A flagship for Austral temperate forest conservation: an action plan for Darwin's frogs brings key stakeholders together

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Abstract Darwin's frogs *Rhinoderma darwinii* and *Rhinoderma rufum* are the only known species of amphibians in which males brood their offspring in their vocal sacs. We propose these frogs as flagship species for the conservation of the Austral temperate forests of Chile and Argentina. This recommendation forms part of the vision of the Binational Conservation Strategy for Darwin's Frogs, which was launched in 2018. The strategy is a conservation initiative

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led by the IUCN SSC Amphibian Specialist Group, which in 2017 convened 30 governmental, non-profit and private organizations from Chile, Argentina and elsewhere. Darwin's frogs are iconic examples of the global amphibian conservation crisis: *R. rufum* is categorized as Critically Endangered (Possibly Extinct) on the IUCN Red List, and *R. darwinii* as Endangered. Here we articulate the conservation planning process that led to the development of the conservation strategy for these species and present its main findings and recommendations. Using an evidence-based approach, the Binational Conservation Strategy for Darwin's Frogs contains a comprehensive status review of *Rhinoderma* spp., including critical threat analyses, and proposes 39 prioritized conservation actions. Its goal is that by 2028, key information gaps on *Rhinoderma* spp. will be filled, the main threats to these species will be reduced, and financial, legal and societal support will have been achieved. The strategy is a multi-disciplinary, transnational endeavour aimed at ensuring the long-term viability of these unique frogs and their particular habitat.

Keywords Amphibians, Argentina, Chile, conservation strategy, Darwin's frogs, extinction, *Rhinoderma darwinii*, *Rhinoderma rufum*

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Introduction

Halting biodiversity loss depends largely on developing effective conservation policies and planning (Johnson et al., 2017). Evidence-based, inclusive, participatory conservation strategies are recommended when specific actions are needed to save species from extinction (IUCN, 2017). Key species can act as umbrellas or flagships, transforming species-level conservation plans into ecosystem-wide benefits (Superina et al., 2018).

The northern and the southern Darwin's frog (*Rhinoderma rufum* and *Rhinoderma darwinii*) are named after Charles Darwin, who was the first to collect *R. darwinii*, in 1834. These species are the only known amphibians in which the males brood their offspring within their vocal sacs (Plate 1). In *R. rufum* the later larval stages develop in water, whereas in *R. darwinii* the entire larval development, lasting up to 8 weeks and including metamorphosis, takes place within the male's vocal sac (Formas et al., 1975; Formas, 2013; Supplementary Fig. 1). Endemic to the Austral temperate forests of South America, both species are highly threatened as a result of dramatic population declines, particularly during the last 4 decades (Crump & Veloso, 2005; Bourke et al., 2012; Soto-Azat et al., 2013a). The habitat of Darwin's frogs is an ecoregion characterized by a high degree of endemism and is thus of high conservation priority (Myers et al., 2000). *Rhinoderma rufum* has not been recorded since 1981 and remaining populations of *R. darwinii* are small and isolated (Soto-Azat et al., 2013a; IUCN, 2019). Darwin's frogs are found only in native forest (generally old-growth), and *R. darwinii* abundance has been positively correlated with the structural complexity of its forest habitat (Valenzuela-Sánchez et al., 2019a). Although habitat loss is a threat, population declines and extirpations have also been documented within protected areas and undisturbed ecosystems (Crump & Veloso, 2005; Soto-Azat et al., 2013a).

Plate 1 A brooding male southern Darwin's frog *Rhinoderma darwinii* in a typical humid substrate of the Valdivian temperate forest.

Recently, there has been growing concern about Darwin's frogs, evidenced by several independent and uncoordinated research and conservation efforts. The majority (75%) of all publications on Darwin's frogs indexed in the Web of Science were published during 20010–2019, when a number of in situ and ex situ conservation projects were established for *R. darwinii*. Thus, we identified an opportunity for collaboration to provide efficient and cost-effective conservation outcomes for these unique and highly threatened frogs. In 2017 the Chilean section of the IUCN SSC Amphibian Specialist Group convened stakeholders to develop a conservation plan for Darwin's frogs, and as a result the Binational Conservation Strategy for Darwin's Frogs was launched in 2018. Here we summarize the process of the strategy's development, present its main findings and recommendations and discuss the major challenges and opportunities of implementation. This work adds to the scarce peer-reviewed literature on species conservation planning and seeks to stimulate its use as a biodiversity conservation tool.

Study area

The Austral temperate forests, which include the habitat of Darwin's frogs (32–47 °S), cover > 20 million ha, mainly in

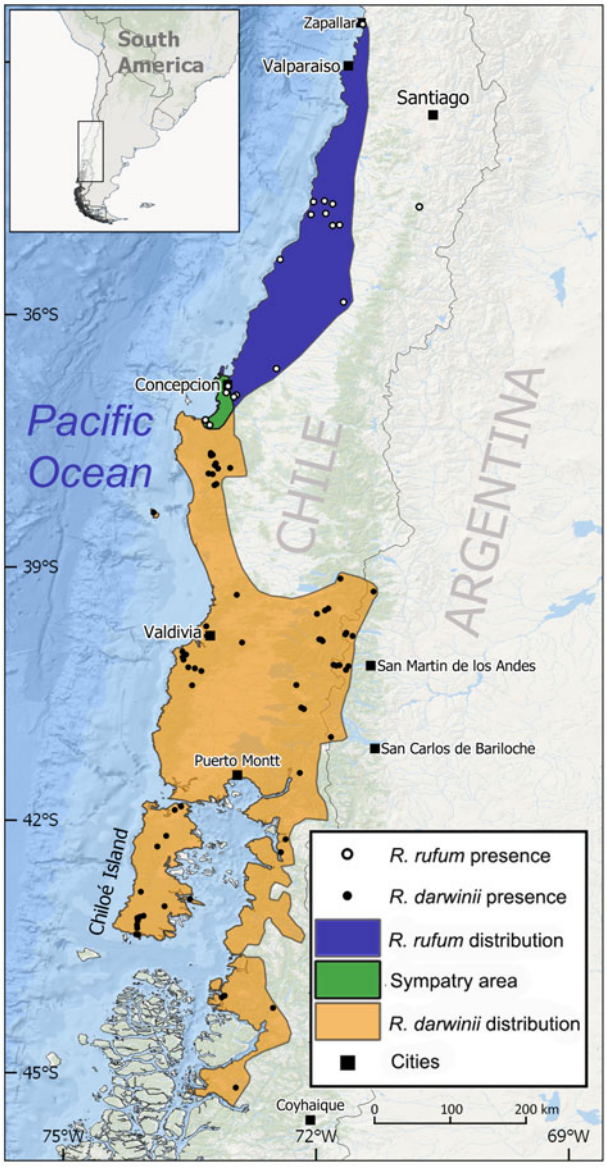

FIG. 1 Distribution of Darwin's frogs in Chile and Argentina. Historical distribution of *Rhinoderma rufum*, *Rhinoderma darwinii* and the area of sympatry around Concepción. Localities with known current presence of *R. darwinii* are shown in solid dots. No population of *R. rufum* is currently known, but historical localities are shown in open dots. There is one unusual historical record for *R. rufum* in the Chilean foothills of the Andes (Barros, 1918).

Chile but also in Argentina (4.6 and 16.0 million ha for *R. rufum* and *R. darwinii*, respectively; IUCN, 2019). *Rhinoderma rufum* is endemic to the coastal range of Chile at 0–500 m altitude (Bourke et al., 2012; Soto-Azat et al., 2013a; Cuevas, 2014). *Rhinoderma darwinii* is found in both the coastal range of Chile (including Mocha Island and the Chiloé Archipelago) and the Andes of Chile and Argentina (Soto-Azat et al., 2013a) at 0–1,340 m altitude (Úbeda & Pastore, 2015). Historical distributions of *Rhinoderma* spp. are shown in Fig. 1.

Methods

Conservation assessment

In July 2015, 19 Chilean herpetologists met at Universidad Andres Bello in Santiago to update the IUCN Red List assessment of Chilean amphibians (Soto-Azat et al., 2015). This work highlighted the urgent need for conservation planning for Darwin's frogs. Re-assessments of *R. darwinii* and *R. rufum* followed the IUCN Red List methodology: literature and data searches, assessments by experts and external review.

Development of the strategy

Development of the Binational Conservation Strategy for Darwin's Frogs was facilitated by an Amphibian Specialist Group co-chair, a programme officer and a thematic group chair and followed IUCN guidelines for species conservation planning (IUCN, 2017). Initially, a 1-day symposium in September 2017 convened 292 participants interested in the conservation of Darwin's frogs. Here, 27 national and international speakers presented advances on *Rhinoderma* spp. research and conservation, and discussed IUCN guidelines for effective conservation planning (IUCN, 2017). Subsequently, 30 stakeholders that had been selected for their expertise, influence, and representation of relevant organizations, attended a 3-day conservation strategy workshop where we: (1) formulated the strategy's vision, (2) defined the strategy's time frame, (3) discussed the current status of Darwin's frogs, (4) assessed the challenges, barriers and threats to their conservation, (5) established working groups (see below), (6) developed conservation goals, objectives and actions, (7) prioritized objectives and actions and (8) elected the coordination structure. We formed four working groups based on identified conservation needs: (1) habitat loss, (2) captive breeding, research and climate change, (3) policy and education, and (4) diseases and invasive species. Following a SMART (Specific, Measurable, Achievable, Realistic and Time-bound) approach, each working group proposed goals, objectives and actions, which were later discussed, validated and prioritized by all workshop participants. After the workshop, a draft of the strategy was distributed among participants and others involved in the development of the strategy, for comment and approval.

Results

Conservation assessment

Rhinoderma rufum is categorized as Critically Endangered (Possibly Extinct) based on criterion D because its

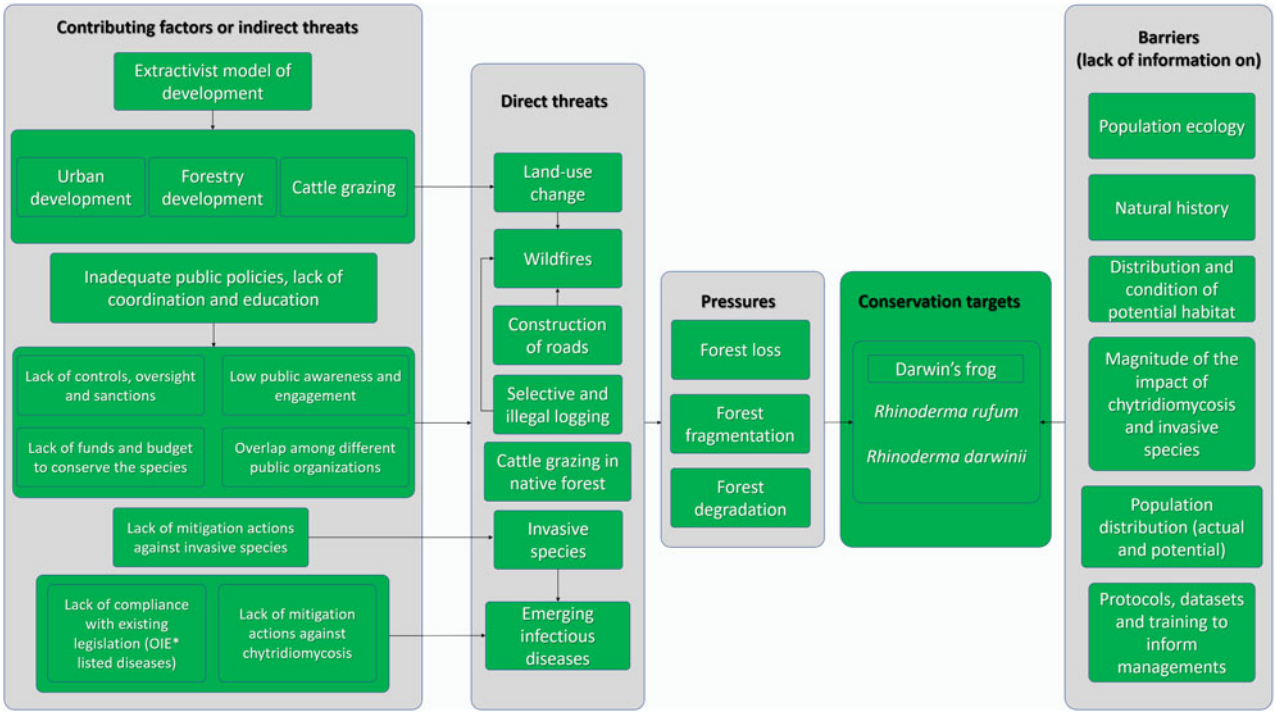

FIG. 2 Conceptual model showing a threat assessment for Darwin's frogs (*R. rufum* and *R. darwinii*). We identified direct and indirect threats, barriers presented by lack of knowledge, contributing factors and pressures, and plotted their interactions with each other and within the binational conservation strategy. *OIE = World Animal Health Organization.

population size is estimated to be < 50 mature individuals (IUCN, 2019). The species has not been recorded since 1981 despite intense searches across its historical range (Busse, 2002; Bourke et al., 2012; Soto-Azat et al., 2013a; Cuevas, 2014). *Rhinoderma darwinii* is categorized as Endangered following criteria B2ab(iii) (IUCN, 2019) because (1) its current area of occupancy is estimated to be 224 km² (< 500 km² threshold; B2), (2) extant populations are small and isolated (a), and (3) the extent and quality of its remaining habitat continues to decline (b(iii); Crump & Veloso, 2005; Soto-Azat et al., 2013a; Uribe-Rivera et al., 2017; Bourke et al., 2018). Only *R. darwinii* has been kept and bred in captivity.

A conservation strategy

Under the vision 'Darwin's frogs, unique in the world for their reproductive peculiarity, are conserved and valued as an emblem for the protection of the native forests of southern Chile and Argentina', the Binational Conservation Strategy for Darwin's Frogs was launched in October 2018. The strategy is divided into two main components: a status review of *Rhinoderma* spp., and the conservation strategy itself, comprising a threat assessment (Fig. 2) and a list of prioritized conservation actions. The strategy aims to achieve the following goals by 2028: (1) obtain key information on the biology, management and status of *Rhinoderma* populations, (2) reduce the main threats to Darwin's frogs, and (3) provide the financial, legal and societal support needed for the proposed conservation actions. To this end, the strategy contains 39 actions, grouped under 12 objectives (Supplementary Table 1). Each conservation action lists responsible stakeholders, deadlines, indicators, potential collaborators and funding sources. The strategy (IUCN ASG–Chile, 2018) has been distributed among relevant authorities, conservation organizations, local communities and the general public.

Website

The full Binational Conservation Strategy for Darwin's Frogs can be downloaded from the strategy's website (see full reference in IUCN ASG–Chile, 2018). This website provides information on *Rhinoderma* biology and conservation along with relevant literature and other resources. The strategy is intended to be a dynamic and adaptive document, and the website will help with the coordination of identified actions.

Darwin's Frog Alliance

A key outcome of the conservation planning process was the creation of the Darwin's Frog Alliance, a network of 47 individuals, representing 30 institutions and a diverse array of stakeholders (from academia, government, zoological

institutions, local communities, NGOs and the private sector; Supplementary Table 2), to enhance collaboration for the conservation of Darwin's frogs. The Alliance is led by members of the Amphibian Specialist Group, and endorsed by the Chilean and Argentinian Ministries of Environment.

Threat assessment

The status review supported previous claims that the decline of Darwin's frogs has been largely driven by habitat loss, chytridiomycosis and climate change (Bourke et al., 2010, 2012, 2018; Soto-Azat et al., 2013a, 2013b; Uribe-Rivera et al., 2017; Valenzuela-Sánchez et al., 2017). Here we provide a brief synthesis of this review.

Status of populations Using species distribution modelling, Bourke et al. (2012) identified areas with potential remnant *R. rufum* populations, providing guidance for future efforts to rediscover this species. Soto-Azat et al. (2013a) dated its extinction to 1982 (95% CI: 1980–2000) using historical sightings. In contrast, *R. darwinii* is found in small and isolated populations (Soto-Azat et al., 2013a; Valenzuela-Sánchez et al., 2015). During the development of the strategy, we identified 56 extant populations in Chile and 10 in Argentina (Fig. 1). In Chile, *R. darwinii* has recently disappeared from, or drastically declined in, many localities where it was abundant only decades ago (Crump & Veloso, 2005; Soto-Azat et al., 2013a). The size of extant populations is c. 10–145 reproductive individuals (Crump, 2002; Soto-Azat et al., 2013a; Valenzuela-Sánchez et al., 2014, 2017, 2019a). In Argentina, the species has been less well studied but, based on museum collections, it was probably much more abundant in the past (Úbeda & Pastore, 2015).

Habitat loss The original habitats of *R. rufum*, the Coastal Mediterranean and Maulino deciduous forests (32–36 °S), have been almost completely replaced by exotic pine and eucalypt plantations and agriculture, with < 7% of Maulino forest remaining (Smith-Ramírez, 2004; Echeverría et al., 2006). The Valdivian temperate rainforest (36–47 °S) is the typical habitat of *R. darwinii*. To the north, the situation for *R. darwinii* is similar to that for *R. rufum*, but further south the native forest becomes more continuous as the coverage of protected areas increases, thus providing more suitable habitat for the species.

Amphibian chytridiomycosis Caused by the fungus *Batrachochytrium dendrobatidis*, this emerging disease is known for its catastrophic and ongoing impacts on amphibian populations worldwide (Scheele et al., 2019). This pathogen has been identified from museum specimens of wild

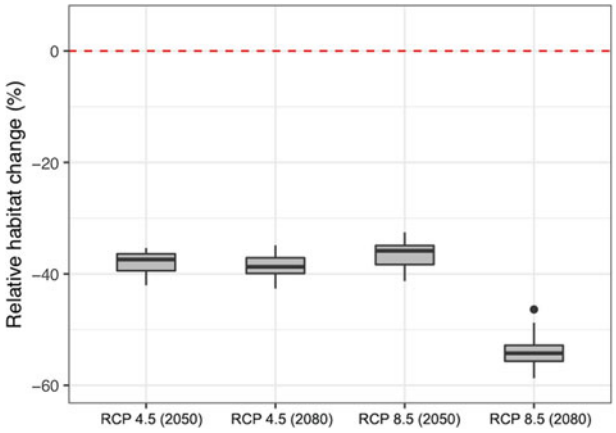

FIG. 3 Boxplot (median, 25th, and 75th percentiles) of relative changes in the extent of potential habitat (suitable and accessible) of *R. darwinii*, projected to two temporal windows (2050 and 2080) and two climate change scenarios (Relative Concentration Pathway 4.5 and 8.5; IPCC, 2014). The dashed line represents a scenario of no change compared to the present situation.

Chilean amphibians collected since the 1970s (Soto-Azat et al., 2013b). This coincides with the documented onset of South American amphibian declines (Scheele et al., 2019). Surveys in Chile have demonstrated that *B. dendrobatidis* is infecting *R. darwinii* in the wild (Bourke et al., 2010), with evidence of lethal chytridiomycosis (Soto-Azat et al., 2013b), which leads to extirpation of infected populations (Valenzuela-Sánchez et al., 2017).

Climate change Because of its specific habitat requirements (Valenzuela-Sánchez et al., 2019a), slow life-history strategy (Valenzuela-Sánchez et al., 2017) and dispersal limitations (Valenzuela-Sánchez et al., 2014, 2019b), *Rhinoderma* spp. are expected to be particularly susceptible to climate change (Soto-Azat et al., 2013a). Using a dispersal-constrained species distribution model, Uribe-Rivera et al. (2017) estimated that during 1970–2010, climate change led to a reduction of suitable habitat for this species by 23–40%. Bourke et al. (2018) predicted an expansion of climatically suitable areas for *R. darwinii* by 2080, especially in the south of its range. However, unless assisted by translocations, *R. darwinii* would not naturally colonize most of the emerging suitable areas (Uribe-Rivera et al., 2017). Incorporating dispersal limitations analyses of climate change projections for 2050 and 2080 show reductions of 33–56% in the potential distribution of *R. darwinii* (Fig. 3; Uribe-Rivera et al., 2017).

Other threats

Collection of wild *Rhinoderma* spp., mainly for hobbyists and museums, was common in the past (J.C. Ortiz, pers.

obs., 1988; Soto-Azat et al., 2013a; Supplementary Fig. 1). Other threats and barriers include livestock farming in forest habitats, non-compliance with current legislation, and lack of public awareness and engagement (Fig. 2).

Ongoing conservation

Although there are 30 protected areas (28 in Chile and two in Argentina) within the range of *R. darwinii*, none protect any of the historical sites of *R. rufum*. Since 2009, three in situ conservation projects have been implemented for *R. darwinii*: in Huilo Huilo, Tantauco and Melimoyu private parks. Currently, there are two independent ex situ conservation projects for *R. darwinii*: one led by Universidad de Concepción in conjunction with Zoo Leipzig, Germany (since 2009), and another by the National Zoo of Chile (since 2010). There are also several education initiatives focused on Darwin's frogs: one at the National Zoo of Chile (visited by > 860,000 people in 2018), a Darwin's frog education centre in Huilo Huilo (> 100,000 visitors in 2018), and an education programme run by NGO Ranita de Darwin, which has reached > 15,000 people in local communities within the range of *Rhinoderma* spp.

Discussion

Multi-pronged strategies that combine research, management, education and policy are required to achieve successful species conservation (Superina et al., 2018). The Binational Conservation Strategy for Darwin's Frogs is a multi-sectoral, participatory effort and follows an evidence-based process to achieve the long-term conservation of Darwin's frogs. Additionally, this strategy promotes these species as non-traditional flagships for the conservation of the Austral temperate forest, which has been identified as one of the world's 25 biodiversity hotpots (Myers et al., 2000).

Conservation challenges

Habitat protection The coastal range of central Chile has the greatest terrestrial species richness in the country, but almost entirely lacks protection and has experienced a rapid loss of biodiversity (Smith-Ramírez, 2004), especially since the 1970s (Echeverría et al., 2006). If *R. rufum* is rediscovered, it will be challenging to guarantee its immediate in situ protection, considering that it may occur on private land. In contrast, protected areas have allowed the persistence of *R. darwinii*. In Chile, 93% of known populations (52 out of 56; Fig. 1) are within areas with some level of protection, mostly private parks (43%). Although < 5% of the range of *R. darwinii* lies in Argentina, all known populations (10) in this country are in two large and contiguous national parks: Lanín and Nahuel Huapi (Úbeda & Pastore, 2015). Private reserves (which cover 1.5 million ha in central and southern Chile) are key for the conservation of Darwin's frogs. Similarly, a partnership with the forestry sector can boost the protection of Darwin's frog habitat. Forestal Arauco is the largest forestry company in South America (owning 1.4 million ha in Chile and Argentina) and a participating member of the Binational Conservation Strategy for Darwin's Frogs. Most of their land is planted with exotic pines and eucalypts, but > 110,000 ha of native forests are protected as conservation areas, five of which currently protect populations of *R. darwinii* (Arauco, 2017). Improving the conservation status of Darwin's frogs depends on increasing the area and connectivity of its habitat (Soto-Azat et al., 2013a). The traditional approach to achieving this would be to create or expand protected areas (Smith-Ramírez, 2004), but a novel initiative is being implemented in southern Chile. In collaboration with local landowners and regional government, NGO Ranita de Darwin promotes amphibian conservation by voluntary agreements (Ranita de Darwin, 2020a) to encourage planting of native forest, habitat management and monitoring of the Darwin's frog population by landowners (Santangeli et al., 2016).

Managing wildfires Wildfires are considered an emerging threat to Darwin's frogs. During 2017 and 2018, central and southern Chile experienced the largest wildfires in recent history; > 500,000 ha were burnt in 2017, 20% of which involved native forest (CONAF, 2017). Climate change projections predict a trend of increasing damage by wildfires (Urrutia-Jalabert et al., 2018). Fire prevention or rapid containment is a key aspect of future conservation management plans for *Rhinoderma* spp.

Reintroductions There are plans to reintroduce *R. darwinii* individuals from captive breeding projects to areas from which they have been extirpated, or to use them for population reinforcement. Translocation success will depend on evidence-based management of the threats that led to the extirpations or declines at the release sites (IUCN, 2013; Molina-Burgos et al., 2018).

Policy and public engagement The Chilean Ministry of Environment administers the legal instrument of Recovery, Conservation and Management (RECOGE) Plans to execute research, protection and conservation programmes for threatened species. The Ministry has been part of the development of the Binational Conservation Strategy for Darwin's Frogs since its inception; inclusion of RECOGE criteria in the strategy will facilitate its adoption. In Argentina, where *R. darwinii* is present only in two national parks, the National Park

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Administration is responsible for implementing the strategy. Once signed by the environment authorities of both countries, the strategy will facilitate interdisciplinary and international working amongst public agencies. Another area in which both countries can take action involves animal health departments, with the enforcement of amphibian import regulations and the implementation of biosecurity protocols aimed at limiting the spread of *B. dendrobatidis* (and other invasive species) both at national and local levels (Valenzuela-Sánchez et al., 2018; Bacigalupe et al., 2019). Official recognition of the strategy is also relevant for establishing nation-wide conservation education programmes. Improving the public's knowledge of and attitudes towards Darwin's frogs will be critical to achieve the strategy's objectives (Márquez-García et al., 2018).

Future research

Studies on population trends and threats to *R. darwinii* in Argentina are lacking and little is known about the genetic diversity of *Rhinoderma*. There have been no genetic studies of *R. rufum* and limited information is available for *R. darwinii* (Crump & Veloso, 2005). A characterization of the genetic structure of *Rhinoderma* spp. across their range would inform in situ management and assessment of potential reintroductions using captive-bred animals (IUCN, 2013).

Other critical investigations include improving our understanding of two known major threats: amphibian chytridiomycosis and climate change (Soto-Azat et al., 2013b; Uribe-Rivera et al., 2017). For *R. darwinii*, research is underway to assess mitigation actions addressing infections with *B. dendrobatidis* (Ranita de Darwin, 2020b). Besides phenotypic plasticity, amphibians have two options to deal with climate change: evolutionary adaptation and dispersal (Uribe-Rivera et al., 2017). No information exists concerning evolutionary or phenotypic responses to rapid and ongoing climate change (IPCC, 2014); studies addressing this issue will allow us to predict, and potentially mitigate, the impacts of climate change on *Rhinoderma*.

Conclusions

The Binational Conservation Strategy for Darwin's Frogs is the first conservation strategy exclusively dedicated to amphibians at the species level in both Chile and Argentina. It provides an informative case study of a comprehensive programme for iconic, yet under-appreciated, fauna and an example of how small ectothermic animals can become flagship species for conservation, a role usually assigned to larger charismatic mammals. The development of the strategy is a constructive example of stakeholders, including local communities and industry, working together to generate a robust instrument to combat the amphibian extinction crisis. This multi-disciplinary conservation planning initiative is an effort to coordinate existing work in Chile and Argentina and to catalyse further conservation actions based on scientific evidence. Successful implementation of the strategy will help to ensure the long-term viability of these unique frogs and, by extension, of their habitat, the Austral temperate forest.

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Conflict of interests None.

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References

ARAUCO (2017) *2017 Sustainability Report*. Forestal Arauco, Santiago, Chile. arauco.cl/na/sostenibilidad/reportes-de-sostenibilidad [accessed 26 February 2020].

Bacigalupe, L.D., Vásquez, I.A., Estay, S.A., Valenzuela-Sánchez, A., Alvarado-Rybak, M., Peñafiel-Ricaurte, A. et al. (2019) The amphibian-killing fungus in a biodiversity hotspot: identifying and validating high-risk areas and refugia. *Ecosphere*, 10, e02724.

Barros, R. (1918) Notas sobre el 'sapito vaquero' (*Rhinoderma darwinii* Dum. & Bibron). *Revista Chilena de Historia Natural*, 22, 71–75.

Bourke, J., Ulmer, P., Mutschmann, F., Busse, K., Werning, H. & Böhme, W. (2010) *Batrachochytrium dendrobatidis* in Darwin's frog (*Rhinoderma darwinii*), Chile. *Diseases of Aquatic Organisms*, 92, 217–221.

Bourke, J., Busse, K. & Böhme, W. (2012) Searching for a lost frog (*Rhinoderma rufum*): identification of the most promising areas for future surveys and possible reasons of its enigmatic decline. *North-Western Journal of Zoology*, 8, 99–106.

Bourke, J., Busse, K. & Böhme, W. (2018) Potential effects of climate change on the distribution of the Endangered Darwin's frog. *North-Western Journal of Zoology*, 14, 165–170.

Busse, K. (2002) Darwin's frogs in danger; *Rhinoderma*, are there any *Rhinoderma rufum* left in Chile? *Reptilia*, 25, 63–67.

CONAF (Corporación Nacional Forestal) (2017) *Análisis de la Afectación y Severidad de los Incendios Forestales Ocurridos en Enero y Febrero de 2017 sobre los Usos de Suelo y los Ecosistemas Naturales Presentes entre las Regiones de Coquimbo y Los Ríos de Chile.* Informe Técnico, Santiago, Chile.

Crump, M.L. (2002) Natural history of Darwin's frog *Rhinoderma darwinii*. *Herpetological Natural History*, 9, 21–31.

Crump, M.L. & Veloso, A. (2005) El aporte de observaciones de terreno y del análisis genético para la conservación de *Rhinoderma darwinii* en Chile. In *Historia, Biodiversidad y Ecología de los*

Bosques Costeros de Chile (eds C. Smith-Ramírez, J.J. Armesto & C. Valdovinos), pp. 452–455. Editorial Universitaria, Santiago, Chile.

Cuevas, C.C. (2014) Native forest loss impacts on anuran diversity: with focus on *Rhinoderma rufum* (Philippi 1902) (Rhinodermatidae) in coastal range, south-central Chile. *Gestión Ambiental*, 27, 1–18.

Echeverría, C., Coomes, D., Salas, J., Rey-Benayas, J.M., Lara, A. & Newton, A. (2006) Rapid deforestation and fragmentation of Chilean Temperate Forests. *Biological Conservation*, 130, 481–494.

Formas, J.R. (2013) External morphology, chondrocranium, hyobranchial skeleton, and external and internal oral features of *Rhinoderma rufum* (Anura, Rhinodermatidae). *Zootaxa*, 3641, 395–400.

Formas, J.R., Pugín, E. & Jorquera, B. (1975) La identidad del batracio chileno *Heminectes rufus* Philippi, 1902. *Physis Section C*, 89, 147–157.

IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Core Writing Team, eds R.K. Pachauri & L.A. Meyer). IPCC, Geneva, Switzerland.

IUCN (2013) *Guidelines for Reintroductions and Other Conservation Translocations*. Version 1.0. IUCN Species Survival Commission, Gland, Switzerland. portals.iucn.org/library/efiles/documents/2013-009.pdf [accessed 28 August 2019].

IUCN (2017) *Guidelines for Species Conservation Planning*. Version 1.0. IUCN, Gland, Switzerland. portals.iucn.org/library/sites/library/files/documents/2017-065.pdf [accessed 28 August 2019].

IUCN (2019) *The IUCN Red List of Threatened Species*. Version 2019-2. IUCN, Gland, Switzerland. iucnredlist.org [accessed 28 August 2019].

IUCN ASG–Chile (2018) *Estrategia Binacional de Conservación de la Ranitas de Darwin*. IUCN SSC Amphibian Specialist Group–Chile, Santiago, Chile. estrategiarhinoderma.org [accessed 28 August 2019].

Johnson, C.N., Balmford, A., Brook, B.W., Buettel, J.C., Galetti, M., Guanchum, L. et al. (2017) Biodiversity losses and conservation responses in the Anthropocene. *Science*, 356, 270–275.

Márquez-García, M., Jacobson, S.K. & Barbosa, O. (2018) Evaluating biodiversity workshops in Chile: are farmers responding with conservation action? *Environmental Education Research*, 24, 1669–1683.

Molina-Burgos, B.E., Valenzuela-Sánchez, A., Alvarado-Rybak, M., Klarian, S. & Soto-Azat, C. (2018) Trophic ecology of the Endangered Darwin's frog inferred by stable isotopes. *Endangered Species Research*, 36, 269–278.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B. & Kent, J. (2000) Biodiversity hotspots for conservation priorities. *Nature*, 403, 853–858.

Ranita de Darwin (2020a) *Iniciativa de Conservación de Tierras para Anfibios*. Organización No Gubernamental Ranita de Darwin, Santiago and Valdivia, Chile. ranitadedarwin.org/conservaciondetierras [accessed April 2020].

Ranita de Darwin (2020b) *Proyecto Emerge. Estudio Metapoblacional de Ranas del Bosque Templado Austral y Gestión Epidemiológica*. Organización No Gubernamental Ranita de Darwin, Santiago and Valdivia, Chile. ranitadedarwin.org/emerge [accessed April 2020].

Santangeli, A., Arroyo, B., Dicks, L.V., Herzon, I., Kukkala, A. S., Sutherland, W.J. et al. (2016) Voluntary non-monetary approaches for implementing conservation. *Biological Conservation*, 197, 209–214.

Scheele, B.C., Pasmans, F., Berger, L., Skerrat, L.F., Martel, A., Beukema, W. et al. (2019) Amphibian fungal panzootic causes catastrophic and ongoing loss of biodiversity. *Science*, 363, 1459–1463.

Smith-Ramírez, C. (2004) The Chilean coastal range: a vanishing center of biodiversity and endemism in South American temperate rainforests. *Biodiversity and Conservation*, 13, 373–393.

Soto-Azat, C., Valenzuela-Sánchez, A., Collen, B., Rowcliffe, J.M., Veloso, A. & Cunningham, A.A. (2013a) The population decline and extinction of Darwin's frogs. *PLOS ONE*, 8, e66957.

Soto-Azat, C., Valenzuela-Sánchez, A., Clarke, B.T., Busse, K., Ortiz, J.C., Barrientos, C. et al. (2013b) Is chytridiomycosis driving Darwin's frogs to extinction? *PLOS ONE*, 8, e79862.

Soto-Azat, C., Valenzuela-Sánchez, A., Ortiz, J.C., Díaz-Páez, H., Castro, C., Charrier, A. et al. (2015) ASG Chile leads update of the extinction risk of Chilean amphibians for the IUCN Red List of Threatened Species. *FrogLog*, 23, 6–7.

Superina, M., Cortés Duarte, A. & Trujillo, F. (2018) Connecting research, management, education and policy for the conservation of armadillos in the Orinoco Llanos of Colombia. *Oryx*, 53, 17–26.

Úbeda, C.A. & Pastore, H. (2015) *Distribución de* Rhinoderma darwinii *en Argentina (Anura, Rhinodermatidae), con Comentarios sobre su Estatus y Conservación*. Resúmenes 6to Congreso Chileno de Anfibios y Reptiles, Red Chilena de Herpetología, Valdivia, Chile.

Uribe-Rivera, D.E., Soto-Azat, C., Valenzuela-Sánchez, A., Bizama, G., Simonetti, J.A. & Pliscoff, P. (2017) Dispersal and extrapolation on the accuracy of temporal predictions from distribution models for the Darwin's frog. *Ecological Applications*, 27, 1633–1645.

Urrutia-Jalabert, R., González, M.E., González-Reyes, Á., Lara, A. & Garreaud, R. (2018) Climate variability and forest fires in central and south-central Chile. *Ecosphere*, 9, e02171.

Valenzuela-Sánchez, A., Harding, G., Cunningham, A.A., Chirgwin, C. & Soto-Azat, C. (2014) Home range and social analyses in a mouth brooding frog: testing the coexistence of paternal care and male territoriality. *Journal of Zoology*, 294, 215–223.

Valenzuela-Sánchez, A., Cunningham, A.A. & Soto-Azat, C. (2015) Geographic body size variation in ectotherms: effects of seasonality on an anuran from the southern temperate forest. *Frontiers in Zoology*, 12, 37.

Valenzuela-Sánchez, A., Schmidt, B.R., Uribe-Rivera, D.E., Costas, F., Cunningham, A.A. & Soto-Azat, C. (2017) Cryptic disease-induced mortality may cause host extinction in an apparently-stable host–parasite system. *Proceedings of the Royal Society B*, 284, 20171176.

Valenzuela-Sánchez, A., O'Hanlon, S.J., Alvarado-Rybak, M., Uribe-Rivera, D.E., Cunningham, A.A., Fisher, M.C. et al. (2018) Genomic epidemiology of the emerging pathogen *Batrachochytrium dendrobatidis* from native and invasive amphibian species in Chile. *Transboundary and Emerging Diseases*, 65, 309–314.

Valenzuela-Sánchez, A., Schmidt, B.R., Pérez, C., Altamirano, T., Toledo, V., Pérez, Í. et al. (2019a) Assessing habitat quality when forest attributes have opposing effects on abundance and detectability: a case study on Darwin's frogs. *Forest Ecology and Management*, 432, 942–948.

Valenzuela-Sánchez, A., Cayuela, H., Schmidt, B., Cunningham, A.A. & Soto-Azat, C. (2019b) Slow natal dispersal across a homogeneous landscape suggests the use of mixed movement behaviours in the Darwin's frog. *Animal Behaviour*, 150, 77–86.