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Potential distribution and effectiveness of the protected area network for the crocodile lizard, *Shinisaurus crocodilurus* (Reptilia: Squamata: Sauria)

Mona van Schingen[1,2], Flora Ihlow[3], Truong Quang Nguyen[2,3,4], Thomas Ziegler[1,2], Michael Bonkowski[2], Zhengjun Wu[5] & Dennis Rödder[3]

[1)] Cologne Zoo, Riehler Str. 173, 50735 Cologne, Germany

[2)] Dept. of Terrestrial Ecology, University of Cologne, Zülpicher Str. 47b, 50674 Cologne, Germany

[3)] Herpetology Section, Zoologisches Forschungsmuseum Alexander Koenig, Adenauerallee 160, 53113 Bonn, Germany

[4)] Institute of Ecology and Biological Resources, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet Road, Hanoi, Vietnam

[5)] Key Laboratory of Rare and Endangered Animal Ecology, Guangxi Province, College of Life Science, Guangxi Normal University, Guilin, 541004, China

Corresponding author: Dennis Rödder, e-mail: d.roedder@zfmk.de

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Abstract. The crocodile lizard, *Shinisaurus crocodilurus* Ahl, 1930, is a monotypic taxon, restricted in occurrence to southern China and northern Vietnam. Wild populations are presently suffering tremendous declines, mainly due to illegal poaching, habitat destruction, and fragmentation, which already led to the extinction of populations in Guangxi and Hunan provinces in China. In order to accelerate the discovery of so far unknown populations of *S. crocodilurus* and to identify suitable priority areas for conservation strategies, we determined the species' potential distribution using correlative species distribution models (SDMs) based on locality records and a set of satellite-based environmental predictors. In addition, we evaluated the coverage of the species' potential distribution with designated protected areas according to IUCN standards. The resulting SDM revealed potentially suitable habitats to be scattered and disconnected while being very small in size. Moreover, present coverage with nature reserves is extremely poor, underlining the urgent need for improved habitat protection measures and potential population restoration of *S. crocodilurus*.

Key words. Shinisauridae, Diploglossa, Conservation planning, Habitat suitability modelling, Species distribution modelling, Southeast Asia, Vietnam.

Introduction

The crocodile lizard, *Shinisaurus crocodilurus* Ahl, 1930, is the only living representative of the monotypic family Shinisauridae, and despite its striking appearance, it was only described relatively recently (Hu et al. 1984, Zhang 1991). The species usually is found along slow-flowing rocky streams in montane evergreen forests. The altitudinal range of this species was reported to reach from 200 to 1,500 m in China and from 400 to 800 m in Vietnam. (Zhao et al. 1999, Le & Ziegler 2003, Huang et al. 2008). So far, the occurrence of *S. crocodilurus* has been confirmed from Guangxi and Guangdong provinces in southern China while a couple of populations in Hunan and Guangxi provinces have already been extirpated (Huang et al. 2008, Zollweg & Kühne 2013, Z. Wu pers. comm.). In northern Vietnam, the species has been reported from the contiguous nature reserves Tay Yen Tu in Bac Giang Province and Yen Tu in Quang Ninh Province (Hecht et al., 2014, Le & Ziegler 2003, Ziegler et al. 2008, Nguyen et al. 2009). However, a variety of anthropogenic hazards have caused severe population declines within the last decades, reducing estimated population densities in China from 6,000 to 950 individuals between 1978 and 2008 (Zhao et al. 1999, Mo & Zou 2000, Huang et al. 2008). Illegal poaching for the international pet trade, traditional medicine and food represents the main driver fuelling the ongoing population decline, while habitat degradation, electro-fishing and fishing with poison also contribute to the species' demise (Huang et al. 2008). The Vietnamese populations are currently also threatened by habitat loss and alterations caused by intensive coal mining and illegal timber logging (Ziegler et al. 2008, M. van Schingen pers. obs.). The species' small body size combined with its striking appear-

ance makes *S. crocodilurus* a desired target for poachers supplying the international pet trade (Le & Ziegler 2003, Huang et al. 2008). Therefore, the already heavily diminished populations of *S. crocodilurus* will likely continue to decline in China as well as in Vietnam if no immediate preventative conservation measures are initiated. While the species has not been assessed by the 'IUCN Red List' yet, it was assigned to Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and classified as a Category-I species under the 'Wild Animal Protection Law' in China (Huang et al. 2008, CITES 2013). This species has also been proposed to be included in the checklist of protected species in Vietnam (Nguyen 2011).

Correlative species distribution models (SDMs) have been used successfully to reveal potentially suitable habitats and investigate the effectiveness of protected areas (e.g., Araújo et al. 2004, Araújo et al. 2007, Hannah et al. 2007, Rödder & Schulte 2010, Rödder et al. 2010). The poikilothermic species' strong dependence on environmental conditions (e.g., water, ambient temperature) (Zhao et al. 1999, Ning et al. 2006, Wang et al. 2009) in combination with a preference for specific microhabitat characteristics renders *S. crocodilurus* an ideal taxon for performing species distribution modelling approaches. Thus, it is the aim of the present paper to predict the potential distribution of *S. crocodilurus* by applying SDMs and to identify potentially suitable habitats to guide further field exploration as a basis for improved protected area management planning.

Methods

We performed SDMs based on locality records and a set of environmental predictors that combine environmental variables and remote sensing data. We compiled a total of 20 occurrence records, partly from our own field research in northern Vietnam and southern China, as well as from literature (Huang et al. 2008). We computed a set of twelve environmental predictors based on temporal transformations of remote sensing data, using the *dismo* and *raster* packages for *Cran R* (Hijmans & van Etten 2012, Hijmans et al. 2012, R Core Team 2012). A set of pre-processed remote sensing variables derived from MODIS sensors of two NASA satellites (spatial resolution = 30 arc sec; temporal resolutions: MOD11A2 = 8-day averages; MCD43B4 = 16-day averages [Mu et al. 2007, Scharlemann et al. 2008]) was obtained from the EDENext project (imagery produced by the TALA Research Group, Oxford University using methods described in Scharlemann et al. 2008). The raw remote sensing dataset comprised monthly averages of the enhanced vegetation index (EVI), the normalized vegetation index (NDVI), and day- and nighttime land surface temperatures, collected between 2001 and 2005. The derived environmental predictors comprise variables describing annual averages as well as seasonal variability (Tab. 1).

We computed pairwise coefficients of determination based on Spearman rank correlations to assess co-linearity. A subset of twelve variables was selected with $R^2 < 0.75$, which was clipped to the spatial extent of the species' geographical range. We modelled the potential distribution of *S. crocodilurus* using the *biomod2* package v. 2.1.15 (Thuiller et al. 2013) for *Cran R*, applying the following algorithms: 'Generalised Boosting Models' (GBM), 'Multivariate Adaptive Regression Splines' (MARS), 'Generalized Linear Models' (GLM), 'Generalized Additive Models' (GAM), 'Classification Tree Analyses' (CTA), 'Artificial Neuronal Networks' (ANN), 'Surface Range Envelopes' (SRE), and 'Maxent'. The models were trained using a randomly selected subset of the species' occurrence records (80%), while the remaining 20% were used to analyse model performance with five iterations per algorithm, applying the 'receiver operating characteristic curve' (ROC) (Swets 1988), 'Cohen's Kappa', and the 'True Skill Statistic' (TSS) (Allouche et al. 2006). We used 1,000 randomly created pseudo-absence records within a circular buffer of 50 km, encompassing each presence record for model building. Based on the SDMs, we computed an ensemble integrating all SDMs with ROC > 0.7 ranked according to their performance. The final ensemble was projected onto a rectangular area slightly larger than the area covered by the species records to highlight potentially suitable habitats in northern Vietnam and southern China. As a presence/absence threshold, we selected the minimum score observed in the species' records. Areas characterized by environmental conditions exceeding those available within the 50 km buffer enclosing all species records were excluded from projections as extrapolations beyond the training range of the ensemble, as these would likely increase the uncertainty factor.

Potential habitat suitability for *S. crocodilurus* as well as the coverage with designated protected areas according to IUCN standards (categories I, II, IV, V, VI; IUCN 2013) were evaluated across the study area in order to reveal potentially suitable habitat yet unexplored for the occurrence of the species and to ease the future management planning of reserves. We obtained protected area shape files from the World Database of Protected Areas (IUCN, UNEP-WCMC 2013). To characterize the realized and potential niche of the species, we extracted all environmental variables from the existing species records as well as from the available environmental background within the 50 km buffer and computed density estimates using the *sm* package for *Cran R*.

Results

New population record

As a result of our recent field research in northern Vietnam in 2013, another population of *S. crocodilurus* was discovered in the Dong Son – Ky Thuong Nature Reserve on the eastern side of Yen Tu Mountain in Quang Ninh Province. The new population is distant by about 40 km from the known subpopulations in Vietnam (Bac Giang and Quang Ninh provinces) and 380 km from the closest subpopulation in China (Guangxi Province). We could also extend the known altitudinal range of the species in Vietnam (from

Table 1. Environmental variables and derived variables sets used for SDM development.

Abbreviation	Set variable	Derived variable
ED15078_bio10	MODIS V4 Band 07 + 08 Synoptic Months: Day- + Night-time Land Surface Temperature	Mean Temperature of Warmest Quarter
ED15078_bio11	MODIS V4 Band 07 + 08 Synoptic Months: Day- + Night-time Land Surface Temperature	Mean Temperature of Coldest Quarter
ED15078_bio2	MODIS V4 Band 07 + 08 Synoptic Months: Day- + Night-time Land Surface Temperature	Mean Diurnal Range (Mean of Monthly max–min Temp.)
ED15078_bio3	MODIS V4 Band 07 + 08 Synoptic Months: Day- + Night-time Land Surface Temperature	Temperature Isothermality (BIO2/BIO7) (* 100)
ED15078_bio4	MODIS V4 Band 07 + 08 Synoptic Months: Day- + Night-time Land Surface Temperature	Seasonality of Temperatures
ED15078_bio5	MODIS V4 Band 07 + 08 Synoptic Months: Day- + Night-time Land Surface Temperature	Maximum Temperature Warmest Month
ED15078_bio7	MODIS V4 Band 07 + 08 Synoptic Months: Day- + Night-time Land Surface Temperature	Temperature Annual Range (BIO5-BIO6)
ED1514_bio1	MODIS V4 Band 14 Synoptic Months: Normalised Difference Vegetation Index (NDVI)	Annual Mean NDVI
ED1514_bio7	MODIS V4 Band 14 Synoptic Months: Normalised Difference Vegetation Index (NDVI)	Annual Range of NDVI
ED1515_bio1	MODIS V4 Band 15 Synoptic Months: Enhanced Vegetation Index (EVI)	Annual Mean EVI
ED1515_bio5	MODIS V4 Band 15 Synoptic Months: Enhanced Vegetation Index (EVI)	Maximum Monthly EVI
ED1515_bio7	MODIS V4 Band 15 Synoptic Months: Enhanced Vegetation Index (EVI)	Annual Range of EVI

400 to 800 m, see Le & Ziegler 2003, Ziegler et al. 2008) by discovering individuals occurring from 180 m a.s.l. in the Dong Son – Ky Thuong Nature Reserve to 850 m a.s.l. in the Yen Tu Nature Reserve, revealing a similar altitudinal range compared to Chinese populations (from 200 to 1,500 m, see Huang et al., 2008, Zhao et al. 1999).

Realized and potential niche

With respect to all univariate comparisons, *S. crocodilurus* occupied an environmental niche nested in the overall available niche space (Fig. 1). The comparisons revealed only slightly smaller spans of the realized niches compared to the available niches, but different density maxima (Fig. 1), as *S. crocodilurus* occupies areas with relatively low NDVI scores compared to the overall NDVI range, indicating its close dependence on intact vegetation. Furthermore, *S. crocodilurus* inhabits areas with an annual temperature range that is relatively constant without extreme maxima. The overall relatively low annual temperature range is consistent with mountainous habitats.

Potential distribution

With 'excellent' ROC values being obtained for the ensemble (ROC_{test} = 0.996, Kappa = 0.239, TSS = 0.957), the model shows a strong ability to discriminate between suitable and unsuitable habitats. The variable ED1514_bio7 (Annual Range of NDVI) had the strongest effect on the model (52%) as measured by permutation importance, followed by ED15078_bio7 (Temperature Annual Range) (50%), ED15078_bio4 (Seasonality of Temperatures) (41%), ED15078_bio10 (Mean Temperature of Warmest Quarter) & ED15078_bio3 (Temperature Isothermality) (38%), ED15078_bio2 (Mean Diurnal Temperature Range), and ED1515_bio5 (Maximum Monthly EVI) (37%), whereas the remaining variables contributed on average less than 35% to the final model. The ensemble revealed only small proportions of the study extent to provide suitable habitats (China: 1.12%; Vietnam: 4.29%; Fig. 2). Only a fraction of the selected study region was found to be covered by protected areas in Vietnam (17.29%) while only 6.31% of the study region was found to be covered by reserves in China. Furthermore, only a fraction of habitat deemed suitable is presently located within designated protected areas (1.74% in China and 0.15% in Vietnam; Fig. 2). The model suggests potential additional occurrences of *S. crocodilurus* to exist, amongst others, in the Shiwandashan Nature Reserve (SNR) in southern China. According to our model, the SNR situated between the confirmed localities in southern China and northern Vietnam represents the largest contiguous area of potentially suitable habitat in China (Fig. 2). Small fragmented areas with high predicted probabilities for the occurrence of *S. crocodilurus* are scattered across northwestern Vietnam, but are presently not protected.

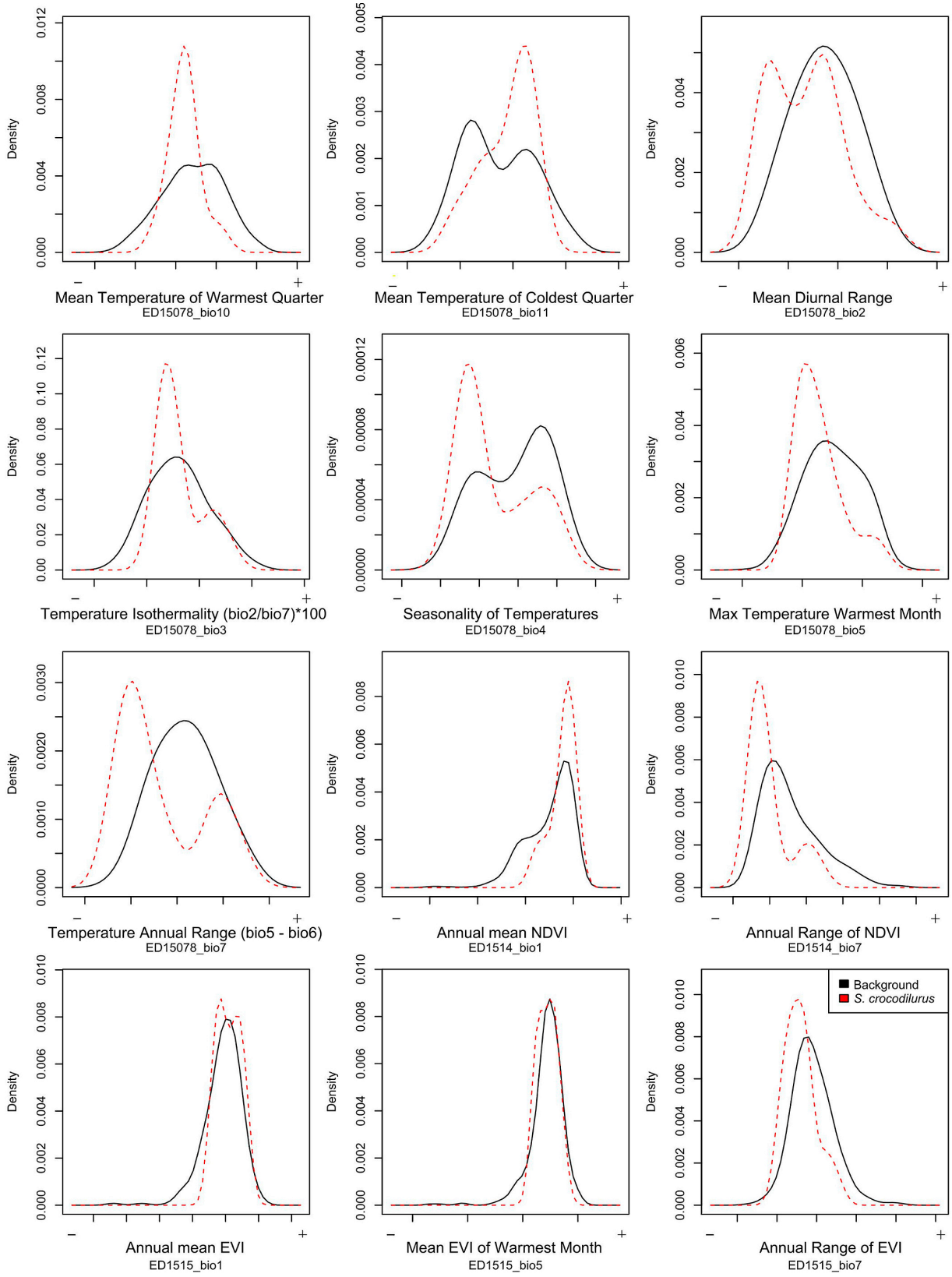

Figure 1. Comparisons of density distributions of the realised bioclimatic space of *Shinisaurus crocodilurus* with the potential available space along 12 environmental variables. Note that derived variables comprise relative scores specific to the study area. Therefore, only qualitative units are shown.

Discussion

Density estimates across the 12 environmental gradients revealed different characteristics of the available vis-à-vis realised niche, indicating that *S. crocodilurus* is a habitat specialist. Denoted already by Ning et al. (2006), the vegetation index proved to be a determinant for the occurrence of *S. crocodilurus*. In accordance with previous studies (Zhao et al. 1999, Wang et al. 2009), temperature-related variables revealed a strong contribution to the SDMs, as the species occupies habitats characterised by low temperatures as well as a low diurnal and annual temperature range. These microhabitat conditions are also characteristics of mountainous habitats. Our model revealed several spots covered by potentially suitable habitats to be situated in northwestern Vietnam. To date, the species has not been confirmed to occur in this area, and the Red River might serve as a geographical barrier, restricting the species' distribution to northeastern Vietnam. However, SDMs are not able to identify geographical barriers and the accessibility of a potentially suitable habitat so that this hypothesis has to be verified by further field surveys. The small size of potentially suitable habitats combined with heavy fragmentation and poor coverage with designated protected areas underlines the urgent need for significant improvements of the existing reserve network to increase effectiveness for the conservation of *S. crocodilurus.* Therefore, potentially suitable habitats with high detection probabilities should be surveyed for occurrences of the rare species. Due to its limited dispersal capacity, its close dependence on water (Zhao et al. 1999, Le & Ziegler 2003, Zollweg & Kühne 2003, Zheng & Zhang 2004, Ning et al. 2006, Huang et al. 2008), and a rather sedentary lifestyle, we expect locations situated in close proximity or between confirmed populations, such as the SNR in southern China or the Khe Ro Sector within Tay Yen Tu Nature Reserve in Vietnam, to be most promising. Such areas might represent important stepping stones for the species. The few existing reserves presently holding populations of *S. crocodilurus* (Tay Yen Tu, Yen Tu, and Dong Son – Ky Thuong nature reserves in northern Vietnam and the Luokeng, Daguishan, and Linzhouding nature reserves in southern China) need to be subjected to significant law enforcement to reduce the collection of individuals to a minimum and prevent electro-fishing and fishing with poison. Moreover, these protected areas should be considered for status elevation to prevent further habitat loss and fragmentation. The alarmingly rapid population declines observed recently throughout the species' distributional range highlights the urgency of an assessment for the IUCN Red List, which is currently undertaken by the IEBR and the Cologne Zoo, as well as the need for a zero quota on the commercial trade of wild-caught specimens. Not only the status, but also the size of the remaining populations should be analysed or re-analysed contemporarily to clarify whether scientifically coordinated population restoration is required besides improved habitat protection measures.

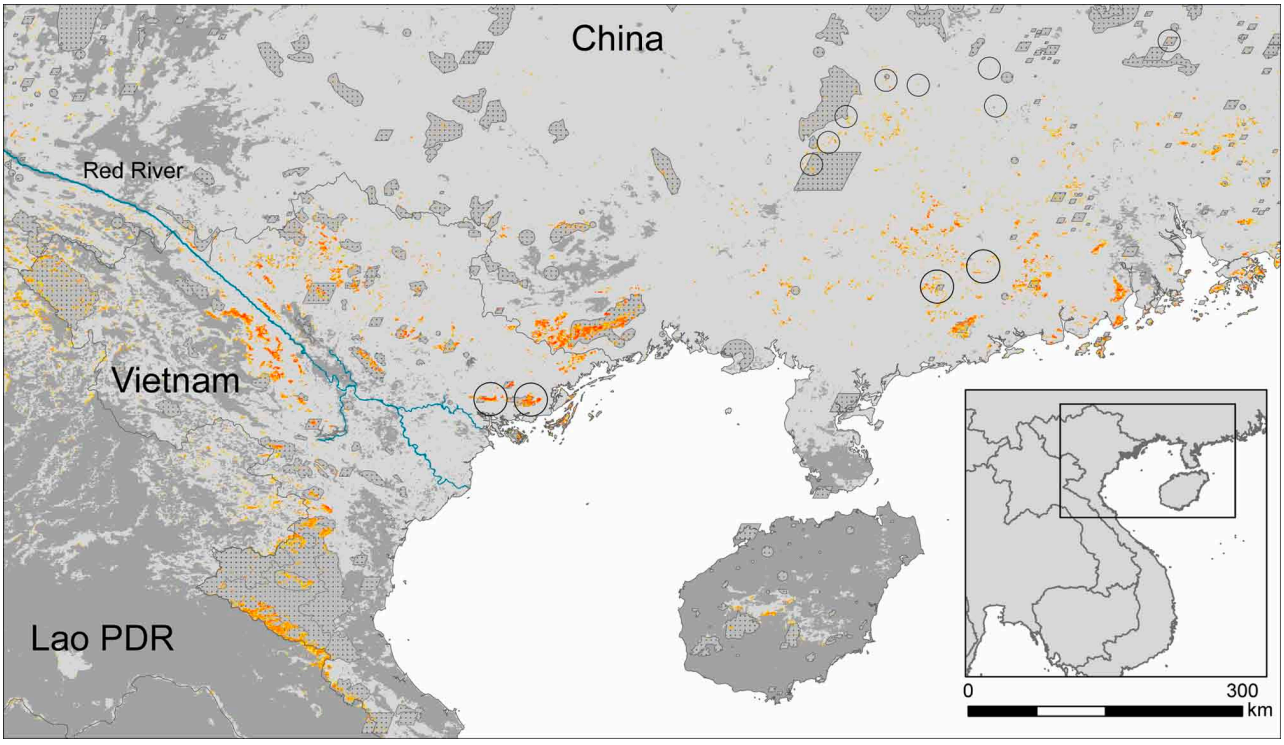

Figure 2. Occurrence records of *Shinisaurus crocodilurus* are displayed as black circles, with potential habitat suitability ranging from low (yellow) to high (red), coverage with designated reserves (stippled polygons), and the course of Red River (blue). For dark grey areas, no predictions could be made, as environmental conditions exceed the training range of the SDM. Only vague locality information is displayed in order to protect remnant populations.

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