Herpetological Conservation and Biology 10(3):948–958.
Submitted: 9 August 2015; Accepted: 16 October 2015; Published: 16 December 2015.

FIRST ECOLOGICAL ASSESSMENT OF THE ENDANGERED CROCODILE LIZARD, *SHINISAURUS CROCODILURUS*, AHL, 1930 IN VIETNAM: MICROHABITAT CHARACTERIZATION AND HABITAT SELECTION

MONA VAN SCHINGEN[1,2], CUONG THE PHAM[3], HANG AN THI[3], TRUONG QUANG NGUYEN[3], MARTA BERNARDES[1,2], MICHAEL BONKOWSKI[2], AND THOMAS ZIEGLER[1,2,4]

[1]Cologne Zoo, Riehler Straße 173, 50735, Cologne, Germany
[2]Department of Terrestrial Ecology, Institute of Zoology, University of Cologne, Zülpicher Straße 47b, 50674, Köln, Germany
[3]Institute of Ecology and Biological Resources, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet Road, Hanoi, Vietnam
[4]Corresponding author, e-mail: ziegler@koelnerzoo.de

***Abstract.*—The monotypic Crocodile Lizard (*Shinisaurus crocodilurus*) is a habitat specialist, adapted to headwaters of remote mountain streams within the tropical rainforests of southern China and northern Vietnam. Due to the anthropogenic pressures namely poaching for international pet trade and local consumption as well as habitat destruction, this living fossil is now at the brink of extinction. While research on natural history had already been conducted on Crocodile Lizards in China and relevant management programs have been established there, comparable knowledge is lacking for Crocodile Lizards in Vietnam. We provide the first comprehensive habitat characterization for Crocodile Lizards in Vietnam, which is essential for species conservation and the protection of remaining natural habitats. Our results showed that perch characterization was different between age classes, and between populations in China and Vietnam. Furthermore, our study found that Crocodile Lizards had specific needs of stream physiology and water quality. We found that few inhabited streams were affected by coal-mining activities in Vietnam, suggesting the importance of immediate measures to ensure habitat conservation of Crocodile Lizards.**

Key Words.—Shinisauridae; microhabitat characterization; niche segregation; Southeast Asia; species conservation; sustainable management

INTRODUCTION

The Crocodile Lizard (*Shinisaurus crocodilurus*, Ahl 1930) represents an ancient but prominent anguid lizard clade, which was recently described as a new species, genus and family (Zhao et al. 1999; Huang et al. 2008). Furthermore, Crocodile Lizards are habitat specialists, which prefer small, remote streams along mountain ridges within undisturbed tropical rainforest (Ning et al. 2006; Huang et al. 2008; Zollweg, 2011a; van Schingen et al. 2014a). The critical taxonomic position, long evolutionary history as well as specific life-history traits and high sensitivity to environmental conditions make this species particularly important for understanding the evolution and ecology of lizards.

Currently, the distribution range of the Crocodile Lizard is restricted to fragmented sites in southern China and northern Vietnam, where suitable habitats are small, isolated, and steadily shrinking (Le and Ziegler 2003; Huang et al. 2008; van Schingen et al. 2014a). Li et al. (2012) even predicted the loss of all original habitats in China during 2081–2100 as consequence of climate change. One report revealed that Crocodile Lizards in China are suffering a tremendous decline with a rate of about 85%, and the present population size might be fewer than 1,000 individuals in China (Huang et al. 2008). A similar study in 2013 revealed that the effective population size of Crocodile Lizards might be fewer than 100 individuals in Vietnam (van Schingen et al. 2014b), which is dramatically below the threshold of viable populations (Shaffer et al. 2002; Reed et al. 2003; Traill et al. 2007; Traill et al. 2010). Poaching for the international pet trade is currently regarded as the most severe threat causing population declines and even the extinction of several wild subpopulations (Huang et al. 2008; van Schingen et al. 2015). Consequently, the protection needs of Crocodile Lizards have received increasingly attention from all around the world. The species is listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and was recently classified in the IUCN Red List of Threatened species as Endangered (Nguyen et al. 2014). However, wild populations are still in peril due to extensive collection and the lack of adequate habitat protection (van Schingen et al. 2015). Immediate conservation measures such as the restocking of wild population at protected sites are needed to ensure the persistence of the species (van Schingen et al.

2014b). Information about habitat requirements and ecology of the species is essential for planning successful conservation programs. First studies on natural history of Crocodile Lizards in China were already conducted and led to the establishment of breeding facilities and the first trials in releasing animals into the wild (Long et al. 2007; Zollweg 2011b, 2012). By contrast, the natural history and habitat requirements of Crocodile Lizards from Vietnam still remain poorly studied since its discovery in 2002 (Le and Ziegler 2003).

Our study aims to provide the first habitat characterization of Crocodile Lizards in Vietnam to get an insight into its ecological requirements, thereby promoting the protection-related breeding and sustainable management plans for this species. We assumed that we would detect differences in habitat use between juveniles and adults because of observed distinct behaviors (Zollweg and Kühne 2013; Mona van Schingen, pers. obs.), which has been also recorded for other lizards (Snyder et al. 2010). Additionally, we compared our findings with previous studies on Crocodile Lizards in China to identify a potential ecological difference between extant subpopulations, which is crucial to understand the evolutionary history, taxonomic status, and threat potential of the species and respective populations. Populations of Crocodile Lizards in China and Vietnam are separated by at least 500 km (Le and Ziegler 2003) and are exposed to slightly different climatic conditions (annual moderate temperatures in northern Vietnam vs. cold winters and hot summers in southern China; Zollweg and Kühne 2013). Thus, we assumed differences in microhabitat characteristics and habitat selection between subpopulations from China and Vietnam as divergences generally evolve rapidly in allopatric lizard populations (e.g., Herrel et al. 2008).

MATERIALS AND METHODS

Study site.—We conducted fieldwork in June and July 2013 to make the data comparable to preliminary microhabitat studies done in the summer on Crocodile Lizards in China (Ning et al. 2006). May to October is known to be the active season of Crocodile Lizards in China (Huang et al. 2008; Ning et al. 2006). We visited all known Crocodile Lizard localities in northeast Vietnam in the Tay Yen Tu Nature Reserve (NR) in Bac Giang Province, Yen Tu and Dong Son - Ky Thuong NRs in Quang Ninh Province (Le and Ziegler 2003; Hecht et al. 2014; van Schingen et al. 2014a). All three NRs are part of the last remaining contiguous Evergreen Tropical Broadleaf Rainforest in northeast Vietnam, which has been extensively cleared in the region (Tordoff et al. 2000; BirdLife International. 2014. Sourcebook. Available from http://www.birdlife.org [Accessed 23 September 2013]). Northeast Vietnam is characterized by a monsoon tropical climate with cool winters (minimum temperature of coldest month about 12° C) and summer rains (Nguyen et al. 2000). The flora of this region belongs to the South-Chinese floristic unit and north Vietnam also shares close zoogeographic affinities with adjacent southern China (Zhu et al. 2003; Ziegler et al. 2008).

Data collection.—We conducted night excursions between 1845 and 2230 because Crocodile Lizards are diurnal and perch above water during the night (Huang et al. 2008; Ning et al. 2006; van Schingen et al. 2014b; Zollweg and Kühne 2013). We surveyed seven streams (two in Tay Yen Tu, two in Yen Tu and three in Dong Son-Ky Thuong NRs) inhabited by Crocodile Lizards, each with a team of four members. Every night we surveyed upstream for 3.45 h, covering 650–3,500 m of the stream length. We surveyed the streams in Tay Yen Tu NR three to five times, while other streams could only be surveyed once or twice due to inaccessibility and climatic constraints. We conducted 14 night surveys in habitats of Crocodile Lizards. We georeferenced each lizard we found with a GPS unit (Garmin GPSMAP® 64s, Garching, Germany) and measured 24 abiotic parameters characterizing the microhabitat and perch site of Crocodile Lizards. We measured water and air temperatures and air humidity with a digital thermometer and hygrometer (Exo Terra, PT2470, Hagen, Germany), and O_2 saturation, concentrations of nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+) / ammonia (NH_3), phosphorus (PO_4^{3-}), iron (Fe^-), silicate (SiO_2), carbonate hardness (KH), and total hardness (GH) of water (Testlab 25502, Joachim Böhme Ludwigshafen (JBL), Neuhofen, Germany) to determine the water quality of each surveyed stream. The pH was determined with a digital pH meter.

We documented the stream sections at the perch sites of Crocodile Lizards, which we classified as pool, riffle, run, or waterfall. We characterized pools by slow flow velocity and small substrate sizes (Fig. 1), run sections by medium depth, medium flow velocity, and smooth flowing waters, and we defined riffles as shallow sections with high flow velocity and large substrate rocks (Jowett 1993). We measured the flow velocity with a digital flow meter (Windaus ZMFP126-S, Clausthal-Zellerfeld, Germany). To characterize the resting perch of Crocodile Lizards, we recorded perch height in cm (distance between perch and water surface or ground), perch diameter in mm, vertical distance from perch to shore in cm, water depth in cm, stream width in m, percentage vegetation coverage above perch, perch substrate (as branch, liana, bamboo, shrub, fern, rock, forest floor and water), and stream substrate (as loam,

FIGURE 1. Habitat of *Shinisaurus crocodilurus* in Vietnam. (A). Macro-habitat. (B and C). Typical microhabitat with backwater pool. Arrow indicates a Crocodile Lizard (*Shinisaurus crocodilurus*). (Photographed by Mona van Schingen and Marta Bernardes).

sand, gravel, cobbles). Definitions of water hardness (KH) follow US Geological Survey standards for the water hardness classification (USGS Water-Quality Information. Available from http://water.usgs.gov). We obtained interpolated annual temperature data for the localities from the Worldclim-Global Climate Data (WorldClim. 2013. Global Climate Data. Available from www.worldclim.org [Accessed 7 June 2013]; Hijmans et al. 2005). For comparing the habitat selection of different age classes, we measured the snout-vent lengths (SVL) of the lizards with a digital caliper to the nearest 0.1 mm. Based on these measurements, we categorized lizards into different age classes: < 100 mm = juvenile; 100–140 mm = sub-adult; and > 140 mm = adult (see van Schingen et al. 2014b). We caught lizards by hand and subsequently released them on the same perch.

Statistical analyses.—We performed a One-Way ANOVA combined with a Tukey posthoc test to test for differences of habitat parameters among localities by age. We used Barlett's test to verify homogeneity of variances and the Shapiro-Wilk test to verify normal distribution. If required, we log transformed data to meet assumptions of normality and constant variance. We used a chi-square test to examine whether perch preferences differed among localities. We tested correlations between environmental parameters with a Pearson's rank correlation. We further applied a principal component analysis (PCA) of 12 selected abiotic factors describing the perch site (pH, O_2-saturation, concentrations of NO_3, NO_2, NH_4/ NH_3, PO_4, KH total hardness and GH, altitude, perch height, perch width, the perch's vertical distance to the shore and canopy cover) to detect subordination of factors describing the habitat selection of Crocodile Lizards. Statistical analyses were performed with the program PAST (Hammer et al. 2001) and for all tests, $\alpha = 0.05$.

RESULTS

Habitat characterization.—We found Crocodile Lizards exclusively within first order streams, often close to the stream source, where the streams were shallow and narrow. Stream habitats were densely vegetated, mainly by broad-leafed trees and scattered bamboo, while macro-algae were mostly absent within the streams (Fig. 1). All streams were slow to medium

TABLE 1. Abiotic parameters of streams inhabited by *Shinisaurus crocodilurus* in northeast Vietnam in the Tay Yen Tu Nature Reserve (NR) in Bac Giang Province and in Yen Tu and Dong Son - Ky Thuong NRs in Quang Ninh Province. Values for canopy cover and flow velocities are approximate.

Parameter	Tay Yen Tu NR	Dong Son – Ky Thuong	Yen Tu NR	Total
pH	4.5–5	6.66–7.37	5.43–5.58	4.5–7.37
NO_2 [mg/l]	< 0.01	< 0.01	< 0.01	< 0.01
NO_3 [mg/l]	4–5	< 0.5–5	1–5	< 0.5–5
NH_3/NH_4 [mg/l]	< 0.05–0.1	< 0.05	< 0.05	< 0.05–0.1
PO_4 [mg/l]	0.05–0.1	< 0.02	< 0.02	< 0.02– 0.1
Fe [mg/l]	< 0.02–0.05	< 0.02–0.05	< 0.02	< 0.02–0.05
O_2 [mg/l]	8	6–10	8	6–10
SiO_2 [mg/l]	3–6	5–6	1.2–6	1.2–6
KH [d°]	1–2°	1°–2°	1°–2°	1°–2°
GH [d°]	< 1°	1°–2°	< 1°–1°	< 1°–2°
Stream width [m]	1–3	5–6	1–8	1–8
Stream depth [cm]	13–40	18–34	5–73	5–73
Canopy cover [%]	50–100	80–100	0–100	0–100
Flow velocity [m/s] (max)	0–0.47 (1.67)	0–0.3 (1.45)	0–0.15 (1.74)	0–0.47 (0–1.74)
Substrate type	Sand > Gravel	Loam > Gravel	Gravel > Sand	Gravel > Sand > Loam
Humidity [%]	78–86	87–88	85–88	87–88
Elevation [m] above sea level	330–505	180–330	728–847	180–847

in water flow, being shallow (5–73 cm) and with relatively narrow width (1–8 m; Table 1). The river bed was dominantly composed of sand, gravel, and some boulders from numerous riffle zones with big truncated tree branches residing in the water. Furthermore, many streams contained several small waterfalls followed by

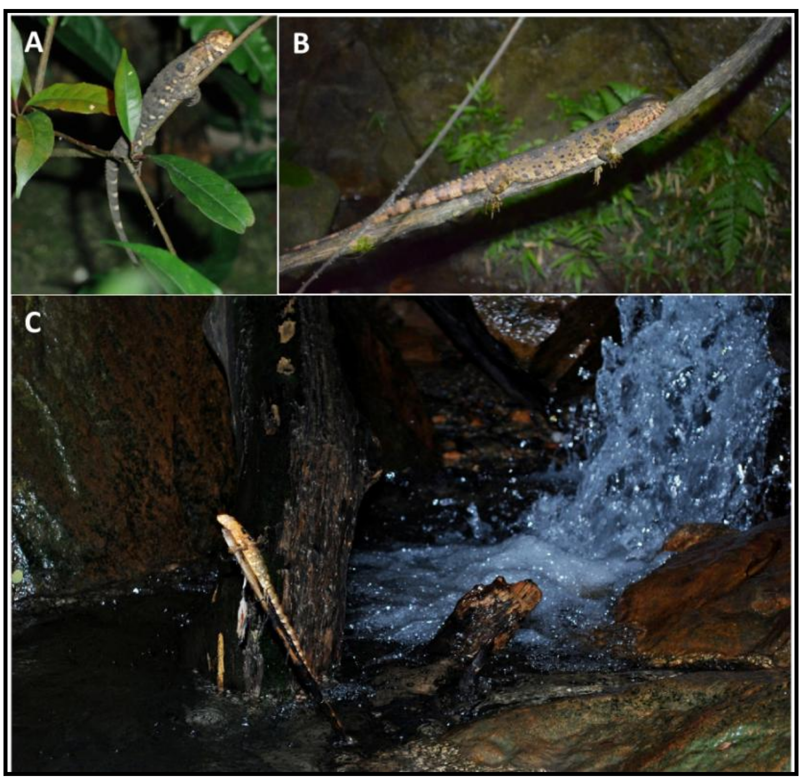


FIGURE 2. Resting perches of Crocodile Lizards (*Shinisaurus crocodilurus*) in Vietnam. (A). Juvenile. (B). Adult. (C). Sub-adult above backwater pool (Photographed by Mona van Schingen and Marta Bernardes).

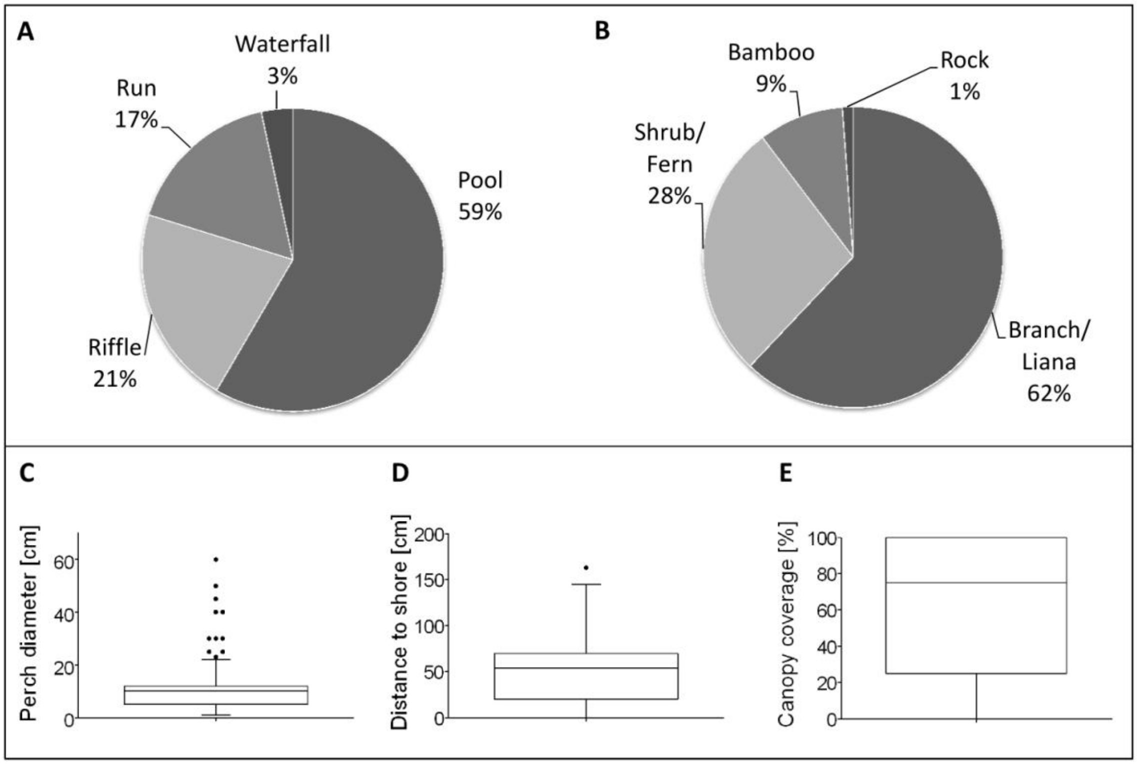


FIGURE 3. Perch selection of Crocodile Lizards (*Shinisaurus crocodilurus*) in Vietnam. (A). Stream section selection. (B). Substrate selection. (C-E). Box plots of perch characteristics (perch width, distance to the shore, canopy coverage).

backwater pools (Fig. 1B-C).

The streams inhabited by Crocodile Lizards were further characterized by oxygen-rich and soft waters with low nutrient concentrations of nitrate and phosphate (Table 1). Chemical parameters were similar among the three NRs, except for pH. Among the three surveyed sites, pH values were 4.50–5.00 in Yen Tu NR, 5.43–5.58 in Tay Yen Tu NR, and 6.70–7.40 in Dong Son - Ky Thuong NR (Table 1). The increase in pH from acid to relatively neutral waters was negatively correlated with the altitude of the surveyed streams (r_s = -0.873; P < 0.001), suggesting that streams at lower elevations had higher pH values. While we observed a high proportion (92.3%) of sub-adults and adults along the pH gradient from 4.5–7.4, we only found juveniles at pH values between 5.4–5.6. The yearly temperature at each locality was approximately 11–23° C, without high fluctuations.

Habitat selection.—We made 94 observations of 62 individual lizards (40 from Tay Yen Tu, 12 from Yen Tu, and 10 from Dong Son - Ky Thuong). We found that Crocodile Lizards preferred to rest directly above the water body or the stream bank but never above the ground soil. We encountered lizards most frequently resting above backwater pools (59%, Fig. 2C, Fig. 3A), with low numbers of lizards found above riffle or run sections (21% and 17%, respectively), and we found only a few lizards above small waterfalls (3%; Fig. 3A). We further found that Crocodile Lizards almost exclusively rested within the vegetation. We observed only one lizard resting on a rocky cliff and never saw lizards on the forest floor or in the water during night. We observed that the majority (about 62%) of lizards rested on branches and liana (Fig. 2A-B) and fewer rested on shrubs (28%; Fig. 3B). Adults commonly occupied liana and bamboo (about 30%) where we never found juveniles. We found juveniles frequently on ferns. The diameters of the resting perches were relatively small ranging from 1–120 mm (mean = 13.1 ± 15.7 mm, n = 91; Fig. 2A, 3C). Resting perches were located 0–163 cm from shore (mean = 51.8 ± 36 cm, n = 92, Fig. 3D), and this distance was not different among age classes. The distance of resting perches to the shore for juveniles was positively correlated with water depth (r_s = -0.38, P = 0.017), which was not the case for sub-adults or adults.

The mean canopy coverage above resting individuals was 60.66 ± 37.6 % (n = 83, Fig. 3E). Sub-adults and adults preferred resting sites with significantly higher canopy cover compared with juveniles ($F_{2,86}$ = 14.27, P < 0.001), and sub-adults exclusively preferred sites with dense coverage. The heights of the resting perches ranged from 11–210 cm above water (mean = 101.33 ±

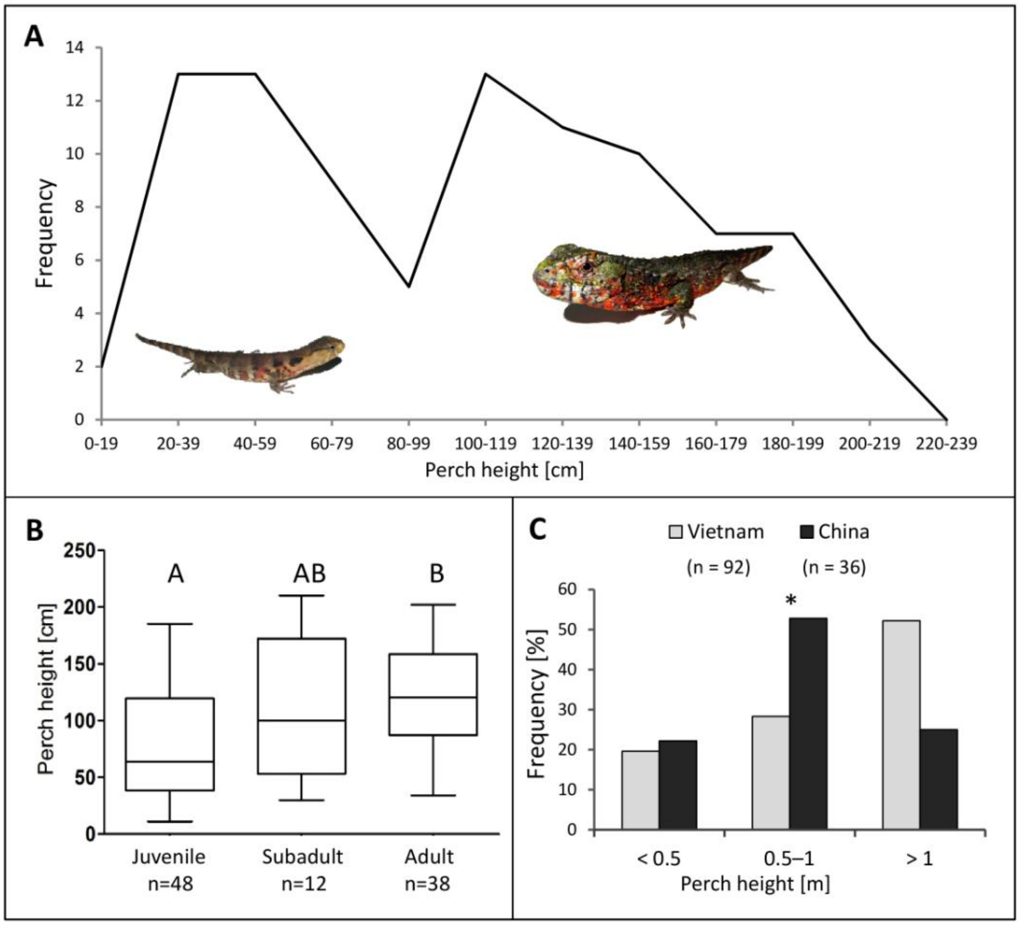


FIGURE 4. Perch heights of Crocodile Lizards (*Shinisaurus crocodilurus*). (A). Frequency histogram. (B). Spatial distribution of different age classes. (C). Spatial distribution of Vietnamese and Chinese individuals. Data for Chinese individuals from Ning et al. (2006).

53.3 cm, n = 92). There were two peaks of preferred perch heights at 20–59 cm and 100–119 cm above water (Fig. 4A), and adults occupied significantly higher perches than juveniles ($F_{2,89}$ = 5.60 P = 0.005, Fig. 4B). The perch height was further positively correlated (r_s = 0.460; P < 0.001) with the canopy coverage. Our PCA with 12 abiotic factors describing the perch site of Crocodile Lizards revealed the first principal component (PC) to explained 88.6% of the overall variance. Principle Component 1 was strongly positively correlated with altitude (Table 2, Fig.5).

DISCUSSION

Habitat characterization.—The three surveyed sites differed significantly in elevation, each with a small altitudinal range, which is comparable with subpopulations in China (Zhao et al. 1999). We found that the factor altitude explained most of the distribution of Crocodile Lizards, but we do not assume that elevation is the ultimate factor determining their occurrence. We further found that elevation was correlated with both pH and stream width. In this context the small altitudinal ranges of each subpopulation compared to the whole species distribution range (200–1100 m: Huang et al. 2008; van Schingen et al. 2014a) emphasizes the importance of the need by this species of specific habitat conditions and a small realized ecological niche. The ecological niche appears to be restricted to very small sections of clean and remote streams. We found that Crocodile Lizards are strongly associated with mountainous streams mostly in untouched tropical broadleaf forests (Yen Tu and Tay Yen Tu NRs) with some occurrences in intermixed bamboo forests (Dong Son-Ky Thuong NR). This corresponds to habitat preferences of Crocodile Lizards in China (Wu et al. 2007). While annual habitat temperatures remain moderate and relatively constant, temperatures in Chinese habitats show comparatively high annual fluctuations (Zhao et al. 1999).

We further found that stream habitats generally were of soft and oxygen-rich waters, with low nutrient

TABLE 2. Factor loadings of first four principal components (explaining 99.97% of the total variance) in microhabitat selection of *Shinisaurus crocodilurus* in the Tay Yen Tu Nature Reserve (NR) in Bac Giang Province, Vietnam, Yen Tu and Dong Son - Ky Thuong NRs in Quang Ninh Province, Vietnam, and at a site in northeast Vietnam.

Factor	PC 1	PC 2	PC 3	PC 4
Perch width [cm]	-0.00937	-0.00070	-0.00019	0.00914
Perch height [cm]	0.03358	0.88150	0.04590	-0.46860
Altitude [m]	0.99900	-0.03836	0.01934	0.00140
Distance to shore [cm]	-0.01095	0.17940	0.88770	0.42380
pH	-0.00196	0.00415	-0.00161	0.00210
Canopy cover [%]	0.02430	0.43470	-0.4577	0.77480
O2 [mg/l]	0.00155	0.00571	-0.00394	0.00735
NH4 [mg/l]	0.00012	0.00015	$1.47E^{-5}$	0.00018
NO2 [mg/l]	$-4.57E^{-6}$	$1.64E^{-5}$	$-6.97E^{-6}$	$6.44E^{-6}$
NO3 [mg/l]	-0.00467	-0.01211	-0.00152	-0.01159
PO4 [mg/l]	-0.00027	-0.00021	-0.00056	-0.00037
GH [°d]	0.00378	0.00093	$1.16E^{-5}$	0.00288
KH [°d]	0.00677	0.00879	-0.00246	0.01162

concentrations and few macro-algae growth. These are typical characteristics of headwaters in mountain streams (Brehm and Meijering 1996). Stream widths ranged from 1–8 m and depth was 5–73 cm. In China, streams inhabited by Crocodile Lizards were slightly smaller and more shallow during summer (83.3% of lizards were found in streams with depth below 30 cm: Ning et al. 2006; Zollweg 2011a). However, stream depth is always variable depending on rainfall and season. The flow velocity of inhabited streams was generally slow to medium. We observed Crocodile Lizards only at sections of slow or without any flow velocity similar to observations in China (Ning et al. 2006).

We found that pH values were higher at lower elevations, which could have been due to the increased nutrient inputs from the riparian zone and the buffering capacities of the soils (Haines 2011). Juveniles of Crocodile Lizards were abundant (92% of all observed juveniles) at slightly acid sections with mean pH of 5.6 in Tay Yen Tu NR. Habitats in China are situated in limestone forest, where pH values are more basic (Michael Zollweg, pers. com.) due to the limestone (Cravotta and Trahan 1999), while most habitats in Vietnam are situated in granitic forest. Only Dong Son - Ky Thuong NR is located at the border to a limestone area, which might also explain higher pH values in these streams. Therefore, we do not think that the rock type is

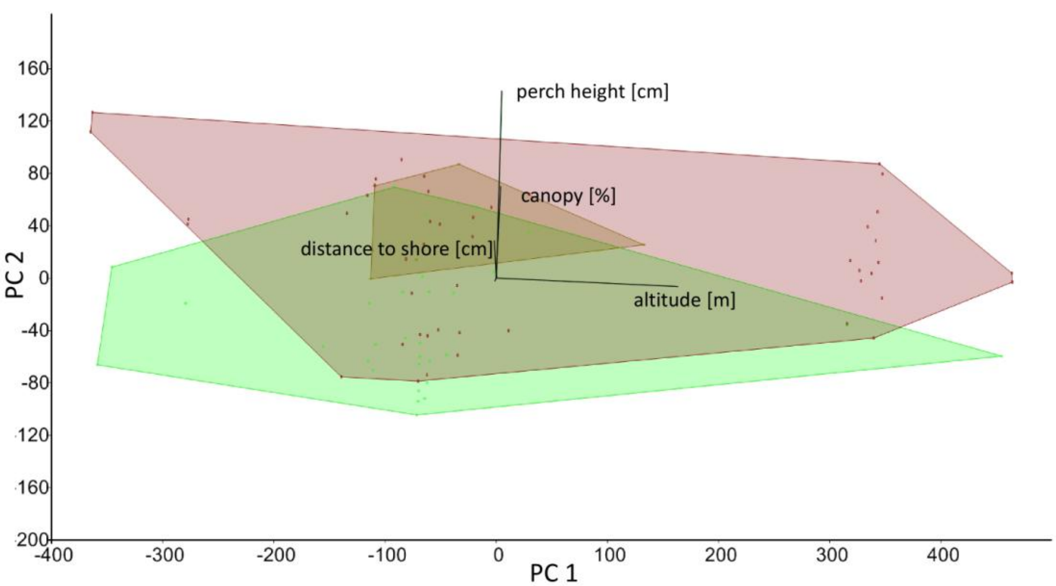


FIGURE 5. Biplot of the first and second principal components using 12 factors describing the perch selection of different age classes of Crocodile Lizards (*Shinisaurus crocodilurus*) (displayed with convex hulls). Adults (red), subadults (orange), and juveniles (green). Factors are presented as lines, whose lengths represent explanatory power of variance.

an essential factor for the habitat choice of Crocodile Lizards.

The high water quality might be another important habitat character for Crocodile Lizards because highest abundances of these lizards have been recorded in streams in Tay Yen Tu NR, where we also found abundant indicator species for high quality water, such as water-penny beetles of the family Psephenidae and stoneflies (Arnett and Thomas 2002). All inhabited streams were oxygen rich and depleted of phosphorous and nitrogen, indicating a low anthropogenic eutrophication of stream habitats. Thus, the water quality might also be an indirect factor indicating the influence of human settlements, which has already been reported as a restricting factor of the species occurrence for China (Ning et al. 2006). Accordingly, we found lowest abundances of Crocodile Lizards in Dong Son - Ky Thuong NR, where the distance to human settlements was least (see also van Schingen et al. 2014b and van Schingen et al. 2015). We also considered other biotic variables such as competitors or predators affecting the abundance and survival success of Crocodile Lizards (Irschick et al. 2005). Few Crocodile Lizards were found at sites with abundant syntopic semi-aquatic reptiles (such as the Water Dragon, *Physignathus cocincinus*, or the colubrid snake *Sinonatrix aequifasciata*).

Habitat selection.**—**We confirmed the assumption that different age classes of Crocodile Lizards have different perch choices. Juveniles occupied perches with significantly lower heights than those of sub-adults and adults. Similar observations have been reported for gekkonids (Snyder et al. 2010). We assumed that climbing up by lizards for shelter is associated with energy costs. We even assumed that juveniles have to feed more regularly than adults and therefore have to quit their perches more frequently. Thus, the reasons for the use of lower perches by juveniles might be regarded as a trade off to reduce the energy costs associated with climbing. However, this hypothesis needs to be tested.

Another explanation for a segregation of resting perches might be the reduction in interactions between conspecifics, as suggested by Irschick et al. (2005). Besides the height of perches, we found vegetation differences between juveniles and adults, with juveniles preferring ferns, while sub-adults and adults prefer branches and lianas, which also were more densely covered than the vegetation in which we found juveniles. While appropriate observations are lacking for other lizards, comparable spatial niche segregation between adults and sub-adults has been observed in the American Alligator, *Alligator mississippiensis* (Webb et al. 2009).

We also found inter-population differences in perch heights between Crocodile Lizards from Vietnam and from China. Individuals encountered in Vietnam occupied significantly higher perches (mostly higher than 1 m, up to 2.1 m) than Crocodile Lizards from Guangdong Province, China, where the majority of lizards were observed on perches 0.5–1 m above the ground (Ning et al. 2006). We assumed that this difference might be a result of the respective water depth below the perch, which was generally shallower in China. Because Crocodile Lizards jump into the water instead of climbing down to forage (Mona van Schingen, pers. obs.) or to escape (Huang et al. 2008), we assumed that perch height might be limited by water depth to prevent injuries while jumping into the water.

Implications.—The stenoecious habitat specialization and sedentarism of the Crocodile Lizard makes the species in particular prone to extinction in view of the acute ongoing habitat destruction and fragmentation. Habitat quality is steadily decreasing due to coal-mining activities causing the pollution of inhabited streams (van Schingen et al. 2014b; van Schingen et al. 2015). We observed that especially these streams, which are characterized by numerous backwater pools and appear necessary to provide the preferred resting sites for the species, were affected. To cope with local habitat destruction due to agriculture purpose, agreements with respective local farms helped to maintain at least core zones of important habitats intact in the Daguishan Nature Reserve in China. Further, a breeding station was constructed in 2003 and a first trial of releasing lizards back into habitat took place (Long et al. 2007, Zollweg, 2011b, 2012). These efforts have already led to a stable and an even slightly increasing subpopulation size within the Daguishan Nature Reserve in 2011 (Zollweg 2012) and would serve as an example for protection activities in Vietnam. In this context we developed a management program for Crocodile Lizards in Vietnam including the long-term monitoring of wild subpopulations. The present ecological study provides information to improve captive breeding in general and the development of a stable reserve population at the Me Linh Station for Biodiversity (see Ziegler 2015; Ziegler and Nguyen 2015). This study adds baseline data to identify suitable sites for a restocking program in Vietnam, which is planned for the near future. We also initiated an awareness campaign, including workshops, lectures, participation at conferences, and articles and poster to inform Vietnamese about this species. This has been done in close collaboration with the Forest Protection Department (FDP) of Tay Yen Tu NR to improve habitat conservation (see van Schingen et al. 2015; Ziegler 2015; Ziegler and Nguyen 2015).

Acknowledgments.—We thank the directorates of the Tay Yen Tu, Yen Tu and Dong Son – Ky Thuong nature reserves, Forest Protection Departments of Bac Giang and Quang Ninh provinces for support of our field work and issuing relevant permits. We thank Canh Xuan Le and Thai Huy Tran (Hanoi) for supporting our research. Our field work in Vietnam was funded by the Cologne Zoo, the European Union of Aquarium Curators (EUAC), the University of Cologne, Michael Zollweg, Harry Wölfel, and many private donations. Research of Truong Quang Nguyen in Germany was funded by the Alexander von Humboldt Foundation (VIE 1143441).

LITERATURE CITED

Arnett, R.H. and M.C. Thomas. 2002. American Beetles: Polyphaga: Scarabaeidoidae through Curculionidea. 1st Edition. CRC Press, Boca Raton, Florida, USA.

Brehm, J., and M.P.D. Meijering. 1996. Fließgewässerkunde. Einführung in die Ökologie der Quellen, Bäche und Flüsse. 3rd Edition. Quelle und Meyer Verlag, Wiesbaden, Hessen, Germany.

Cravotta, C.A., and M.K.Trahan. 1999. Limestone drains to increase pH and remove dissolved metals from acidic mine drainage. Applied Geochemistry 14:581–606.

Haines, T.A. 2011. Acidic precipitation and its consequences for aquatic ecosystems: a review. Transactions of the American Fisheries Society 110:669–707.

Hammer, O., D.A.T. Harper, and P.D. Ryan. 2001. PAST: Paleontological statistics software package for education and data analysis. Paleontologia Electronica 4:9.

Hecht, V., C.T, Pham, T.T. Nguyen, T.Q. Nguyen, M. Bonkowski, and T. Ziegler. 2014. First report of the herpetofauna of Tay Yen Tu Nature Reserve northeastern Vietnam. Biodiversity Journal 4:507–552.

Herrel, A., K. Huyghe, B. Vanhooydonck, T. Backeljau, K. Breugelmans, I. Grbac, R. Van Damme, and D.J. Irschick. 2008. Rapid large-scale evolutionary divergence in morphology and performance associated with exploitation of a different dietary resource. Proceedings of the National Academy of Sciences 105:4792–4795.

Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones, and A. Jarvis. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25:1965–1978.

Huang, C.M., H. Yu, Z. Wu, Y.B. Li, F.W. Wei, and M.H. Gong. 2008. Population and conservation strategies for the Chinese Crocodile Lizard (*Shinisaurus crocodilurus*) in China. Animal Biodiversity and Conservation 31:63–70.

Irschick, D.J., B. Vanhooydonck, A. Herrel, and J.J. Meyers. 2005. Intraspecific correlations among morphology, performance, and habitat use within a Green Anole Lizard (*Anolis carolinensis*) population. Biological Journal of the Linnean Society 85:211–221.

Jowett, I.G. 1993. A method for objectively identifying pool, run, and riffle habitats from physical measurements. New Zealand Journal of Marine and Freshwater Research 27:241–248.

Le, K.Q., and T. Ziegler. 2003. First record of the Chinese Crocodile Lizard from outside of China: report on a population of *Shinisaurus crocodilurus* Ahl, 1930 from north-eastern Vietnam. Hamadryad 27:193–199.

Li, X., H. Tian, Y. Wang, R. Li, Z. Song, F. Zhang, M. Xu, and D. Li. 2012. Vulnerability of 208 endemic or endangered species in China to the effects of climate change. Regional Environmental Change 13:843-852.

Long, Q., Y. Zhang, W. Liang, P. Su, B. Luo, and J. Huang. 2007. Monitoring earlier activities of released Chinese Crocodile Lizard (*Shinisaurus crocodilurus*). Sichuan Journal of Zoology 26:308–310.

Nguyen, K.V., T.H. Nguyen, K.L. Phan, and T.H. Nguyen (Ed.). 2000. Bioclimatic Diagrams of Vietnam. Vietnam National University Publishing House, Hanoi, Vietnam.

Nguyen, T.Q., P. Hamilton, and T. Ziegler. 2014. *Shinisaurus crocodilurus*. The IUCN Red List of Threatened Species. 2014.1. Available from http://www.iucnredlist.org. [Accessed 12 June 2014].

Ning, J., C. Huang, H. Yu, D. Dai, Z. Wu, and Y. Zhong. 2006. Summer habitat characteristics of the Chinese Crocodile Lizard (*Shinisaurus crocodilurus*) in the Loukeng Nature Reserve, Guangdong. Zoological Research 27:419–426.

Reed, D.H., J.J. O'Grady, B.W. Brook, J.D. Ballou, and R. Frankham. 2003. Estimates of minimum viable population sizes for vertebrates and factors influencing those estimates. Biological Conservation 113:23–34.

Shaffer, M.L., L.H. Watchman, W.J. Snape, and I.K. Latchis. 2002. Population viability analysis and conservation policy. Pp. 123–142 *In* Population Viability Analysis. Beissinger, S.R., and D.R. McCullough (Ed.). University of Chicago Press, Chicago, Illinois, USA.

Snyder, J., L. Snyder, and A.M. Bauer. 2010. Ecological observations on the Gargoyle Gecko, *Rhacodactylus auriculatus* (Bavay, 1869), in southern New Caledonia. Salamandra 46:37–47.

Tordoff, A.W., V.D. Vu, V.C. Le, Q.N. Tran, and T.L. Dang. 2000. A Rapid Field Survey of Five Sites in Bac Kan, Cao Bang and Quang Ninh Provinces: A Review of the Northern Indochina Subtropical Forests Ecoregion. Conservation Report No. 14, BirdLife International Vietnam Programme and Forest Inventory and Planning Institute, Hanoi, Vietnam.

Traill, L.W., C.J.A. Bradshaw, and B.W. Brook. 2007. Minimum viable population size: a meta-analysis of

30 years of published estimates. Biological Conservation 139:159–166.

Traill, L.W., B.W. Brook, R.R. Frankham, and C.J.A. Bradshaw. 2010. Pragmatic population viability targets in a rapidly changing world. Biological Conservation 143:28–34.

van Schingen, M., F. Ihlow, T.Q. Nguyen, T. Ziegler, M. Bonkowski, Z. Wu, and D. Rödder. 2014a. Potential distribution and effectiveness of the protected area network for the Crocodile Lizard *Shinisaurus crocodilurus* Ahl, 1930 (Reptilia: Squamata). Salamandra 50:71–76.

van Schingen, M., C.T. Pham, H.A. Thi, M. Bernardes, V. Hecht, T.Q. Nguyen, M. Bonkowski, and T. Ziegler. 2014b. Current status of the Crocodile Lizard *Shinisaurus crocodilurus* Ahl, 1930 in Vietnam with implications for conservation measures. Revue Suisse de Zoologie 121:1–15.

van Schingen, M., U., Schepp, C.T. Pham, T.Q. Nguyen and T. Ziegler. 2015. Last chance to see? a review on the threats to and use of the Crocodile Lizard. TRAFFIC Bulletin 27:19–26.

Webb, K.K., W.C. Conway, G.E. Calkins, and J.P. Duguay. 2009. Habitat use of American Alligators in east Texas. Journal of Wildlife Management 73:566–572.

Wu, Z., D.L. Dai, C. Huang, H. Yu, J. Ning, and Y. Zhong. 2007. Selection of *S. crocodilurus* on forest type in mountain streams in Luokeng Nature Reserve of Guangdong Province. Chinese Journal of Ecology 26:1777–1781.

Zhao, E., K. Zhao, and K. Zhuo. 1999. Shinisauridae - a major project of the national Natural Science Foundation of China. Fauna Sinica 2:205–209.

Zhu, H., H. Wang, B. Li, and P. Siririgsa 2003. Biogeography and floristic affinities of limestone flora in southern Yunnan, China. Annals of Missouri Botanical Garden 90:444–465.

Ziegler, T. 2015. *In situ* and *ex situ* reptile projects of the Cologne Zoo: implications for research and conservation of South East Asia's herpetodiversity. International Zoo Yearbook 49:8–21.

Ziegler, T. and T.Q. Nguyen. 2015. Neues von den Forschungs- und Naturschutzprojekten in Vietnam und Laos. Zeitschrift des Kölner Zoos 58:79–108.

Ziegler, T., Q.T. Le, T.N. Vu, R. Hendrix, and W. Böhme. 2008. A comparative study of Crocodile Lizards (*Shinisaurus crocodilurus* AHL, 1930) from Vietnam and China. The Raffles Bulletin of Zoology 56:181–187.

Zollweg, M. 2011a. Zu Besuch bei der Krokodilschwanzechse. Reptilia 91:39–46.

Zollweg, M. 2011b. Neues aus dem Projekt zum Schutz der Krokodilschwanz-Höckerechse. Zoologische Gesellschaft für Arten- und Populationsschutz e.V. (ZGAP) Mitteilungen 27:11–13.

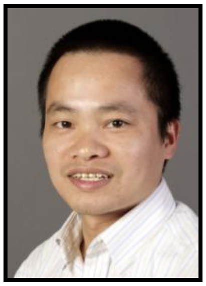
Zollweg, M. 2012. Erfolgreiches Projekt zum Schutz der Krokodilschwanz-Höckerechse in China. Zoologische Gesellschaft für Arten- und Populationsschutz e.V. (ZGAP) Mitteilungen 28:15.

Zollweg, M., and H. Kühne. 2013. Krokodilschwanzechsen - *Shinisaurus crocodilurus*. Natur und Tier – Verlag, Münster, North Rhine-Westphalia, Germany.

MONA VAN SCHINGEN is a Ph.D. candidate at the Zoological institute of the University of Cologne and the Cologne Zoo, Germany. She studied Biology (B.Sc.) at the University of Cologne and graduated with a taxonomic based study on Asian gekkonids in 2011. In 2012 she conducted ethological studies on lizards at the Lajuma Research Center in South Africa. She was a Master's student at the University of Cologne and graduated with a conservation-based ecological study on the Crocodile Lizard in Vietnam. Since then she has been engaged in research and conservation projects on the species in its natural environment, focusing on ecology, natural history, genetics, and population dynamics. (Photographed by Bastian Barenbrock).

CUONG THE PHAM is a researcher of the Institute of Ecology and Biological Resources (IEBR) - Vietnam Academy of Science and Technology (VAST). He is member of the Cologne Zoo's Biodiversity and Nature Conservation Projects in Vietnam as well. He published 15 papers, mainly dealing with herpetodiversity and conducted numerous field surveys in Vietnam. He spent 5 y studying populations of the Crocodile Lizard in Vietnam to further their conservation. (Photographed by Mona van Schingen).

HANG AN THI is a M.Sc. student at the Institute of Ecology and Biological Resources (IEBR), Vietnam Academy of Science and Technology (VAST) focusing on diversity of amphibians in North Vietnam. She also participates in Vietnam in the Biodiversity and Nature Conservation Project of the Cologne Zoo. She has much experience in field research on biodiversity and ecology of reptiles and amphibians as she has accompanied many international researches as a field assistant, including field research on the Crocodile Lizard. (Photographed by Marta Bernardes).



TRUONG QUANG NGUYEN is at the Institute of Ecology and Biological Resources (IEBR)), Vietnam Academy of Science and Technology (VAST) and is a member of the Biodiversity and Nature Conservation Project of the Cologne Zoo. He finished his Ph.D. in 2011 at the Zoological Research Museum Alexander Koenig (ZFMK) and the University of Bonn, Germany (DAAD Fellow). From 2011 to 2014 he worked as a postdoctoral student in the Zoological Institute at Cologne University. He has conducted numerous field surveys and is the co-author of seven books and more than 150 papers relevant to the biodiversity research and conservation in southeast Asia. His research interests are systematics, ecology, and phylogeny of reptiles and amphibians in southeast Asia. (Photographed by Siegfried Werth).

MARTA BERNARDES is a Conservation Biologist and Ecologist with a M.Sc. degree from Lisbon University, Portugal. Since 2007 she has been engaged in the research of amphibians and reptiles and their natural environment with a main interest in diversity, ecology, biogeography, and conservation. In 2010 she initiated ecological research projects in Vietnam, including the study of the Crocodile Lizard. She is currently a Ph.D. candidate at the Zoological Institute of Cologne University, Germany. (Photographed by Mona van Schingen).

MICHAEL BONKOWSKI is a Professor for Terrestrial Ecology in the Institute of Zoology at the University of Cologne, Germany. He studied Biology at the University of Göttingen and then worked as Scientist at the Scottish Crop Research Institute in Dundee (UK), the Centre d' Ecologie Fonctionnelle et Evolutive (CEFE) at the C.N.R.S. Montpellier (France), the Center for Population Biology, Imperial College at Silwood Park (UK), and in the Department of Animal Ecology, Faculty of Biology, Darmstadt University of Technology in Germany. His research is at the interface between community and ecosystem ecology, reaching from plant-microbe interactions to terrestrial carbon and nutrient fluxes and to community ecology of reptiles in Southeast Asia. (Photographed by Robert Koller).

THOMAS ZIEGLER has been the Curator of the Aquarium/Terrarium Department of the Cologne Zoo since 2003. He is also the coordinator of the Cologne Zoo's Biodiversity and Nature Conservation Projects in Vietnam and Laos. Since February 2009, he has been an Associate Professor at the Zoological Institute (Biocentre) of Cologne University. Since 1994, Thomas has published 333 papers and books, mainly dealing with herpetodiversity. He was involved in the discovery of the Crocodile Lizard in Vietnam more than 12 y ago (Le and Ziegler 2003) and since then has lobbied for the investigation and conservation of the Vietnamese populations of this species. (Photographed by Anna Rauhaus).