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Expert-based assessment of the climate change vulnerability of amphibians and reptiles of Uruguay

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Summary

Climate change (CC) is a major threat to biodiversity, increasing species extinction risk. Assessments of its possible impacts on species are crucial for designing conservation strategies. Here, we adjusted a global trait-based approach to the national level and apply it to Uruguay (South America) to evaluate the CC vulnerability of its herpetofauna. A total of 112 species were assessed in a scenario of CC projections for 2050 with regard to three dimensions of vulnerability: sensitivity, low adaptive capacity and exposure. We conducted the assessment through an expert elicitation process based on the Delphi method. We found that most local species (64.6% amphibians; 100% reptiles) were highly sensitive to CC. Among them, seven amphibians 14.6)%) and seven reptiles (10.9%) were identified as highly vulnerable to CC. Important gaps in the life-history traits of the species were found that should guide future research. The structured expert consultation process allowed us to gather more and better information than if it had only been based on published sources. Our study identified challenges associated with changing the scale from global to national that might be used for similar assessments in other countries.

Introduction

Human activities have contributed to increased global surface temperatures, which are currently 1.09°C above pre-industrial levels (IPCC 2022). Global climate change (CC) is recognized as a major threat to many species and to the integrity of whole ecosystems (Pereira et al. 2010, IPCC 2018, 2022). The impacts of CC on biodiversity are already evident for multiple taxa (Pereira et al. 2010, Pacifici et al. 2017) and include shifts in species ranges (e.g., Pounds et al. 1999), changes in phenology (e.g., Walther et al. 2002) and epidemic disease emergencies (e.g., Pounds et al. 2006), which in turn may affect fitness, increasing extinction risk (Pounds et al. 2006, Berriozabal-Islas et al. 2020).

Assessments of the possible deleterious impacts of CC on species performances are crucial for designing conservation strategies. Research related to the CC vulnerability of species is rapidly increasing worldwide (Foden et al. 2019). Although different approaches have been proposed, trait-based assessments have been adopted by many researchers and conservation organizations (Young et al. 2015, Foden et al. 2019). These assessments are built on known or inferred associations between biological traits and possible negative impacts of changes in climatic conditions (Foden et al. 2019). Foden et al. (2013) developed a framework to assess the relative vulnerability of species to CC, and this has been used in several investigations with different biological groups, including corals (Foden et al. 2013), amphibians (Foden et al. 2013, Carr et al. 2014), reptiles (Carr et al. 2014, Böhm et al. 2016, Meng et al. 2016), birds (Foden et al. 2013, Carr et al. 2014, Borges et al. 2019) and mammals (Carr et al. 2014). This framework allows three dimensions of CC vulnerability to be independently assessed: sensitivity, low adaptive capacity and exposure (Foden et al. 2013). 'Sensitivity' in this sense is the lack of potential for a species to persist *in situ* given a certain CC scenario, and it is directly related to life-history traits. 'Low adaptive capacity' implies the inability of a species to endure the negative impacts of CC by dispersal and/or micro-evolutionary changes. 'Exposure' refers to the magnitude and rate at which a species' physical environment is expected to change due to CC (Foden et al. 2013, Carr et al. 2014).

Global vulnerability assessments provide comprehensive pictures of different taxa and facilitate comparisons at a large scale, while regional and country-level analyses are needed for conservation decision-making (Di Minin et al. 2017). Biological information of local populations is often available in local grey literature. Working at finer scales with local field researchers enables data gathering on valuable and variable attributes that would not be available otherwise (Grattarola et al. 2020). Additionally, some species' attributes are sensitive to scale (Ficetola et al. 2018).

In the case of ectothermic organisms such as amphibians and reptiles, humidity and temperature are of particular relevance as they may constrain the timing of several physiological and demographic processes (Wells 2007, Sinervo et al. 2010). Examples of CC impacts on the conservation status of many amphibians and reptiles have been reported elsewhere (e.g., Pounds et al. 1999, Reading 2007). Studies assessing their vulnerability to future CC at global (e.g., Foden et al. 2013, Böhm et al. 2016), regional (e.g., Carr et al. 2014) and local scales (e.g., Laufer 2012, Meng et al. 2016) suggest a range of possible scenarios in which some species would be imperilled. The vulnerability of Uruguayan herpetofauna to CC has been previously evaluated as well (Laufer 2012, Toranza et al. 2012). However, over the last decade, Uruguay has undergone significant changes in land use, mostly agriculture intensification, exotic afforestation and urbanization (Brazeiro et al. 2020). In addition, recent taxonomic changes (e.g., reports of new species and the synonymization of others) and relevant data on life-history traits of many species have also accumulated. These suggest that an updated assessment of the Uruguayan herpetofauna's vulnerability to CC is necessary.

We assessed the relative vulnerability of Uruguayan continental amphibians and reptiles to CC, including 48 amphibian and 64 reptile native species (Frost 2021, Uetz et al. 2021). We excluded alien species occurring in Uruguay: two reptiles (*Hemidactylus mabouia* and *Tarentola m. mauritanica*) and one amphibian (*Lithobates catesbeianus*). To conduct the assessment, we applied the global approach proposed by Foden et al. (2013) with proper adjustments for its use at this level. The evaluation was implemented through an expert elicitation process based on the Delphi method. This process allowed us to identify data gaps in life-history traits, discuss the challenges associated with the change of scale and compare our results with the International Union for Conservation of Nature (IUCN) Red List for Uruguay.

Methods

Study region

Located in the southern Neotropical region (Morrone 2015), Uruguay's climate is temperate wet with average annual precipitation of 1200–1600 mm (statistical period 1980–2009) over a latitudinal range of 30–35°S. The average annual temperature is 17.7°C, varying from 19.8°C in the extreme north-west to 16.6°C over the south-eastern Atlantic coast (MGAP-FAO 2012). The landscape mostly consists of rolling plains, with some low hilly areas up to 513 m altitude, and it is part of the Pampas biome with influences from the Chacoan and Paranaense biogeographical provinces (MVOTMA 2010, Morrone 2014). Uruguay has a coastline of *c*. 670 km (Evia & Gudynas 2000).

Climate change vulnerability framework

We assessed species vulnerability to CC using the sensitivity, low adaptive capacity and exposure dimensions of Foden et al. (2013). The most vulnerable taxa are those exposed to CC, presenting high sensitivity and low adaptive capacity (Fig. 1). Appropriate traits were selected for each dimension during the expert elicitation process (Tables 1 & 2 & Supplementary Appendix S1, available online). Species received the scores 'low', 'high' or 'unknown' for each trait. Those that scored 'high' in at least one of the traits of a dimension were classified as 'high' with regard to that dimension. Species qualifying as 'high' in all three dimensions were considered to be highly vulnerable to CC. Species were also classified as potential adapters (i.e., sensitive and exposed but highly adaptable), potential persisters (exposed with low adaptive capacity but not sensitive) or with high latent risk (sensitive with low adaptive capacity but currently not exposed; Fig. 1).

Fig. 1. Framework to assess vulnerability to climate change (CC): 1 – highly vulnerable species: sensitive, with low adaptive capacity and exposed to CC (greatest concern); 2 – potential adapters: sensitive and exposed species but highly adaptable; 3 – potential persisters: exposed species with low adaptive capacity but not sensitive; 4 – high latent risk: sensitive species with low adaptive capacity but not exposed at the moment. Modified from Foden et al. (2013).

For the assessment of sensitivity, we used the following trait sets: specialized habitat and/or microhabitat requirements; narrow environmental tolerance or thresholds that are likely to be exceeded due to CC at any stage in the life cycle; dependence on a specific environmental trigger or triggers likely to be disrupted by CC; and dependence on interspecific interactions that are likely to be disrupted by CC. For low adaptive capacity, we used the following trait sets: poor dispersibility; and poor evolvability. Finally, for exposure, we used the following trait sets: exposure to sea-level rise; and range decline due to shift in climatic conditions (described in Appendix S1).

Temperature and precipitation inferences were based on the local and regional climatic projections that rely on the ensemble of four general circulation models (ACCESS1.0, CanESM2, CCSM4 and HadGEM2) presented by Nagy et al. (2016), who considered two emissions scenarios (4.5 and 8.5 Representative Concentration Pathways (RCPs)) for 2050 (2040–2060; Appendix S1 & Figs S1 & S2). The cited authors also calibrated satellite data with tidal scales installed at different places over the Uruguayan coast. The coastal zones of Uruguay are considered to be among the most exposed to extreme events and sea-level rise in Latin America (Losada et al. 2013).

Expert elicitation and score integration

The trait-based vulnerability assessment was implemented through a structured elicitation process based on the Delphi method, combining expert judgement with data collection, in an anonymous and iterative way. Anonymity minimizes the social pressures of group approaches but poses the risk of a lack of

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Table 1. Traits of amphibians considered for the three dimensions of climate change vulnerability.

Trait group	Trait	Description	Thresholds
Sensitivity			
A. Specialized habitat and/or microhabitat requirements	Habitat specialization	Number of IUCN habitat types a species occurs in	Low > 1 High = 1
	Dependence on a particular microhabitat	Freshwater-dependent larval development and occurs exclusively in an unbuffered habitat (i.e., not forest)	Low = False High = True
B. Narrow environmental tolerances or thresholds that are likely to be exceeded due to climate change at any stage in the life cycle	Physiological tolerance (distributional range and latitude)	Species that present moderate regional distribution (i.e., north limit of it is ≥26°S)	Low = False High = True
C. Dependence on a specific environmental trigger or triggers likely to be disrupted by climate change	Dependence on an environmental trigger	Explosive breeder on rainfall or increased water availability cue and with few reproductive events per year (not in forest)	Low = False High = True
D. Dependence on interspecific interactions that are likely to be disrupted by climate change	Increasing negative interactions with other species	Increasing negative interactions with other species (i.e., competition and predation)	Low = False High = True
	Diet specialist	Diet composed mainly of up to three categories of prey[a]	Low > 3 categories High ≤ 3 categories
	Increasing susceptibility to diseases	Record of infection by *Batrachochytrium dendrobatidis* or probable future infection or another pathogen	Low = False High = True
Low adaptive capacity			
A. Poor dispersibility	Low intrinsic dispersal capacity	Species has not become established outside its natural range, not associated with flowing water and range size ≤4000 km^2	Low = False High = True
	Extrinsic barriers to dispersal	Fragmented distribution in Uruguay due to barriers (including urbanization and/or inadequate microhabitats) and/or occurs only in the hilly range (in Uruguay)	Low = False High = True
B. Poor evolvability	Low reproductive capacity	Annual reproductive output ≤50 or viviparous	Low = False High = True
Exposure			
A. Exposure to sea-level rise	Habitat types exposed to sea-level inundation	Occurs largely in inundation-exposed coastal habitats (i.e., coasts of Rio de la Plata, Atlantic Ocean or rivers) and at most one other habitat type in Uruguay	Low = False High = True
B. Range decline due to shift in climatic conditions	Latitudinal range of the species	Species has its northern distribution boundary in Uruguay (≥30°S latitude)	Low = False High = True

[a] Food categories: spiders, ticks, other mites, cockroaches, mantises, butterflies, moths, beetles, bees, aphids, cicadas, fleas, flies, dragonflies, ants, centipedes, millipedes, non-arthropod invertebrates, amphibians, fish and birds.
IUCN = International Union for Conservation of Nature.

accountability in the responses. This problem was limited through a face-to-face discussion workshop after the anonymous responses were received (Mukherjee et al. 2015).

The expert consultation process consisted of three stages: pre-elicitation (planning the consultation); the elicitation itself; and post-elicitation. The first stage involved the definition of objectives and gathering contextual information, identifying a group of experts, clarifying the number of rounds, selecting which items remained in successive rounds and determining how the level of consensus was going to be quantified (Diamond et al. 2014, Mukherjee et al. 2015).

The number of rounds established *a priori* was two in order to avoid participant fatigue and a higher attrition rate (Powell 2003). Groups of four experts on amphibians (Claudio Borteiro, Diego Baldo, Carlos Prigioni and Gabriel Laufer) and three experts on reptiles (the same experts as for amphibians except Diego Baldo) were invited to participate as co-authors. A primary session was conducted as an online workshop to introduce the methodology. Subsequently, we organized a second workshop to define the traits to include, in which we selected those relevant for the evaluation that we considered would offer useful information for scoring the Uruguayan herpetofauna. Additionally, the arbitrariness of some thresholds used to set the scores can be problematic (Foden et al. 2019). To avoid this, discussions were held to define the thresholds as clearly and objectively as possible. This resulted in the selection of seven traits for the sensitivity dimension of amphibians, three traits for low adaptive capacity and two for exposure (Tables 1 & S1). For reptiles, eight traits were selected for sensitivity, four for low adaptive capacity and two in the case of exposure (Tables 2 & S2).

For the first round, experts were provided with a document containing the methodology and a spreadsheet containing the list of species and traits to be considered. Each expert conducted an initial individual round of evaluation, in which every species was assigned scores of 'low', 'high' or 'unknown' for all traits based on published and grey literature, their own field knowledge or inference from related species (as occurred for the diets of *Melanophryniscus atroluteus*, *Melanophryniscus devincenzii*, *Melanophryniscus lanogonei*, *Melanophryniscus pachyrhynus* and *Melanophryniscus sanmartini*). The 'unknown' category was used when the expert did not feel confident in supporting a trait assignment using the data available, thus avoiding scoring with high uncertainty. The first round of responses was integrated, leaving

Table 2. Traits of reptiles considered for the three dimensions of climate change vulnerability.

Trait group	Trait	Description	Thresholds
Sensitivity			
A. Specialized habitat and/or microhabitat requirements	Habitat specialization	Number of IUCN habitat types a species occurs in by expert criterion	Low > 1 High = 1
	Dependence on a particular microhabitat	Species is dependent in one or more of the identified microhabitats[a]	Low = False High = True
B. Narrow environmental tolerances or thresholds that are likely to be exceeded due to climate change at any stage in the life cycle	Physiological tolerance (distributional range and latitude)	Species that present moderate regional distribution (i.e., northern limit of it is ≥26°S)	Low = False High = True
	Tolerance of flooding/ waterlogging	Species relies upon a specific flooding regime (or lack thereof) across its entire range	Low = False High = True
	Temperature-dependent sex determination	Sex of offspring is known to be dependent on temperature during incubation	Low = False High = True
C. Dependence on a specific environmental trigger or triggers likely to be disrupted by climate change	Dependence on an environmental trigger	Species relies upon a change in weather/ climate to initiate one or more of the following: breeding; egg deposition; arrival of prey (e.g., following tree fruiting); aestivation (or emergence from)	Low = False High = True
D. Dependence on interspecific interactions that are likely to be disrupted by climate change	Diet specialist	Species' diet consists of a low number of species from a single dietary category[b]	Low = False High = True
	Interspecific habitat creation/modification	Species is dependent upon another to modify or create habitat suitable for itself	Low = False High = True
Low adaptive capacity			
A. Poor dispersibility	Low intrinsic dispersal capacity	Species has not become established outside its natural range and is not associated with water flow and the size of the range ≤4000 km^2; or species is fossorial	Low = False High = True
	Extrinsic barriers to dispersal	Verification of fragmented distribution in Uruguay due to barriers (including urbanization) and/or inadequate microhabitats and/or occurs only in the hilly range (in Uruguay)	Low = False High = True
B. Poor evolvability	Low reproductive capacity	Reproductive output (mean litter size × mean number of litters per year)	Low = Highest 75% High = Lowest 25%
	Genetic turnover	Generation length (here replaced by longevity as a proxy for generation length)	Low = Shortest 75% High = Longest 25%
Exposure			
A. Exposure to sea-level rise	Habitat types exposed to sea-level inundation	Occurs largely in inundation-exposed coastal habitats (i.e., coasts of Rio de la Plata, Atlantic Ocean or rivers) and at most only one other habitat type in Uruguay	Low = False High = True
B. Range decline due to shift in climatic conditions	Latitudinal range of the species	Species has its northern distribution boundary in Uruguay (≥30°S latitude)	Low = False High = True

[a] Identified microhabitats: streams or ravines in Uruguayan hilly range; ephemeral ponds, vines, fallen trees, dead wood, tree hollows, trees at the water's edge, gallery or riparian forests, anthills, termite mounds, dunes, open patches in grasslands, rocky areas and outcrops, cliffs and caves; freshwater or forest dependent.
[b] Food categories: leaf matter; fruit; seeds; nectar; a single taxonomic group of arthropod; a range of arthropods; other invertebrates; small mammals ≤300 mm snout–vent length; large mammals >300 mm snout–vent length; adult/subadult birds; bird eggs/juveniles; adult/juvenile reptiles; reptile eggs; adult amphibians; amphibian larvae; freshwater fish; faeces; and an 'other' category for anything outside of these parameters.
IUCN = International Union for Conservation of Nature.

for the second round of anonymous consultations only those species for which there was no full consensus (i.e., no total agreement of the experts for a given score). At the second and last round, experts were supplied with the anonymous answers of their counterparts from the first round and the same spreadsheet format previously used. By doing this, each participant could carefully reconsider their own answers in case of doubt.

For score integration, when the majority of the experts agreed on a given score, that score was assigned to the trait. When score assignments were tied, the traits were considered as 'high' when they competed with any other score and 'low' when the alternative was 'unknown'. To account for the uncertainty, we repeated the analysis treating the 'unknown' scores as 'low' in an optimistic scenario (results in main manuscript; Tables S3–S8) and as 'high' in a pessimistic one (results in Tables S5, S6, S9 & S10).

Results

For most of the species and traits analysed, the available information enabled the assessment to be completed. Yet there were some important data gaps. For instance, in the case of amphibians, the trait 'increasing susceptibility to diseases' was scored as 'unknown' for 62.5% of the species (Fig. 2 & Tables S1 & S3). Reptile data gaps were more important for 'generation length' (73.4% of species)

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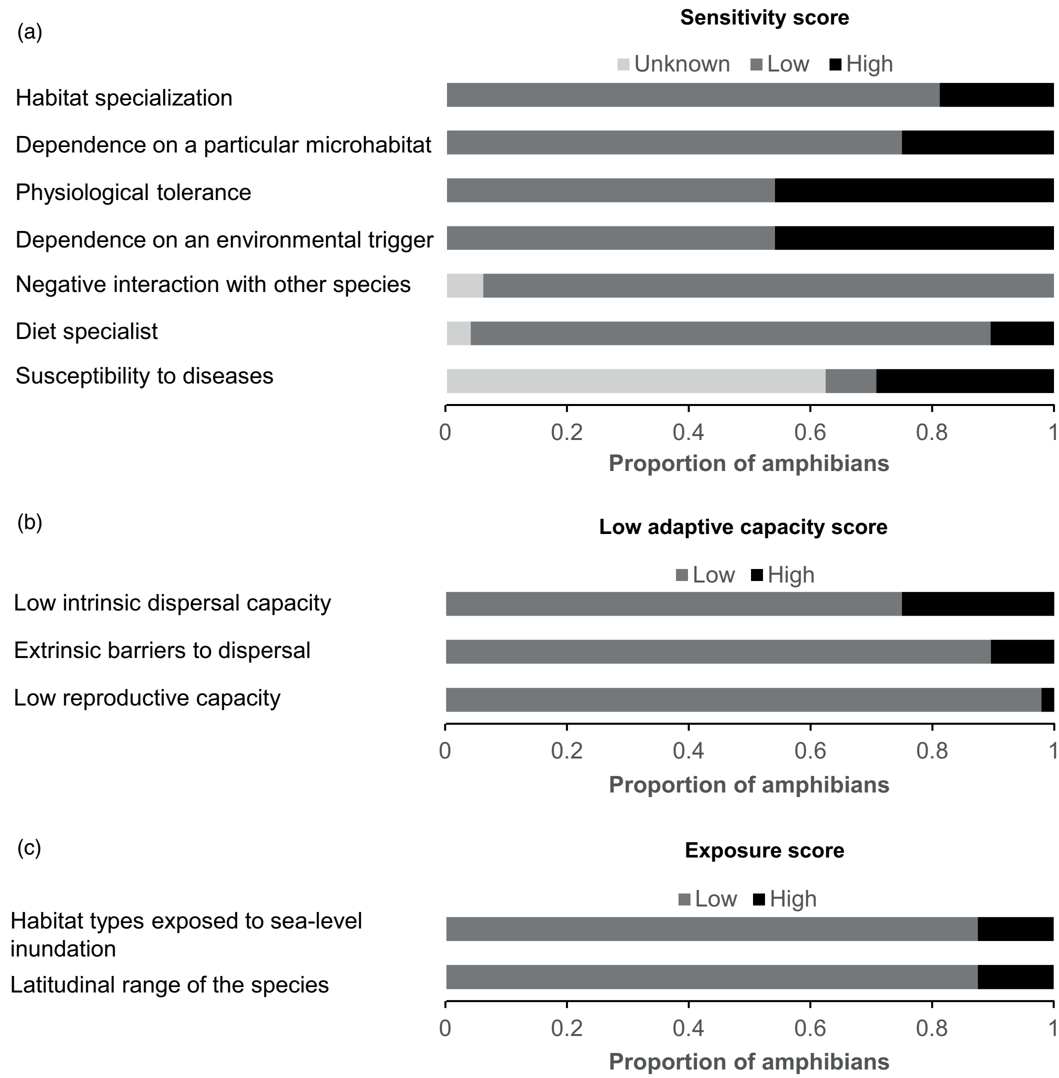

Fig. 2. Proportions of amphibian species classified as 'high', 'low' or 'unknown' for each trait considered for the three dimensions of vulnerability: (a) sensitivity score, (b) low adaptive capacity score and (c) exposure score.

and, to a lesser extent, 'temperature-dependent gender' (12.5%; Fig. 3 & Tables S2 & S4). However, data gaps viewed at the species level were of less importance, providing strong support for the analysis.

Seven amphibians and seven reptiles were classified as highly vulnerable to CC (i.e., qualifying as vulnerable in all three dimensions), representing 14.6% and 10.9%, respectively, of the species assessed from both groups (Fig. 1 & Table 3). One amphibian was categorized as a potential adapter (i.e., sensitive and exposed but adaptable). Six amphibians and 19 reptiles (12.5% and 29.7%, respectively) were presented as bearing high latent risk (sensitive with low adaptive capacity but currently not exposed). There were no species classed as potential persisters (exposed with low a daptive capacity but not sensitive), while 17 amphibians and 38 reptiles were only seen as sensitive (35.4% and 59.4%, respectively; Tables 3, S7 & S8).

Regarding sensitivity, 64.6% of amphibians and 100% of reptiles were scored as highly sensitive to CC (Tables S1–S4). The traits that contributed the most for amphibians were 'physiological tolerance' (45.8% of the species) and 'dependence on an environmental trigger' (45.8%; Fig. 2), while those for reptiles were 'dependence on an environmental trigger' (98.4%), followed by 'temperature-dependent gender' (67.2%; Fig. 3).

Remarkably, most of the studied species were presented as being potentially adaptable to CC, as only 13 amphibians (27.1%) and 26 reptiles (40.6%) presented low adaptive capacity (Tables S1–S4). For amphibians, the trait that contributed the most in this regard was 'low intrinsic dispersal capacity', which scored high in 25% of the species (Fig. 2 & Table S3), with seven of them showing poor adaptability exclusively due to this. For reptiles, the trait that contributed the most in this regard was 'low reproductive capacity' (21.9%), with six species meeting the criteria for poor adaptability exclusively due to this trait. The next most common trait for reptiles scoring 'high' in this regard was 'low intrinsic dispersal capacity' (18.8%; Fig. 3 & Table S4).

Only eight amphibians (16.7%) and seven reptiles (10.9%) were rated as exposed to CC (Tables S1–S4). For amphibians, the two traits defined for this dimension ('habitat types exposed to sea-level inundation' and 'latitudinal range of the species') contributed equally (12.5% of species). For reptiles 'latitudinal range of the species' contributed the most (7.8%; Figs 2 & 3 & Tables S3 & S4).

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Table 3. Number and percentage of species in each of the four climate change vulnerability categories. Numbers in parentheses represent a pessimistic scenario (i.e., treating 'unknowns' as 'high'). Crosses represent dimensions classified as 'high', dashes represent dimensions classified as 'low'.

				Amphibians		Reptiles	
Vulnerability category	Sensitivity	Low adaptive capacity	Exposure	No.	%	No.	%
Highly vulnerable (1)[a]	×	×	×	7 (7)	14.6 (14.6)	7 (7)	10.9 (10.9)
Potential adapters (2)	×	–	×	1 (1)	2.1 (2.1)	0 (0)	0 (0)
Potential persisters (3)	–	×	×	0 (0)	0 (0)	0 (0)	0 (0)
High latent risk (4)	×	×	–	6 (6)	12.5 (12.5)	19 (53)	29.7 (82.8)
Sensitive only	×	–	–	17 (34)	35.4 (70.8)	38 (4)	59.4 (6.3)
Low adaptive capacity only	–	×	–	0 (0)	0 (0)	0 (0)	0 (0)
Exposed only	–	–	×	0 (0)	0 (0)	0 (0)	0 (0)
None	–	–	–	17 (0)	35.4 (0)	0 (0)	0 (0)
Total number of species				48	100	64	100

[a]Numbers in parentheses represent the climate change vulnerability categories indicated in Fig. 1.

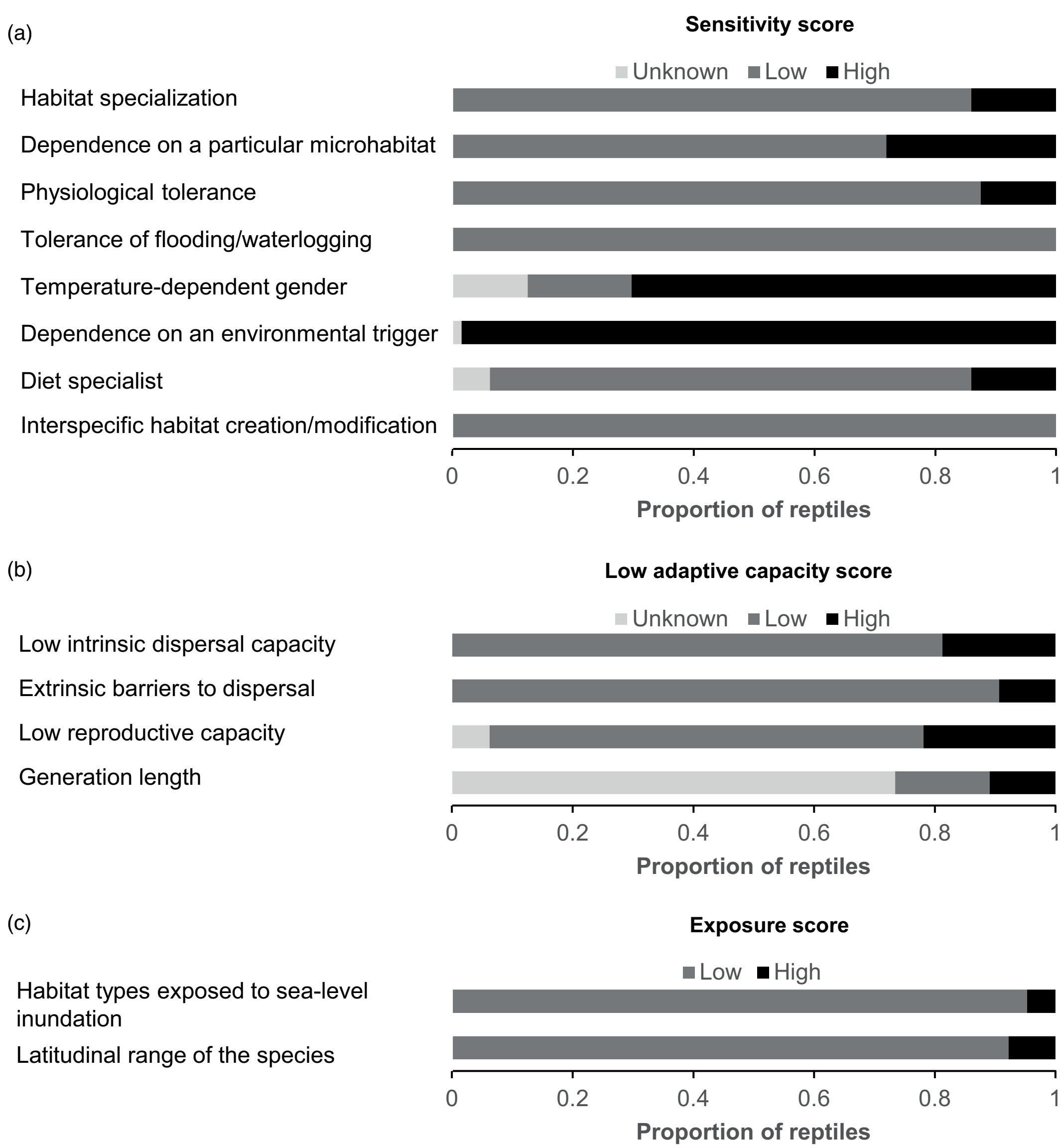

Fig. 3. Proportions of reptile species classified as 'high', 'low' or 'unknown' for each trait considered for the three dimensions of vulnerability: (a) sensitivity score, (b) low adaptive capacity score and (c) exposure score.

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Four of the seven amphibian species (57.1%) classified here as highly vulnerable to CC were also categorized as Threatened according to the IUCN Red List for Uruguay (& Table S7). On the other hand, only two of the seven reptile species classified herein as highly vulnerable to CC (28.6%) are locally threatened (Table S8).

Discussion

We identified 14 species of the continental Uruguayan herpetofauna as highly vulnerable to CC, with almost two-thirds of amphibians and all reptiles being highly sensitive. Many of these species are strongly influenced by specific environmental factors affected by CC. This is more evident in reptiles, which are highly dependent on weather/climate signals for reproduction (e.g., Balestrin & Cappellari 2011, Verrastro & Rauber 2013). Similarly, nearly half of the local amphibian fauna are explosive breeders depending on the rainfall regime (Kolenc 1987, Moreira et al. 2014).

Highly vulnerable amphibians share some biological characteristics such as being explosive breeders with few reproductive events per year and small geographical ranges. Most of these species (*M. langonei*, *M. montevidensis*, *M. sanmartini*, *Ceratophrys ornata*, *Odontophrynus maisuma* and *Physalaemus fernandezae*) are local habitat specialists (García 1972, Kolenc 1987, Rosset 2008). Additionally, populations of *M. montevidensis*, *C. ornata*, *O. maisuma* and *Nyctimantis siemersi* seem to depend on coastal habitats (García 1972, Prigioni & Garrido 1989, Rosset 2008). These frogs may be severely affected by an increase in sea level. Additionally, *M. langonei* and *M. sanmartini* dwell exclusively in hilly areas, and these species plus *M. montevidensis*, *C. ornata* and *O. maisuma* also depend on seasonal ephemeral environments (García 1972, Prigioni & Garrido 1989, Borteiro et al. 2010) that are very fragile and would be particularly affected by CC (Foden et al. 2013).

On the other hand, it was suggested that some amphibians with northern distributions in the country are likely to expand their geographical ranges in a southwards direction (Toranza et al. 2012). In the case of *Dendropsophus minutus*, *Scinax nasicus*, *Scinax fuscovarius* and *Physalaemus riograndensis*, local southwards expansions have been already observed (Laufer et al. 2021b). This phenomenon, if occurring in reptiles (i.e., ophidians), would be more difficult to observe due to the magnitude of the sampling effort required.

All of the highly vulnerable reptiles are dependent on weather or seasonal changes to initiate breeding or egg deposition (Balestrin & Cappellari 2011, Verrastro & Rauber 2013). The habitat specialists *Liolaemus wiegmannii* and *Liolaemus occipitalis* depend on coastal areas, particularly the microhabitats of sand dunes (Etheridge 2000), areas highly exposed to extreme events due to CC. Additionally, *Phrynops williamsi* may present sex determination mediated by temperature during egg incubation. Imbalance in the sex ratios of embryos has already been demonstrated in laboratory studies exposing the eggs of painted turtles (*Chrysemys picta*) to temperature fluctuations (Valenzuela et al. 2019). Consequently, if thermal fluctuations rise with CC, a sex imbalance in populations could occur, leading to extinction (Böhm et al. 2016, Valenzuela et al. 2019).

Important data gaps were identified, particularly on susceptibility to diseases. We considered this trait as 'high' if there was a previous record of skin infection by *Batrachochytrium dendrobatidis* or other pathogens, since this fungus has been implicated in population and species declines worldwide (e.g., Jani & Briggs 2014), and CC has been suggested as a potential trigger of chytridiomycosis (Pounds et al. 2006). Several cases of infection are known for Uruguayan species (Borteiro et al. 2009, 2018, 2019), and we are unaware of the epidemiological relevance of locally invasive and currently expanding American bullfrogs (*Lithobates catesbeianus*), carriers of amphibian chytrids (Laufer et al. 2008, 2018) that also compete with and predate upon local species (Gobel et al. 2019, Laufer et al. 2021a). Among reptiles, there is sparse information regarding the impacts of life-history traits on species longevity and temperature-dependent sex determination of offspring, in spite of the latter trait's relevance in a CC scenario.

We observed an overall correspondence (57.1%) between the level of concern in IUCN local categorizations of local amphibians and our vulnerability assessment to CC. While the local Red List considered all six species of *Melanophryniscus* as vulnerable to CC (following Zank et al. 2014), we only considered *M. langonei*, *M. montevidensis* and *M. sanmartini* in this regard. By contrast, we did not find a clear association between threatened reptiles in the local Red List and those with high vulnerability to CC. Only two species among those classified here as highly vulnerable to CC (28.6%) are locally threatened according to the IUCN (*L. wiegmannii* and *L. occipitalis*; Table S12). However, the IUCN Red List for reptiles did not take CC as an explicit classification criterion, as in the published Red List for local amphibians (Carreira & Maneyro 2015). It is noteworthy that CC is only one of the agents of the global changes to which species are exposed as their conservation status is also a function of habitat loss due to human activities and losses to pet trade and consumption. Therefore, multi-factorial studies that combine these factors are needed to precisely define the status of these species (Ficetola & Maiorano 2016).

When compared with previous local evaluations of the vulnerability of native amphibians to CC (Laufer 2012, Toranza et al. 2012), only *M. montevidensis* has been consistently classified as highly vulnerable (Table S11). However, this species was classed as a potential adapter (sensitive and exposed but adaptable) at a global level (Foden et al. 2013). *M. langonei* and *M. sanmartini* are considered vulnerable to CC in the present study as well as by Laufer (2012). Despite the differences among the studies, *Melanophryniscus* species appear to be highly vulnerable to CC, which also accords with Zank et al. (2014). Regarding reptiles, only one species (*L. wiegmannii*) shared the classification of vulnerability with the previous local study by Laufer (2012). Our study identified four additional amphibians and six additional reptiles as potentially highly vulnerable to CC.

We followed the approach of Foden et al. (2013) but made some adjustments that introduce caveats to consider, as we are applying an approach developed for global assessments to a local level. The challenges associated with changing the scale include adjusting the traits to the available information and modifying trait definitions to account for geographical variations, ecosystems and species' habitats. For instance, regarding the trait 'extrinsic barriers to dispersal' used by Carr et al. (2014) and Böhm et al. (2016) to distinguish species restricted to high-altitude habitats (>1000 m above sea level), this is useless as such in Uruguay, where altitude is not critical to defining well-differentiated environments as in other ecoregions/biomes. Nevertheless, there are species exclusively associated with Uruguayan hilly areas (150–513 m), clearly defining low-altitude ecosystems. In this sense, we took into account those species that occur only in the hilly range (in Uruguay). Similarly, some authors have used for exposure an approach based on projections of the climatic variables of temperature and precipitation with arbitrary thresholds (Foden et al. 2013, Carr et al. 2014, Meng et al. 2016), while we used the northern limits of species' global ranges as a proxy of the area that will be exposed to changes of temperature and precipitation in the near future (i.e. by 2050). An advantage of this proxy is that it represents absolute rather than relative measures. These adjustments should better represent processes that occur at finer scales, such as the criteria used in the regional IUCN Red List (IUCN 2012). Lastly, we want to stress one overarching advantage of trait-based approaches: the use of the current understanding of species ecology and evolutionary biology to infer how they will respond to changes that might not have been experienced by species in the past (e.g., Norris 2004). Species distribution models use statistical associations between patterns of abundance and demography and habitat and climatic characteristics within the range of conditions observed in the present or the past to predict possible responses of populations to future CC (e.g., Austin & Van Niel 2011). By contrast, trait-based approaches inform management decisions on the basis of what ecological and evolutionary theories predict on how species will adapt to changing conditions (e.g., Carroll et al. 2014).

Our assessment using an expert consultation process might be biased because personal judgements may be overconfident (Moore & Healy 2008), poorly calibrated, self-serving or not based on solid data, in turn leading to poor inferences (Martin et al. 2012). Additionally, here we considered expert assessments as being of equal weight, while the data provided by each researcher depend on their degree of knowledge regarding each particular species (Marti et al. 2021). To overcome these difficulties, we conducted a face-to-face workshop after the rounds of anonymous consultations. However, we consider the Delphi method and the posterior data synthesis to be a useful framework as it allows for the gathering of more and better information than if we had only relied on published sources. In addition, this process enables the systematizing of a large quantity of data for further analysis (Knol et al. 2009). Finally, the involvement of experts in conservation evaluations provides a means to bridge the widely recognized research–implementation gap in management and conservation science (Knight et al. 2008).

In this study, we classed species into different categories of vulnerability that could be at risk in the near future due to CC, and we identified the traits associated with this risk. These are species in which conservation efforts should be concentrated; the highly vulnerable species need to be the highest priority (Fig. 1). Species-specific studies on longevity, temperature-dependent sex determination, physiological tolerance and the effects of *B. dendrobatidis* on native amphibians would be valuable to better inform the outputs of future CC vulnerability assessments. We contend that our adjustment of an approach developed for global assessments to a local scale is also applicable to CC vulnerability assessments in other regions.

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References

Austin MP, Van Niel KP (2011) Improving species distribution models for climate change studies: variable selection and scale. *Journal of Biogeography* 38: 1–8.

Balestrin RL, Cappellari LH (2011) Reproduction and feeding ecology of *Amphisbaena munoai* and *Anops kingi* (Amphisbaenia, Amphisbaenidae) in the Escudo Sul-Rio-Grandense, southern Brazil. *Iheringia Série Zoologia* 101: 93–102.

Berriozabal-Islas C, Ramírez-Bautista A, Torres-Ángeles F, Mota Rodrigues JF, Macip-Ríos R, Octavio-Aguilar P (2020). Climate change effects on turtles of the genus *Kinosternon* (Testudines: Kinosternidae): an assessment of habitat suitability and climate niche conservatism. *Hydrobiologia* 847: 4091–4110.

Böhm M, Cook D, Ma H, Davidson AD, García A, Tapley B et al. (2016) Hot and bothered: using trait-based approaches to assess climate change vulnerability in reptiles. *Biological Conservation* 204: 32–41.

Borges FJA, Ribeiro BR, Lopes LE, Loyola R (2019) Bird vulnerability to climate and land use changes in the Brazilian Cerrado. *Biological Conservation* 236: 347–355.

Borteiro C, Cruz JC, Kolenc F, Aramburu A (2009) Chytridiomycosis in frogs from Uruguay. *Diseases of Aquatic Organisms* 84: 159–162.

Borteiro C, Gobel N, Kolenc F, Laufer G, Martínez Debat C, Ubilla M (2018) Skin-mates or neighbors? A seasonal study of amphibian chytrid and dermocystid infection in *Boana pulchella* (Anura: Hylidae). *Cuadernos de Herpetología* 32: 101–108.

Borteiro C, Kolenc F, Pereyra MO, Rosset S, Baldo D (2010) A diploid surrounded by polyploids: tadpole description, natural history and cytogenetics of *Odontophrynus maisuma* Rosset from Uruguay (Anura: Cycloramphidae). *Zootaxa* 261: 1–15.

Borteiro C, Kolenc F, Verdes JM, Martínez Debat C, Ubilla M (2019) Sensitivity of histology for the detection of the amphibian chytrid fungus *Batrachochytrium dendrobatidis*. *Journal of Veterinary Diagnostic Investigation* 31: 246–249.

Brazeiro A, Achkar M, Toranza C, Bartesaghi L (2020) Agricultural expansion in Uruguayan grasslands and priority areas for vertebrate and woody plant conservation. *Ecology and Society* 25: 15.

Carr JA, Hughes AF, Foden WB (2014) *A Climate Change Vulnerability Assessment of West African Species*. UNEP-WCMC Technical report. Cambridge, UK: UNEP-WCMC.

Carreira S, Maneyro R (2015) *Lista Roja de los Anfibios y Reptiles del Uruguay. Una evaluación del estado de conservación de la herpetofauna de Uruguay sobre la base de los criterios de la Unión Internacional para la Conservación de la Naturaleza*. Montevideo, Uruguay: Dirección Nacional de Medio Ambiente (DINAMA).

Carroll SP, Jørgensen PS, Kinnison MT, Bergstrom CT, Denison RF, Gluckman P et al. (2014) Applying evolutionary biology to address global challenges. *Science* 346: 1245993.

Di Minin E, Soutullo A, Bartesaghi L, Rios M, Szephegyi MN, Moilanen A (2017) Integrating biodiversity, ecosystem services and socio-economic data to identify priority areas and landowners for conservation actions at the national scale. *Biological Conservation* 206: 56–64.

Diamond IR, Grant RC, Feldman BM, Pencharz PB, Ling SC, Moore AM, Wales PW (2014) Defining consensus: a systematic review recommends methodologic criteria for reporting of Delphi studies. *Journal of Clinical Epidemiology* 67: 401–409.

Etheridge R (2000) A review of lizards of the *Liolaemus wiegmannii* group (Squamata, Iguania, Tropiduridae), and a history of morphological change in the sand-dwelling species. *Herpetological Monographs* 14: 293–352.

Evia G, Gudynas E (2000) *Ecología del paisaje en Uruguay: aportes para la conservación de la diversidad biológica*. Seville, Spain: DINAMA and Junta de Andalucia.

Ficetola GF, Lunghi E, Canedoli C, Padoa-Schioppa E, Pennati R, Manenti R (2018) Differences between microhabitat and broad-scale patterns of niche evolution in terrestrial salamanders. *Scientific Reports* 8: 10575.

Ficetola GF, Maiorano L (2016) Contrasting effects of temperature and precipitation change on amphibian phenology, abundance and performance. *Oecologia* 181: 683–693.

Foden WB, Butchart SHM, Stuart SN, Vié JC, Akçakaya HR, Angulo A et al. (2013) Identifying the world's most climate change vulnerable species: a systematic trait-based assessment of all birds, amphibians and corals. *PLoS ONE* 8: e65427.

Foden WB, Young BE, Akçakaya HR, Garcia RA, Hoffmann AA, Stein BA, Thomas C (2019) Climate change vulnerability assessment of species. *Wiley Interdisciplinary Reviews: Climate Change* 10: 1–36.

Frost DR (2021) Amphibian Species of the World: an Online Reference. Version 6.1. New York, NY, USA: American Museum of Natural History [www document]. URL https://amphibiansoftheworld.amnh.org

García JE (1972) Ampliación de la distribución geográfica de *Ceratophrys ornata* (Bell) (Anura, Ceratophrynidae) y algunas observaciones ecológicas. *Physis* 31: 656–658.

Gobel N, Laufer G, Cortizas S (2019) Changes in aquatic communities recently invaded by a top predator: evidence of American bullfrogs in Aceguá, Uruguay. *Aquatic Sciences* 81: 1–11.

Grattarola F, Martínez-Lanfranco JA, Botto G, Naya D, Maneyro R, Mai P et al. (2020) Multiple forms of hotspots of tetrapod biodiversity and the challenges of open-access data scarcity. *Scientific Reports* 10: 1–15.

IPCC (2018) IPCC Special Report 2018. Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to Eradicate Poverty [www document]. *URL* https://www.ipcc.ch/sr15/chapter/spm

IPCC (2022) Summary for policymakers. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 3–33). Cambridge, UK and New York, NY, USA: Cambridge University Press.

IUCN (2012) *Guidelines for Application of IUCN Red List Criteria at Regional and National Levels: Version 4.0*. Gland, Switzerland and Cambridge, UK: IUCN.

Jani AJ, Briggs CJ (2014) The pathogen *Batrachochytrium dendrobatidis* disturbs the frog skin microbiome during a natural epidemic and experimental infection. *Proceedings of the National Academy of Sciences of the United States of America* 111: E5049–E5058.

Knight AT, Cowling RM, Rouget M, Balmford A, Lombard AT, Campbell BM (2008) Knowing but not doing: selecting priority conservation areas and the research–implementation gap. *Conservation Biology* 22: 610–617.

Knol AB, de Hartog JJ, Boogaard H, Slottje P, van der Sluijs JP, Lebret E et al. (2009) Expert elicitation on ultrafine particles: likelihood of health effects and causal pathways. *Particle and Fibre Toxicology* 6: 1–19.

Kolenc F (1987) Anuros del género *Melanophryniscus* en la República Oriental del Uruguay. *Aquamar* 30: 16–21.

Laufer G (2012) *Lista de especies de anfibios y reptiles de Uruguay vulnerables al cambio climático global*. IIBCE, MEC technical report. Montevideo, Uruguay: IIBCE, MEC.

Laufer G, Canavero A, Núñez D, Maneyro R (2008) Bullfrog (*Lithobates catesbeianus*) invasion in Uruguay. *Biological Invasions* 10: 1183–1189.

Laufer G, Gobel N, Berazategui M, Zarucki M, Cortizas S, Soutullo A et al. (2021a). American bullfrog (*Lithobates catesbeianus*) diet in Uruguay compared with other invasive populations in southern South America. *North-Western Journal of Zoology* 17: 196–203.

Laufer G, Gobel N, Borteiro C, Soutullo A, Martínez-Debat C, de Sá RO (2018) Current status of American bullfrog, *Lithobates catesbeianus*, invasion in Uruguay and exploration of chytrid infection. *Biological Invasions* 20: 285–291.

Laufer G, Gobel N, Kacevas N, Lado N, Cortizas S, Carabio M, Kolenc F (2021b) Updating the distributions of four Uruguayan hylids (Anura: Hylidae): recent expansions or lack of sampling efforts? *Amphibian and Reptile Conservation* 15: 228–237.

Losada IJ, Reguero BG, Méndez FJ, Castanedo S, Abascal AJ, Mínguez R (2013) Long-term changes in sea-level components in Latin America and the Caribbean. *Global and Planetary Change* 104: 34–50.

Marti D, Mazzuchi TA, Cooke RM (2021) Are performance weights beneficial? Investigating the random expert hypothesis. In: AM Hanea, GF Nane, T Bedford, S French (eds), *Expert Judgement in Risk and Decision Analysis* (pp. 53–82). Cham, Switzerland: Springer.

Martin TG, Burgman MA, Fidler F, Kuhnert PM, Low-Choy S, Mcbride M, Mengersen K (2012) Eliciting expert knowledge in conservation science. *Conservation Biology* 26: 29–38.

Meng H, Carr J, Beraducci J, Bowles P, Branch WR, Capitani C, Chenga J (2016) Tanzania's reptile biodiversity: distribution, threats and climate change vulnerability. *Biological Conservation* 204: 72–82.

MGAP-FAO (2012) *Clima de cambios: Nuevos desafíos de adaptación en Uruguay*. Montevideo, Uruguay: Variabilidad climática de importancia para el sector productivo.

Moore DA, Healy PJ (2008) The trouble with overconfidence. *Psychological Review* 115: 502.

Moreira L, Knauth D, Maltchik L (2014) Checklist of amphibians in a rice paddy area in the Uruguayan savanna, southern Brazil. *Check List* 10: 1014–1019.

Morrone JJ (2014) Biogeographical regionalisation of the neotropical region. *Zootaxa* 3782: 1.

Morrone JJ (2015) Biogeographical regionalisation of the world: a reappraisal. *Australian Systematic Botany* 28: 81–90.

Mukherjee N, Hugé J, Sutherland WJ, McNeill J, Van Opstal M, Dahdouh-Guebas F, Koedam N (2015) The Delphi technique in ecology and biological conservation: applications and guidelines. *Methods in Ecology and Evolution* 6: 1097–1109.

MVOTMA (2010) *Tercera comunicación nacional a la conferencia de las partes en la convencion marco de las naciones unidas sobre cambio climatico*. Montevideo, Uruguay: MVOTMA.

Nagy G, Bidegain M, Verocai J, de los Santos B (2016) *Escenarios climaticos futuros sobre Uruguay. Basados en los nuevos escenarios socioeconómicos RCP*. Montevideo, Uruguay: Ministerio de Vivienda, Ordenamiento Territorial y Medio Ambiente (MVOTMA), División de Cambio Climático (DCC).

Norris K (2004) Managing threatened species: the ecological toolbox, evolutionary theory and declining-population paradigm. *Journal of Applied Ecology* 41: 413–426.

Pacifici M, Visconti P, Butchart SHM, Watson JEM, Cassola FM, Rondinini C (2017) Species' traits influenced their response to recent climate change. *Nature Climate Change* 7: 205–208.

Pereira HM, Leadley PW, Proença V, Alkemade R, Scharlemann JPW, Fernandez-Manjarrés JF, Araújo MB (2010) Scenarios for global biodiversity in the 21st century. *Science* 330: 1496–1501.

Pounds JA, Bustamante MR, Coloma LA, Consuegra JA, Fogden MPL, Foster PN, La Marca E (2006) Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature* 439: 161–167.

Pounds JA, Fogden MPL, Campbell JH (1999) Biological response to climate change on a tropical mountain. *Nature* 398: 611–615.

Powell C (2003) The Delphi technique: myths and realities. *Journal of Advanced Nursing* 41: 376–382.

Prigioni CM, Garrido RR (1989) Algunas observaciones sobre la reproducción de *Melanophryniscus stelzneri montevidensis* (Anura, Bufonidae). *Boletín de la Sociedad Zoológica del Uruguay* 5: 13–14.

Reading CJ (2007) Linking global warming to amphibian declines through its effects on female body condition and survivorship. *Oecologia* 151: 125–131.

Rosset SD (2008) New species of *Odontophrynus* Reinhardt and Lütken 1862 (Anura: Neobatrachia) from Brazil and Uruguay. *Journal of Herpetology* 42: 134–144.

Sinervo B, Mendez-De-La-Cruz F, Miles DB, Heulin B, Bastiaans E, Villagrán-Santa Cruz M et al. (2010). Erosion of lizard diversity by climate change and altered thermal niches. *Science* 328: 894–899.

Toranza C, Maneyro R, Brazeiro A (2012) Efectos del Cambio Climático sobre la Biodiversidad: El caso de los anfibios de Uruguay. In: V Picasso, G Cruz, L Astigarraga, R Terra (eds), *Cambio y Variabilidad Climática: Respuestas Interdisciplinarias* (pp. 35–50). Montevideo, Uruguay: Espacio Interdisciplinario.

Uetz P, Freed P, Hošek J (2021) The Reptile Database [www document]. URL http://www.reptile-database.org

Valenzuela N, Literman R, Neuwald JL, Mizoguchi B, Iverson JB, Riley JL, Litzgus JD (2019) Extreme thermal fluctuations from climate change unexpectedly accelerate demographic collapse of vertebrates with temperature-dependent sex determination. *Scientific Reports* 9: 1–11.

Verrastro L, Rauber RC (2013) Reproducción de las hembras de *Liolaemus occipitalis* Boulenger, 1885, (Iguania, Liolaemidae) en la región sur de Brasil. *Boletin de La Sociedad Zoológica del Uruguay (2ª Época)* 22: 84–98.

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Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin JM (2002) Ecological response to recent climate change. *Nature* 416: 389–395.

Wells KD (2007) *The Ecology and Behavior of Amphibians*. Chicago, IL, USA: University of Chicago Press.

Winter M, Fiedler W, Hochachka WM, Koehncke A, Meiri S, De La Riva I (2016) Patterns and biases in climate change research on amphibians and reptiles: a systematic review. *Royal Society Open Science* 3: 160158.

Young BE, Dubois NS, Rowland EL (2015) Using the climate change vulnerability index to inform adaptation planning: lessons, innovations, and next steps. *Wildlife Society Bulletin* 39: 174–181.

Zank C, Becker FG, Abadie M, Baldo D, Maneyro R, Borges-Martins M (2014) Climate change and the distribution of neotropical red-bellied toads (*Melanophryniscus*, Anura, Amphibia): how to prioritize species and populations? *PLoS ONE* 9: e94625.