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Rapid endangerment of the lizard *Podarcis pityusensis* by an invasive snake demands an immediate conservation response

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***Abstract*.—Fifteen years have elapsed since the arrival of the invasive snake *Hemorrhois hippocrepis* to the island of Ibiza (Balearic Islands, Spain). In that time, the only endemic vertebrate, the Ibiza Wall Lizard (*Podarcis pityusensis*), has disappeared across half of the island, a subspecies restricted to an offshore islet has vanished, and its extinction in its native range is likely to happen in the next several years if managers do not implement conservation measures with alacrity and decisiveness. In light of these findings, our re-assessment of the IUCN extinction risk category for this lizard shows that its risk status has increased by two levels since its last assessment in 2008, from Near Threatened to Endangered. We also classify this snake as producing a Massive (MA) impact under the Environmental Impact Classification for Alien Taxa. Lastly, we suggest six management measures to prevent the extinction of the majority of genetic and taxonomic diversity of this lizard on Ibiza, Formentera, and the numerous surrounding islets.**

Keywords. Balearic Islands, Europe, extinction, Ibiza, invasive species, management

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Introduction

The prominent role of invasive predators in leading to species extinction on islands is well known (e.g., Ebenhard 1988; Courchamp et al. 2003; Blackburn et al. 2004; Reaser et al. 2007). However, most attention has historically focused on the impacts from mammalian predators. With respect to reptiles, the devastation of Guam's native species by the Brown Treesnake (*Boiga irregularis*) was admitted too late to save most of that island's bird and lizard species (Jaffe 1994), but the snake has since become famous for its wide-ranging ecological impacts (Fritts and Rodda 1998; Rodda and Savidge 2007; Rogers et al. 2012; Caves et al. 2013). Subsequently, snake predation has been inferred as contributing to species losses on other islands (Deso and Probst 2007; Cheke and Hume 2008; Smith et al. 2012), though those invasions have been studied less intensively. Because the impacts from invasive snakes on islands can develop quickly, it is imperative that the introductions of snakes to islands be studied soon after establishment.

Ibiza is the largest of the Pityusic Islands, the southwestern portion of the Balearic Islands, and a small archipelago in the western Mediterranean that is politically part of Spain (Fig. 1A). Ibiza has an area of 572 km^2, maximum elevation of 486 m, mean annual temperature of 18.3 °C, and mean yearly rainfall of 413 mm. The island is covered by native pine and juniper forests (*Pinus halepensis* and *Juniperus phoenicea*), cultivated lands, and native shrubland. The Pityusic Islands currently have one endemic vertebrate, the lacertid lizard *Podarcis pityusensis* (Fig. 1B), though an endemic Dwarf Viper (*Vipera latastei ebusitana*) went extinct with the human colonization of Ibiza 4,000 years ago (Torres-Roig et al. 2020). This lizard occupies Ibiza, Formentera, and most of the surrounding rocks of the Pityusic Islands, a total land area of 656 km^2. Ibiza comprises the large majority of this lizard's native range, although there are introduced populations in the Iberian Peninsula (Carretero et al. 1991; García-Porta et al. 2001; Gosá et al. 2015; Colodro et al. 2020). The species has been divided into 23–28 subspecies using morphological criteria, most of which are restricted to individual small rocks surrounding Ibiza and Formentera (Salvador 2015;

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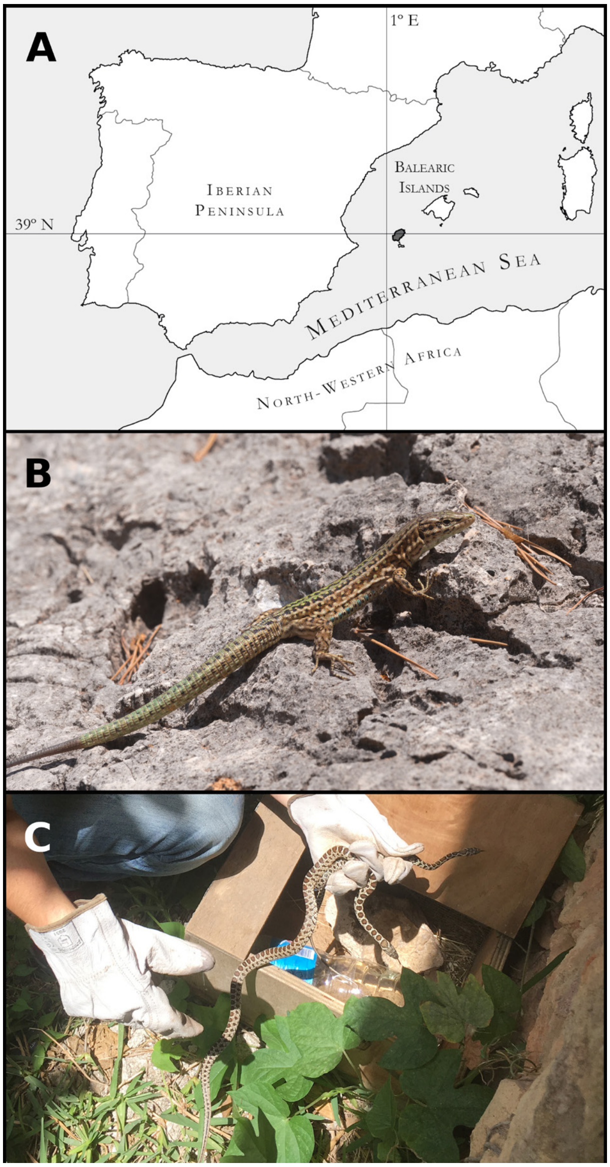

Fig. 1. Basic elements of the system. **(A)** Map showing the location of Ibiza island in relation to the nearest mainland areas in the Iberian Peninsula and northern Africa. **(B)** The endemic lacertid lizard, *Podarcis pityusensis*. **(C)** The invasive colubrid snake, *Hemorrhois hippocrepis. Photos by: Javier Pleguezuelos (A), Juan M. Pleguezuelos (B), and Federico Rey (C).*

Rodríguez et al. 2013). These islet populations are likely evolutionarily significant units (ESU) and, therefore, deserve separate management actions (Pérez-Mellado et al. 2017); however, genetic divergences among the populations are relatively shallow and estimated at ~100,000–300,000 years ago (Rodríguez et al. 2013).

In 2003, the colubrid snake *Hemorrhois hippocrepis* (Fig. 1C) was first reported as introduced to Ibiza via imported olive trees, and it rapidly expanded in numbers and range (Silva-Rocha et al. 2018). Although the exact date of introduction is unknown, it is presumed to be soon before 2003. The primary diet of this snake on Ibiza consists of lizards (Hinckley et al. 2017), which is of concern because of the documented and inferred ability of invasive snakes to exterminate endemic insular vertebrates, including lizards (Fritts and Rodda 1998; Rodda and Savidge 2007; Cheke and Hume 2008; Smith et al. 2012). Consequently, in 2018, we conducted surveys for *P. pityusensis* along 29 500-m line transects in areas with and without established snake populations (Montes et al. 2021). The lizards were found to have disappeared in all but one of the transects with snakes, whereas they maintained healthy populations in areas without snakes. The snakes were found to be expanding their geographic range at a linear rate (Area = 3,189.5 x - 1,384.3, where x = year since 2010, adjusted $R^2 = 0.9800$, $p < 0.0000$), conservatively occupying 28,200 ha (49.3% of Ibiza) by 2018 and projected to occur island-wide by 2027–2028. Those surveys also found snakes swimming far from shore, snakes which had reached some of the offshore islets, and that the lizard subspecies *P. p. hortae*, restricted to S'Ora (0.4 ha), became extinct in the space of 10 months (Montes et al. 2021).

Materials and Methods

Based on our demographic findings (Montes et al. 2021), here we apply the standard threat-assessment methodology (IUCN 2012) to update the red-list status of *P. pityusensis*, and we use the criteria of Blackburn et al. (2014) and IUCN (2019) to assess the impact of the invasive snake. These findings lead us to propose several conservation actions to secure the future of the endemic lizard.

Results

In the current *IUCN Red List of Threatened Species*, *P. pityusensis* is considered Near Threatened (NT) due to hunting and trapping, human intrusions and disturbance, and invasive rats and feral cats (Pérez-Mellado and Martínez-Solano 2009). However, this species was last assessed in 2008, before *H. hippocrepis* had become widespread on Ibiza (range at that time < 1,000 ha). Extrapolating from the rate of range loss in *P. pityusensis* discovered by Montes et al. (2021), bearing in mind that the data in that paper are current to 2018, the lizard is expected to have lost more than 50% of its global range (33,700 ± 1,244 Ha) by the end of 2020—a period of 17 years since the snake was first detected on Ibiza, and only 10 years since the snake occupied only 1,080 ha comprising tree-nurseries and surrounding agricultural and residential areas. The lizard species has been almost completely removed from that range, with just one out of 15 sampled transects in areas inhabited by snakes still containing some lizards (see Table 1 in Montes et al. 2021). Thus, we conclude that *P. pityusensis* should now be classified as globally Endangered, EN A4(bce), based on the observed and projected population reductions, where the cause of reduction is ongoing and, indeed, expanding. This observed population reduction is based on our transect surveys (Montes et al. 2021), which constitute an index of abundance appropriate to the taxon (b), a quantified decline in extent of occurrence (c), and effects of introduced taxa (e) (IUCN 2012). It is remarkable that this species would have jumped two IUCN categories (NT to EN) in just a decade.

Using the IUCN Environmental Impact Classification for Alien Taxa (EICAT), we recognize *H. hippocrepis* as producing a Massive (MA) impact, given that local extinction of the native populations is now widespread, including the endemic subspecies on S'Ora Islet, a harmful irreversible impact (IUCN 2019).

Discussion

In a review of the impacts from invasive herpetofauna, Kraus (2015) noted that massive impacts were often caused by these species, but only rarely via the mechanism of predation. Indeed, only two species—a snake, *B. irregularis*, and a lizard, *Anolis carolinensis*—have been documented to exert these impacts via predation (F. Kraus, unpub. data), though others have retrospectively been inferred to have done so (Cheke and Hume 2008; Smith et al. 2012). Thus, *H. hippocrepis* joins this small contingent of damaging reptiles, being only the third reptile documented during an ongoing invasion to impose massive predation impacts.

It is remarkable that the endemic Ibizan lizard has been virtually extirpated from roughly one-half of its range in less than a decade (Montes et al. 2021). The Brown Tree Snake (*B. irregularis*) required approximately 30–40 years to decimate the native vertebrates on the slightly smaller island of Guam (Fritts and Rodda 1998; Rodda and Savidge 2007), perhaps because there was a greater number of prey items to consume. The rapidity of decline in *P. pityusensis,* and its clear relationship to the expansion of the invasive snake (Hinckley et al. 2017; Montes et al. 2021), demand that immediate conservation actions be taken to save this lizard from extinction. Clearly, the existing trapping and removal efforts implemented by the Balearic Government (COFIB 2017, 2018) are insufficient to protect the lizard.

We suggest six necessary measures if there is to be any hope of preserving *P. pityusensis* from the invasive snake.

1. *Establish captive assurance colonies of P. pityusensis* (in situ *or* ex situ). Our assessment is that *P. pityusensis* could be extinct on Ibiza within a decade, with further extinctions likely on Formentera and the offshore islets as the snake continues trans-marine dispersal. Therefore, it seems critical to develop captive populations of this species as assurance colonies in the event of its extinction in the wild. These colonies should be designed to safeguard the species from extinction, conserve its genetic diversity, and possibly be used to repopulate certain areas should future snake management achievements make this feasible (see Hedrick 1992). It is clearly questionable whether all named subspecies could be conserved in this way, so the first priority should be given to the populations on Ibiza and its nearest islets.

2. *Control the introduction pathway*. Ideally, trade in landscaping trees should be banned to defend against further invasions of snakes and other species. The European Union compels member countries to implement mechanisms to prevent the entrance of invasive species, e.g., EU Regulation 1143/2014 on the prevention and management of introduction and spread of invasive alien species. However, simultaneously, the 1st article of the Council Regulation 2679/98 demands the contradictory goal of removing any obstacle to "free" trade throughout EU territory. This makes it virtually impossible to implement meaningful biosecurity measures that could prevent pest importation, inasmuch as effective biosecurity necessarily imposes a cost to "free" trade. Given that this legal obstruction will not be immediately addressed, we suggest an alternative approach permitting the importation of large trees only from 1 April to 15 June. This would avoid the movement of trees during the cold season (15 October to 15 March), when *H. hippocrepis* hibernates inside such trees (Feriche 2017), as well as during summer (July to September) when eggs are incubating in those same refuges (Pleguezuelos and Feriche 1999). We further suggest that during this 2.5-month period imported trees must also pass quarantine for at least four weeks in an enclosure surrounded by snake-proof fencing (Rodda et al. 2007) containing baited traps (Engeman and Vice 2002). It is essential that the enclosure be located within the Ibiza entrance port facilities, because trees can be sent from many different points of origin in mainland Spain. While in quarantine, the trees should also be searched with detector dogs to minimize any chances of further snake incursions (Clark et al. 2017).

3. *Reinforce existing eradication campaigns* with a greater number of permanent traps, which are showing high capture rates (COFIB 2018) compared to trapping studies in the literature—e.g., 0.0825 snakes/trap-night in high-density locations in this system, compared to 0.044 for aquatic snakes in South Carolina (Durso et al. 2011), 0.0005 for *Python molurus bivittatus* in the Florida Everglades (Reed et al. 2011), 0.127 for *B. irregularis* on Guam (Clark et al. 2012), and 0.019 for *Nerodia fasciata* in southern California (Reed et al. 2016). This measure would aim to reduce snakes in their core area and, hopefully, reduce emigration pressure. Canine teams have demonstrated high detectability of individual snakes (see Ballouard et al. 2019); however, the rock walls used as shelter by these snakes make capturing them virtually impossible. We suggest field testing canine-team effectiveness in concert with thermal fumigation (Kraus et al. 2015) to drive the snakes from these shelters when detected.

4. ***Develop a rapid-response protocol for snake sightings*** in new satellite localities across the southwestern part of Ibiza (where the invasive snake is not yet widespread) and on the islets. This is necessary because the snakes can disperse discontinuously in transported nursery materials and construction materials, or by swimming. This protocol could follow methods developed for other snakes (Stanford and Rodda 2007). We suggest surrounding the area of any new record with baited traps separated at a maximum of 20 m from each other and maintained for four weeks (Engeman and Vice 2002).

5. ***Promote scientific research*** in concert with the above-mentioned actions to solve the problems impeding effective lizard conservation and snake control. Research is needed to optimize the captive management procedures for the lizards, monitor their population trends and range shifts, deepen our understanding of the snake's natural history, and identify biological weaknesses of the snake that may lead to the development of more effective tools to manage it (Andersen et al. 2004). Topics in tool development that require further study include determining optimal spacing among traps, optimal set time for maximizing capture probability per unit area, optimal use of canine teams, possible development of snake toxicants, and the use of thermal fumigation to drive snakes from refuges in stone walls.

6. ***Develop public-education programs*** to improve the reporting of snake sightings and increase the likelihood of snake removal. Immediate reporting of snakes is essential to their successful capture by management personnel, and improved public engagement is needed for this. The Balearic and Ibiza Island governments carry out various campaigns focused on trapping and educating the public by delivering traps and pamphlets to citizens. However, the conflicting system of authorities among the different national, regional, and local administrations—along with fluctuating political interests—make these efforts discontinuous, uncoordinated, and of uncertain duration. We recommend that the already-functioning campaigns become unified and consistent so that Ibiza inhabitants and visitors are provided with a unified message about the problem, the need for continuous and immediate reporting, and the option to place traps around their homes.

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Elba Montes recently finished her Ph.D. at the University of Valencia (Spain), studying the natural history and impacts of the invasive Horseshoe Whip Snake (*Hemorrhois hippocrepis*) on the island of Ibiza. She worked for 11 years in the Ibiza Island Council, and during this time she led the pilot project to control these invasive snakes. She has visited Gran Canaria and Guam to learn about the California Kingsnake (*Lampropeltis californiae*) and the Brown Treesnake (*Boiga irregularis*) invasions and management actions, respectively. Elba is a board member of the Society for Island Biology, an international association that focuses on island biodiversity conservation. *Photo by Federico Rey.*

Fred Kraus is an evolutionary biologist, with about 25 years of experience specializing in the biology and conservation management of invasive species and the systematics of Papuan reptiles and amphibians. He is especially interested in working at the intersection of science and practical conservation. Fred has conducted research in several countries in North America, South America, the Caribbean, Asia, and the Pacific, and he has led 18 biotic-survey expeditions to Papua New Guinea. In addition to conservation work in mainland USA, Hawaii, Fiji, and the Caribbean, he has written a scientific book on invasive reptiles and amphibians, and has many other publications in the field of invasion biology. *Photo by Dickson.*

Juan M. Pleguezuelos was born in northern Africa (in the city of Melilla), and was raised in southern Spain, where he graduated with a Ph.D. in Biology at Granada University. He then taught Zoology and Conservation Biology there for 40 years, and is now retired. Juan's Ph.D. dissertation focused on bird distributions, and for 15 years he worked on the conservation of a large diurnal raptor. From 1985 to the present, his research has focused on reptiles, particularly on the natural history of snakes. But what best defines Juan's career and concerns as a researcher and naturalist is the conservation of biodiversity, mainly in the Western Mediterranean. Most of his studies on the biology and ecology of reptiles were undertaken to understand those traits that would best help the conservation of these animals. Juan has also led the effort to develop the Red List of Spanish and Moroccan amphibians and reptiles. *Photo by Mónica Feriche.*