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Habitat Associations and Distribution Modeling of the Endangered frog *Pseudophilautus zorro* in Sri Lanka

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Abstract.—**Basic ecological information is of critical importance for the development of conservation strategies for endangered amphibian species. The Gannoruwa Shrub Frog (*Pseudophilautus zorro*) is an endangered endemic and a geographically restricted frog found in mid elevations of the central highlands of Sri Lanka whose ecology is little known. We assessed: (1) aspects of microhabitat associations; (2) the realized niche to identify potential areas of occupancy using Ecological Niche Modeling (ENM); and (3) estimated the Extent of Occurrence (EOO) and Area of Occupancy (AOO) of *P. zorro* with new locality data and predicted data. The results indicate that there is a significant positive relationship between leaf litter thickness and number of individuals of *P. zorro* in quadrats and a significant relationship between percentage of canopy cover and number of individuals of *P. zorro* in quadrats. *Pseudophilautus zorro* is more abundant in broad-leaf forests than pine forests. ENM predicted highly suitable areas (suitability > 80%) in the Kandy, Matale, and Kegalle districts in Sri Lanka. The EOO and AOO of *P. zorro* with new occurrence data was 558 km^2 and 9 km^2, and with predicted data, 2,374 km^2 and 612 km^2 respectively, indicating an increase in EOO and AOO. The data on microhabitat preferences and predicted habitats will be invaluable to formulate in-situ and ex-situ conservation strategies for this species.**

Key Words.—amphibians; area of occupancy; canopy cover; conservation; extent of occurrence; Gannoruwa Shrub Frog; leaf litter

Introduction

Anthropogenic activity is a key driver of global biodiversity decline (Pimm et al. 1995). Among vertebrates, amphibians are the most threatened group in the world, with 33% of the global diversity at risk of extinction (International Union for Conservation of Nature [IUCN] 2020). An alarming number of amphibian extinctions have occurred over the last two decades with nearly 35 species becoming extinct and populations of at least 33% of species declining (IUCN 2020), a trend that is likely to accelerate in the future (Stuart et al. 2004). Habitat modification and loss have been identified as key drivers for the decline of amphibians (Delis et al. 1996; Adams 1999; Davidson et al. 2001; Eigenbrod et al. 2008; Smith et al. 2009).

Sri Lanka is remarkably diverse in its amphibian fauna, with a high proportion of endemics and thus is an amphibian hotspot (Meegaskumbura et al. 2002; Manamendra-Arachchi and Pethiyagoda 2005). The island is home to 120 species, 105 (87%) of which are endemic (Batuwita et al. 2019a); however, 67% of Sri Lankan amphibians face extinction and 19 species are already extinct (IUCN 2020) though some species that were thought to be extinct have been rediscovered (Wickramasinghe et al. 2013). As in many parts of the world, habitat loss seems to be the major cause for the decline and extinction of amphibians in Sri Lanka (Pethiyagoda et al. 2006). The majority of the Sri Lankan amphibians are restricted to the south-western wet zone (annual rainfall ≥ 2,500 mm) of the country (Batuwita et al. 2019b) in which > 95% of natural forest cover has been destroyed (Pethiyagoda et al. 2006). The extent of undisturbed forest in the wet zone at best is about 800 km^2 and is severely fragmented (Pethiyagoda et al. 2006). Habitat degradation in the highland (elevation > 900 m above sea level) wet zone is even more severe (Gunetilleke et al. 2008) and coupled with an increase in temperature and decline in precipitation (Abeywickrema et al. 1991), could be detrimental to amphibians in this region. Hence, urgent conservation measures are necessary to mitigate the decline and extinction of amphibians. The development of conservation measures for many amphibian species has been impeded, however, due to the lack of basic ecological information such as habitat preferences and geographic distribution.

The Gannoruwa Shrub Frog, *Pseudophilautus zorro* (Manamendra-Aracchi and Pethiyagoda 2005; Fig. 1) of the family Rhacophoridae, is endemic to Sri Lanka. The species is confined to elevations between 400−800 m in the central highlands of Sri Lanka with an Extent of Occurrence < 5,000 km^2 and an area of occupancy (IUCN, Standards and Petitions Committee. 2019)

Figure 1. An adult male Gannoruwa Shrub Frog (*Pseudophilautus zorro*) from Gannoruwa Forest Reserve, Sri Lanka. (Photographed by Deshan Rupasinghe).

predicted to be < 500 km^2 (Manamendra-Arachchi and Pethiyagoda 2004). Within its range, the species is known only from a few locations, including the Gannoruwa Forest Reserve, Hantana Conservation Area, and the Udawattakele Forest Reserve in the Kandy District (Manamendra-Arachchi and Pethiyagoda 2005), and the Knuckles Conservation Forest (Bandara et al. 2019). The species generally occurs among leaf litter on the forest floor and males ascend shrubs to vocalize at night (Manamendra-Arachchi and Pethiyagoda 2005).

Pseudophilautus zorro inhabits closed canopy forest habitats with sparse understory and occurs also in densely planted residential gardens adjacent to forests (Manamendra-Arachchi and Pethiyagoda 2005). Owing to its restricted distribution, limited number of known localities and predicted habitat decline, *P. zorro* is currently listed as Endangered (Manamendra-Arachchi and Pethiyagoda 2004). Urgent conservation measures are thus needed to prevent this species from becoming critically endangered or extinct in the future. This study was undertaken to identify the habitat associations of *P. zorro* and model the realized niche to identify potentially suitable habitats and environmental correlates that could assist with developing in-situ and ex-situ conservation strategies for this species.

Materials and Methods

Study area.—We conducted the study in Gannoruwa (80.5948° E, 7.2863° N) and Udawattakele Forest Reserves (80.6425° E, 7.2979° N) and the Hantana Conservation Area (80.6203° E 7.2142° N) and adjacent habitats, which are situated in the Central Province of Sri Lanka (Fig. 2). The average annual temperature in this area is 23.5° C and the average annual precipitation is 1,800–2,000 mm (Burt and Weerasinghe 2014). The region experiences two rainy seasons from May through July and October to December, respectively. The driest period of the year is January through to March, when monthly rainfall is often < 100 mm.

Sampling method and data analysis.—We conducted the habitat association study by laying 10 × 10 m quadrats (n = 37) in arbitrarily selected areas in two habitats. The two distinct habitats were broad-leaf vegetation, which included undisturbed tropical dry-mixed evergreen forests and neighboring mahogany (*Sweitenia macrophylla* and *S. mahagoni*) plantations, and Caribbean Pine (*Pinus caribaea*) plantations. As *P. zorro* is a terrestrial litter dwelling species (Manamendra-Arachchi and Pethiyagoda 2005), we cleared the leaf litter in each quadrat using a rake, and then captured, identified, and counted all *P. zorro* present in the quadrats. We identified *P. zorro* following Manamendra-Arachchi and Pethiyagoda (2005). We recorded the GPS location of each quadrat using a

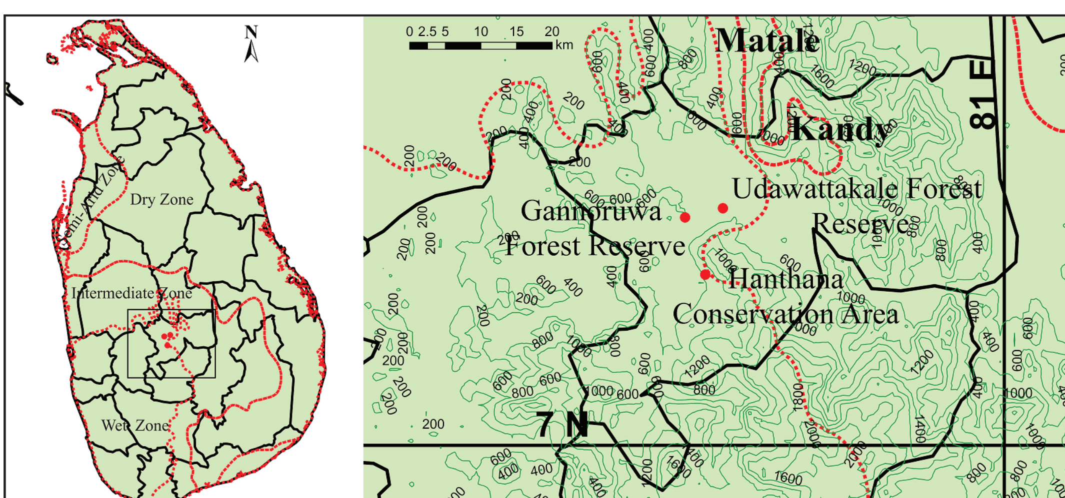

Figure 2. Locations of the study sites, Gannoruwa Forest Reserve, Udawattakale Forest Reserve and the Hanthana Conservation Area in the Kandy District, Sri Lanka. The black lines indicate the administrative district boundaries while green lines represent contour lines.

handheld GARMIN GPSMAP 64s (Garmin Limited, Olathe, Kansas, USA) and recorded parameters such as environmental temperature, leaf litter thickness, percentage canopy cover, and vegetation type, before we raked each quadrat. We measured leaf litter thickness (cm) using a ruler. To determine canopy cover in each plot, we took a digital photograph with constant zoom from the middle of the quadrat at a height of 1.5 m above ground, with the percentage of cover being calculated using Microsoft Visual Studio 2010 software (Microsoft Corporation, Redmond, Washington, USA). The data were not normally distributed, so we performed bivariate Spearman Rank Correlation Tests ($\alpha = 0.05$) to investigate the relationship between leaf litter thickness, canopy cover, and the number of *P. zorro* individuals per quadrat in IBM SPSS 20 software (IBM Corporation, Armonk, New York, USA). To test the association between abundance of *P. zorro* and vegetation type, we compared the number of individuals per quadrat in the two main vegetation types: broad-leaf vegetation and pine plantation using Kruskal-Wallis test at $\alpha = 0.05$.

To determine potential areas of occupancy, we modeled the realized niche of *P. zorro* using the maximum-entropy (Maxent) technique, implemented in the software Maxent (Phillips et al. 2006). We used coordinates of the occurrence localities (n = 9) of *P. zorro* and environmental variable layers as input data in Maxent. We obtained the occurrence localities of *P. zorro* from the present study and published literature (Manamendra-Arachchi and Pethiyagoda 2005; Bandara et al. 2019), while environmental variable layers of the South Asian region (n = 19) came from BIOCLIM (Booth et al. 2014). Additionally, we included the environmental variable layers, land use (Survey Department of Sri Lanka 2015), and elevation (downloaded from WORLDCLIM; Fick and Hijmans 2017) in the analyses as conjectural information suggests that elevation and forest cover could be important determinants of the distribution of this species (Manamendra-Arachchi and Pethiyagoda 2005).

We investigated correlation among the environmental variable layers using Multidimensional Scaling using ENM tools package (Warren et al. 2010) in RStudio (RStudio team 2020). We used a Pearson correlation coefficient > 0.75 as an indication of strong correlation between two environmental variable layers (Warren et al. 2010). To determine the environmental variable layers that contribute most to the model, we used 100 permutations in the enmtools.vip function in ENMtools package (Warren et al. 2010; RStudio team 2020) using all 21 environmental variable layers. Of these, variable importance permutations plot indicated that the following environmental variable layers had the highest importance for the model: Mean Diurnal Range (Mean of monthly [maximum temperature - minimum temperature]; BIO2), Temperature Seasonality (standard deviation of mean monthly temperature × 100; BIO4), Precipitation of Warmest Quarter (BIO18), Temperature Annual Range (BIO7), and Precipitation of Coldest Quarter (BIO19). The final analysis consisted of 10 environmental variable layers, comprising the above five and the following five layers: Elevation, Land Use, Precipitation of Wettest Month (BIO13), Precipitation of Driest Month (BIO14), and Isothermality (BIO3). We excluded all other environmental variable layers in the model building due to spatial autocorrelation. We used 10% of the data points for testing with 10,000 background points (default) and 5,000 iterations for the model building purpose. We processed and interpreted output maps using ArcMap 10.3 (Esri, Redlands, California, USA). We interpreted threshold levels for habitat suitability of the predicted map by maximum training sensitivity and specificity (maxTSS; Liu et al. 2016), and also classified predicted areas in to five groups (100–80%, 80–60%, 60–40%, 40–20%, 20–0%; Kumar and Stohlgren 2009; Sharifi et al. 2017) using ArcMap 10.3.

We determined the extent of occurrence (EOO) with new occurrence data by calculating the area contained within the shortest continuous imaginary boundary, which was drawn to encompass all the known occurrence localities (IUCN 2012), localities obtained from this study, and published literature (Manamendra-Arachchi and Pethiyagoda 2005; Bandara et al. 2019). We calculated the area of occupancy (AOO) with new data by counting the number of 1 km^2 grids that contained occurrence localities using ArcMap 10.3 (IUCN 2012). We predicted the extent of occurrence using the predicted distribution maps using both maxTSS and predicted suitability > 80%. We drew a minimum convex polygon for predicted extent of occurrence by connecting all the grids, which had over 80% suitability for occurrence of *P. zorro* and calculated the area within the polygon using ArcMap 10.3 (IUCN 2012). Similarly, we calculated the predicted EOO through maxTSS threshold by drawing a minimum convex polygon surrounding the entire area predicted to be suitable for *P. zorro* using ArcMap 10.3. We also calculated predicted AOO by counting the number of 1 km^2 squares with over 80% suitability (IUCN 2012). Further, we calculated predicted AOO through maxTSS threshold by counting the number of 1 km^2 grids that contained the predicted suitable area in ArcMap Version 10.3.

Results

Leaf litter thickness and number of *P. zorro* per quadrat was significantly positively correlated ($r = 0.667$, $P \leq 0.001$) when all quadrats including those that did not contain individuals of the species were included

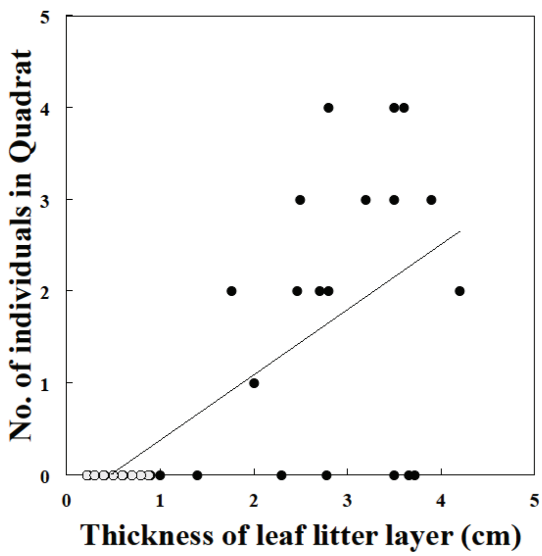

Figure 3. Relationship between the leaf litter thickness and the number of individuals in quadrats of Gannoruwa Shrub Frogs (*Pseudophilautus zorro*) from Sri Lanka.

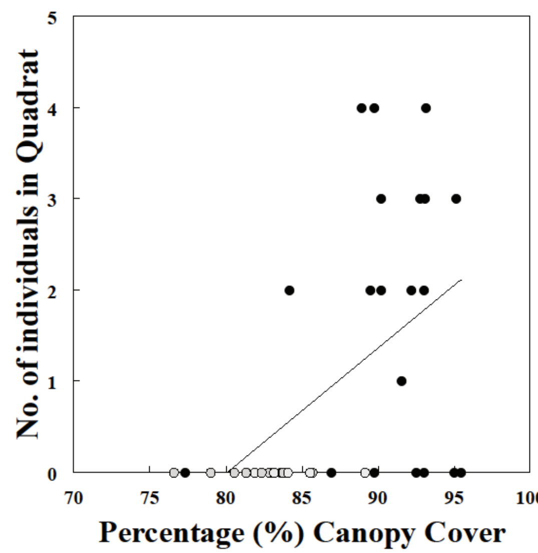

Figure 4. Relationship between the percentage of canopy cover and number of individuals in quadrats of Gannoruwa Shrub Frogs (*Pseudophilautus zorro*) from Sri Lanka.

in the analysis (Fig. 3). This relationship was weaker and insignificant, though, when quadrats that did not contain the species were omitted from the analysis (r = 0.507, P > 0.076). Canopy cover and number of individuals of *P. zorro* in quadrats also was significantly correlated (r = 0.543, P < 0.001; Fig. 4). The variation in the occurrence of *P. zorro* among the two habitat types was significantly different (H = 14.90, df = 1, P < 0.001).

The mean Area Under the Curve (AUC) value was 0.974 indicating good model performance. The Maxent model predicted highly suitable (suitability > 80%) areas in the Central and Sabaragamuwa provinces (Fig. 5). The highly suitable areas in the Central province were mainly in the Kandy District, while a few were in the Matale District. The suitable sites in the Sabaragamuwa province were restricted to a few localities in the Kegalle District (Fig. 5). Suitable areas predicted through maxTSS threshold indicated most of the central highlands of Sri Lanka, which included Kandy, Matale, Kegalle, Nuwara Eliya, and Kurunegala districts (Fig. 6); however, we did not observe this species in predicted areas of Nuwara Eliya and Kurunegala districts during our recent surveys.

The environmental variable layer Mean Diurnal Range had the highest percentage contribution (59%) and permutation importance (58.6%) indicating its significance to the prediction of the model. The predictive contribution of the environmental variable

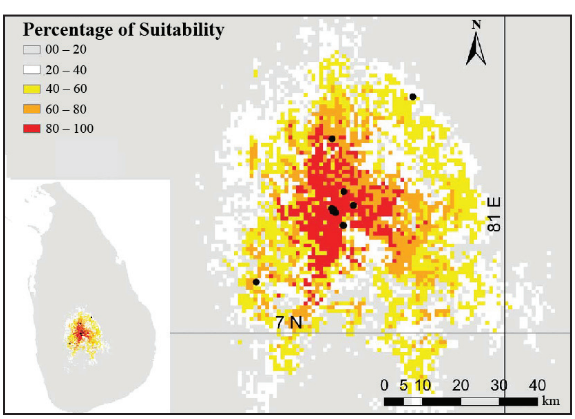

Figure 5. Predicted suitable (threshold > 80%) habitat of Gannoruwa Shrub Frogs (*Pseudophilautus zorro*) in Sri Lanka. Black dots indicate occurrence localities of P. zorro, which were used in Ecological Niche Modeling.

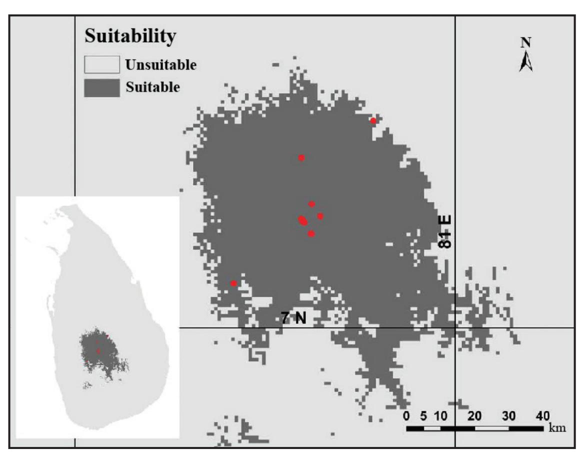

Figure 6. Predicted suitable habitat of Gannoruwa Shrub Frogs (*Pseudophilautus zorro*) in Sri Lanka with maxTSS threshold. Red dots indicate occurrence localities of P. zorro, which were used in ENM.

Table 1. The relative contribution of different environmental layers (BIO#) to the prediction of suitable areas for the Gannoruwa Shrub Frog (*Pseudophilautus zorro*) in Sri Lanka. Only the highest contributing layers are shown here. The Mean Diurnal Temperature Range is calculated as the mean of monthly maximum temperature - minimum temperature. Temperature Seasonality is calculated as the standard deviation of mean monthly temperature × 100.

Variable	Percentage contribution	Permutation importance
Mean Diurnal Temperature Range (BIO2)	59.2	58.6
Precipitation of Driest Month (BIO14)	22.2	1.2
Temperature Seasonality (BIO4)	6.8	24
Temperature Annual Range (BIO5-BIO6 = BIO7)	4.5	2.9
Elevation	2.7	2
Precipitation of Warmest Quarter (BIO18)	2.6	8.5

layers Precipitation of Driest Month and Temperature Seasonality were 22.2% and 6.8% respectively (Table 1). The environmental variable layer with the highest gain when used in isolation was Mean Diurnal Range, which therefore appears to have the most useful information for the model by itself. The environmental variable that decreased the gain most when omitted was also Mean Diurnal Range, which therefore appears to have high predictive value for the prediction that is not present in the other variables. The total EOO for *P. zorro* was 558 km^2, while the AOO was 9 km^2 with new occurrence data. Predicted EOO and AOO calculated from the area > 80% suitability for *P. zorro* was respectively 2,374 km^2 and 612 km^2. Predicted EOO and AOO calculated from the area suitable for *P. zorro* delimited by maxTSS threshold was respectively 8,498 km^2 and 4,687 km^2.

Discussion

We found that *Pseudophilautus zorro* is associated with habitats with thick leaf litter (average = 3 cm) and a dense canopy cover (91%). Further, it is strictly limited to broad-leaf forests rather than exotic pine plantations. New distribution data and ecological niche modeling indicated changes in currently recognized EOO and AOO of the species. Also, ecological niche models indicated highly suitable areas for *P. zorro* in the Kandy, Matale, Kurunegala, and Kegalle districts in the Central, Northwestern and Sabaragamuwa provinces of Sri Lanka.

The positive association between leaf litter thickness and the number of *P. zorro* individuals observed per quadrat could be attributed to a number of factors associated with its terrestrial mode of life (Manamendra-Arachchi and Pethiyagoda 2005). The leaf litter most likely camouflages *P. zorro*, the body coloration of which resembles that of litter. Furthermore, during dry conditions, the frogs can retreat into moist litter to avoid desiccation. A thick litter layer also helps retain moisture in the sub-surface environment, which is essential for direct developing frogs such as *P. zorro* that lay eggs in moist soil (Bahir et al. 2005). The type and quantity of litter may also affect arthropod availability (Heinen 1992), which is the main food source of amphibians (Solé and Rödder 2010). Previous studies of leaf-litter dwelling frogs in the tropics have also revealed strong positive correlations with leaf litter thickness and amphibian species diversity and abundance (Scott 1976; Fauth et al. 1989).

The significant correlation we observed between canopy cover and the number of individuals of *P. zorro* per quadrat has also been reported for other litter dwelling amphibians in the tropics (Heinen 1992). This association probably relates to the fact that leaf litter levels are determined by the overlying canopy cover and the accumulation of litter on the forest floor. The accumulation of litter on the forest floor is dependent upon litter decomposition rates, which are in turn influenced by many other factors such as moisture content, temperature, chemical composition of litter, and soil organisms (Krishna and Mohan 2017). The canopy also provides shade and reduces evaporation of moisture from the leaf litter layer (Tanaka and Hashimoto 2006). Hence, long-term survival of this species depends upon the availability of broad-leaved forest habitats with canopy cover. Thus, it is critical that broad-leaf forests with thick canopy cover in the Kandy, Matale, and Kegalle districts are surveyed for the presence of *P. zorro* and protected to ensure the future survival of this endangered species. Further, the establishment of home gardens (Pushpakumara et al. 2016) with dense canopy cover (> 80%) in anthropogenic environments adjacent to its natural habitats may also provide suitable supplementary habitat for this species as well as many other species of amphibians (Somaweera and Ukuwela 2004; Kumara and Ukuwela 2009). The significant variation in the occurrence of *P. zorro* observed between the two main vegetation types, and the complete absence of *P. zorro* from the exotic pine plantations, indicate a distinct preference for broad-leaf forests by this species. The difference in occurrence between these two habitat types could be due to the ability of broad-leaved habitats to retain more moisture in the leaf litter (Shi et al. 2015; Sheng-ping and Jun 2018), greater diversity and abundance of insect prey (Heinen 1992; Robson et al. 2009) and protection from predators. Alternatively, the origin of pine plantations, which were established in abandoned tea gardens, completely removed natural vegetation more than a century ago, no doubt extirpating *P. zorro*. The absence of *P. zorro* in pine plantations adjacent to *P. zorro* habitat, and the presence of *P. zorro* in broad-leaved non-native mahogany plantations in the Gannoruwa Forest Reserve indicates a failure of *P. zorro* to colonize pine forests.

The high AUC value (0.974) indicated good model performance and accuracy reflecting that the model can discriminate accurately between locations at which the species is present or absent (Pearson 2010; Merow et al. 2013). Because narrow range species have high AUC values; our AUC values may not in fact reflect high model performance (Lobo et al. 2008) but could be an overestimation, and thus should be treated with caution. The use of nine presence points against 10,000 background points (i.e., pseudo-absence points) in this study may have created an imbalance in the analyses; however, model performance and predictive accuracy is higher when 10,000 background points are used (Barbet-Massin et al. 2012). Given that the absolute minimum presence points considered to be permissible for ENM is three for narrow range species (van Proosdij et al. 2016), it is possible that this imbalance between presence points and background points could be less significant in this study.

The prediction of highly suitable areas (suitability > 80%) in the Central and Sabaragamuwa provinces through ENM indicate that the habitats in these regions of Sri Lanka including Kandy, Matale, and Kegalle districts have environmental conditions suitable for *P. zorro*, albeit this needs confirmation through surveys. The prediction of highly suitable areas with maxTSS threshold had a wider region encompassing most of the central highlands of Sri Lanka. Yet, our recent surveys in these areas failed to recover this species in majority of the area predicted by maxTSS threshold. Further, the majority of the natural habitats in the region have been cleared for plantations and human habitations (Wickramagamage 1998) in the last century. Small forest fragments that have not been surveyed within the predicted area may yet persist, with populations of *P. zorro*. Because the land use variable incorporated into the suitability model dates from 2015, some of the suitable areas predicted may no longer be favorable for *P. zorro* due to subsequent deforestation and habitat degradation. Urgent action needs to be taken to survey and confirm the presence of *P. zorro* in the remaining natural habitats and adjacent home gardens.

The EOO in our study (558 km^2) is higher than previous estimates (20.19 km^2; Manamendra-Arachchi and Pethiyagoda 2004). This discrepancy could be due to the previous estimate being limited to Gannoruwa Forest Reserve and the adjacent areas. The present estimate includes localities such as the Hanthana Conservation Area, Udawattakale Forest Reserve, Doteloya forest in the Kegalle District and the Knuckles conservation forest, where the occurrence of *P. zorro* has now been established. Further, the AOO according to this study was 9 km^2, while the predicted EOO through ENM from the two separate thresholds were 2,374 km^2. The marked increase in EOO should be treated with caution until the presence of the species within the region is confirmed. The same caution applies to the EOO predicted through ENM. Both EOO and AOO delimited by maxTSS threshold was comparatively greater than those predicted with 80% suitability threshold. Predicted area delimited by maxTSS includes a large area that is higher than 1,000 m elevation; however, *P. zorro* appears to be restricted to elevations lower than 800 m (Manamendra-Arachchi and Pethiyagoda 2005). The predicted area delimited by maxTSS threshold, therefore, may not represent the actual realized niche or the distribution range of *P. zorro*. Based on available data, the predicted area delimited by > 80% suitability threshold might truly represent the actual range of the species.

In general, the variables linked to temperature (BIO2, BIO4, BIO18) and precipitation (BIO14) had high predictive value in the model. Higher temperatures can increase evaporation from leaf litter (Kreye et al. 2018) and influence the distribution of *P. zorro*, which depends on the leaf litter moisture for survival and reproduction. In general, reduced moisture levels can reduce the survival of adult terrestrial amphibians (Rohr and Madison 2003) and desiccate the direct developing eggs (Bahir et al. 2005). This assertion is further strengthened by the observation that during the comparatively dry months of the study period, *P. zorro* was rarely found at sites in which they had previously been recorded. This may be due to *P. zorro* estivating to avoid unfavorable conditions. Nevertheless, prolonged droughts that could create highly desiccating conditions may severely threaten the existence of *P. zorro* even in the most suitable habitats. Furthermore, one of the prime habitats for *P. zorro*, Gannoruwa Forest Reserve, lacks surface water bodies, making the area more vulnerable to rapid desiccation. Even in good habitats, significantly reduced rainfall, changes in rainfall seasonality and increasing temperatures could pose severe threats to populations of *P. zorro* and many other anuran species in Sri Lanka. This is especially relevant as recent studies indicate trends in increasing temperatures and decreasing rainfall in many regions of Sri Lanka, including our study area (De Costa 2008; Naveendrakumar et al. 2018).

We believe that our study provides a starting point for habitat modeling of threatened species in Sri Lanka. By identifying potential new habitats and variables such as leaf litter thickness and broad-leaved canopy cover, which are positively associated with *P. zorro* abundance, modeling studies can streamline conservation efforts and narrow down survey efforts to sites with a high probability of occurrence. Identifying habitat variables that are positively associated with the abundance of endangered species such as *P. zorro* has implications for both in-situ and ex-situ conservation of endangered species.

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