alien specimens. However, there is still time to change this situation and the rapid development of preventive measures could avoid ecological problems, impacts and associated costs (e.g. eradication and habitat restoration) in the future (Charles & Dukes, 2007; Pimentel et al., 2005; Simberloff et al., 2013). The picture is different for *P. nelsoni*, because climatically suitable areas are smaller for this species, and are far from the most populated areas of the country where the risk of introduction is higher. In addition, although this is a highly traded species, as far as we know there are no reports of established viable populations, suggesting a lower invasive potential.

The situation in the north-east region of the country is particularly worrying (including the provinces of Corrientes, Entre Rios, Santa Fe, Misiones and, to a lesser extent, Chaco and Formosa), because the area is highly suitable for all three species (for *P. nelsoni* only in the areas surrounding the Parana River and restricted parts of Entre Rios and Corrientes provinces). In addition, this extent corresponds to the Argentinian Litoral (including humid Chaco and Argentinian Mesopotamia; Olson et al., 2001), a region characterized by large rivers and many

other water bodies (Bonetto et al., 1986), potential habitats in which the species could become established and spread. This is also one of the most diverse regions for water-dependent vertebrates in the country, including part of the Atlantic Forest ecoregion, a biodiversity hotspot (Mittermeier et al., 2004; Olson et al., 2001). This region is inhabited by seven species of native freshwater turtles: *Trachemys dorbigni*, *Mesoclemmys vanderhaegei*, *Hydromedusa tectifera*, *Phrynops hilarii*, *Phrynops williamsi*, *Phrynops geoffroanus* and *Acanthochelys spixii*, which could be adversely affected by the alien species (Pearson, Avery, & Spotila, 2015).

Furthermore, a large portion of Buenos Aires province, with many potentially inhabitable water bodies, is highly suitable for two species (*T. scripta* and *G. pseudogeographica*). This region corresponds to the most populated area of the country, so introduction rates are likely to be particularly high. Other regions in the north-west part of Argentina, with important urban centres such as Tucuman, Córdoba, Mendoza and Jujuy, are also climatically suitable for these species. The trade and pet ownership of *T. scripta* and *G. pseudogeographica* should, therefore, be prohibited in these provinces. Not by chance, two of the three reported alien specimens of *T. scripta* in Argentina were found there but were quickly removed (Alcalde et al., 2012; Prado et al., 2012). However, given the antecedents, these areas (and those highly suitable in the north east of the country) should be systematically monitored and the individuals of the species removed to avoid potential establishment and its associated problems.

As stated in the Introduction, alien individuals of *Trachemys* are very prone to hybridizing when in contact with related species (Figuereido, 2014; Parham et al., 2013). This is a major threat to the native populations of *T. dorbigni*, given their proximity to the reported feral *T. scripta* specimens (in the north-eastern part of Buenos Aires province; Alcalde et al., 2012; Prado et al., 2012). It is very important to undertake strict monitoring in those areas, aimed at finding and removing new specimens. Moreover, genetic analyses are also needed to find out whether hybrid specimens are present.

Comparisons between invasive and native climatic niches revealed niche conservatism for *G. pseudogeographica* (Figure 2; see also Broennimann et al., 2012 and Guisan et al., 2014 for details). This result indicates that the native climatic niche of a species reflects its climatic tolerance (similar results have been found for other invasive species, e.g. Faleiro, Silva, de Carvalho, Särkinen, & De Marco, 2015; Palaoro, Dalosto, Costa, & Santos, 2013). However, results of this study also emphasised the extensive alien climatic niche of *T. scripta* and suggested that this species has the potential to establish alien populations in places that do not represent the native climatic tolerance of the species (Gallagher et al., 2010). The results are also consistent with those recently found by Rodrigues, Coelho, Varela,

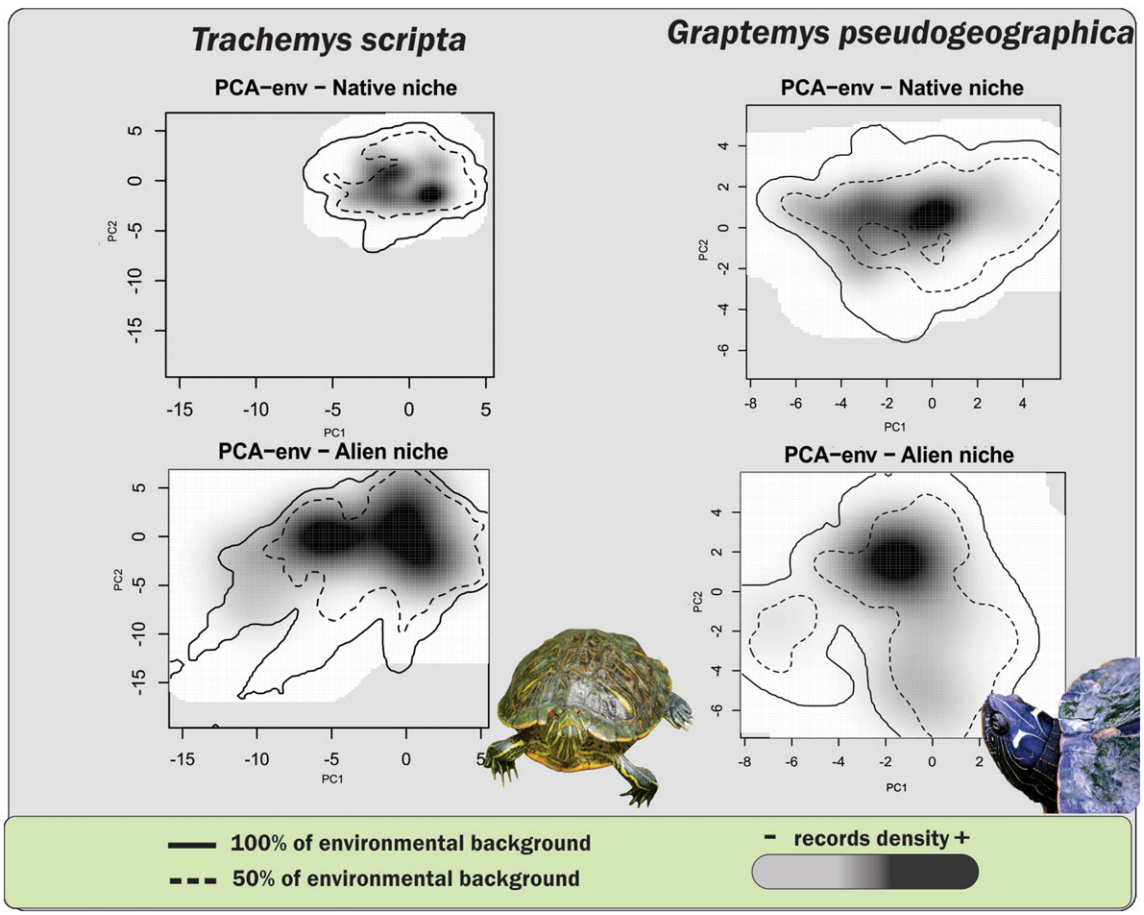

FIGURE 2 Each individual panel represents the niche of the species along the two first axes of the PCA in the North American native niche (upper) and non-native niche (lower). Grey shading shows the density of the occurrences of the species by cell. The solid and dashed contour lines illustrate 100% and 50%, respectively, of the available (background) environment

and Diniz-Filho (2016), providing additional evidence that this species has the potential to change its climatic niche when a new area is invaded – a clear proof of its great invasive potential (Figure 2). Such shifts in realized niches would suggest that the areas identified by BEMs may be underestimations of suitable areas, and that species might be able to establish viable populations in areas that are not predicted in the final map of this study.

Based on the results of BEMs, niche overlap analyses and ecological characteristics of the species, particularly vulnerable places have been determined, and important recommendations for the regulation of trade in freshwater turtles most widely imported to Argentina have been suggested. First, while all three species have the potential to establish viable populations in the country, results of this study show that the import and breeding of *T. scripta* should be strictly banned in the whole of Argentina. Otherwise, given its great invasive potential, this species could establish viable populations across very large areas of the country. Second, the trade and breeding of *G. pseudogeographica* must be prohibited in all of the northern and central provinces of the country. Third, the income and trade of any of the three species must be forbidden in Corrientes, Misiones and Entre Rios provinces where the most vulnerable freshwater ecosystems are located. The recommendations of this study should be considered seriously because an invasion of any of these species could present severe ecological problems and future economic losses associated with the eradication, habitat restoration and potential degradation of ecosystem services (see Introduction, and Simberloff et al., 2013).

Fortunately, Argentinian decision-makers seem to be increasingly aware of potential invaders in general. In fact, around 5% of the national territory (two of the 23 political provinces) have sanctioned policies to establish strict limitations to the trade and possession of non-native species (e.g. environmental provincial law 7343 of Cordoba Province, Argentina). It is hoped that most decision-makers in Argentina will use these policies as an example, at least for the particular species in key sites as reported here, and that interaction between scientists and decision-makers will help to prevent these kinds of ecological problems.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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