
MORPHOLOGICAL VARIATION IN THE MEDITERRANEAN HOUSE GECKO (GEKKONIDAE: *HEMIDACTYLUS TURCICUS*) ALONG GEOGRAPHICAL GRADIENTS IN THE SOUTHEASTERN UNITED STATES

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Abstract.—Sexual size dimorphism (SSD) is present in many herpetofaunal species. Trends in SSD across latitudinal gradients have not been examined in most non-native herpetofaunal species in the United States, which can have important implications for establishing range limitations of exotic herpetofauna. This study examined SSD in the Mediterranean House Gecko (*Hemidactylus turcicus*) in the southeastern United States, and whether patterns of morphological variation change along a longitudinal or latitudinal gradient. We compared SSD in body and head dimensions first between males and females across the entire sampled range followed by a regression analysis to determine whether there is morphological variation influenced by latitudinal or longitudinal trends. Our results support male-dominated SSD in head size and body length, but show no correlation between SSD and latitudinal range. There does appear to be some evidence supporting morphological trends based on longitude, but these findings should be interpreted with caution. Results from this study indicate that morphological variation in *H. turcicus* is largely homogeneous across its introduced range.

Key Words.—Bergmann's rule; exotics; Gekkonidae; invasive species; sexual-size dimorphism

INTRODUCTION

With respect to amphibians and reptiles, it seems that many aspects of their biology are limited by their ability to maintain normal physiological functions (Bullock 1955; Fry 1967; Davies et al. 1981). As poikilotherms, metabolic activity is highly influenced by external environmental conditions (Bullock 1955; Newell 1966; Fry 1967; Hazel and Prosser 1974), and numerous studies have demonstrated that variability in ecological circumstances have direct effects on the phenotypic expression of certain traits (Ford and Seigel 1989; Queral-Regil and King 1998; Losos et al. 2000; Wapstra 2000; Sears and Angilletta 2004). Consistent across these studies is that as environmental conditions become more unpredictable (e.g., greater temperature variation or lower prey availability) certain phenotypic traits appear to be sub-optimal (e.g., lower clutch mass, fewer offspring; Ford and Seigel 1989; Seigel and Ford 1991), and decreased body mass sexual-size dimorphism (SSD; Madsen and Shine 1993; McGarrity and Johnson 2009) compared to conspecifics living in more stable conditions (Rhen and Lang 1995; Queral-Regil and King 1998; Seebacher 2005; Du 2006).

A commonly studied example of environmental conditions effects on the phenotype of an animal is the change of body size based on latitudinal gradients (Ashton et al. 2000; Ashton 2002; Ashton and Feldman

2003; Meiri and Dayan 2003; Sears and Angilletta 2004). This pattern is referred to as Bergmann's scaling rule, in which body mass increases as temperature decreases across a latitudinal gradient (Bergmann 1847). Typically, these patterns are explained as an evolutionary response to minimize heat loss in colder climates (Bergmann 1847; Walters and Hassall 2006; Olalla-Tárraga and Rodríguez 2007). While this pattern is fairly well established in endotherms (Ashton et al. 2000; Ashton 2002; Meiri and Dayan 2003; Blackburn and Hawkins 2004), data on ectotherms is more variable (Mousseau 1997; Ashton et al. 2000; Angilletta et al. 2004; Olalla-Tárraga et al. 2006; Olalla-Tárraga and Rodríguez 2007). Among non-archosaur reptiles, chelonians appear to follow Bergmann's rule, but in general the inverse to Bergmann's rule is observed in squamates (Ashton and Feldman 2003; Olalla-Tárraga and Rodríguez 2007). Data on amphibians are more ambiguous (Olalla-Tárraga and Rodríguez 2007; Adams and Church 2008; McGarrity and Johnson 2009).

Recently, McGarrity and Johnson (2009) explored phenotypic variability in SSD in the introduced Cuban Treefrog (*Osteopilus septentrionalis*) across latitudinal gradients in its introduced range in Florida. Sexual-size dimorphism in *O. septentrionalis* is female-dominated (Meshaka 2001; Vargas-Salinas 2006), a pattern consistent across most anurans (Shine 1979; Howard

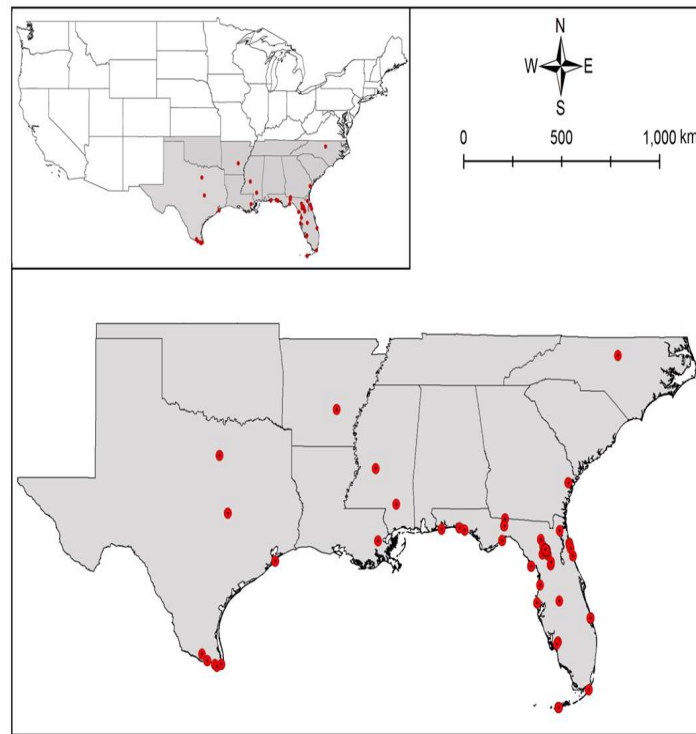


FIGURE 1. Sample localities of the non-native Mediterranean House Gecko (*Hemidactylus turcicus*) in the southeastern United States.

1981; Monnet and Cherry 2002). In *O. septentrionalis* sexual selection is not implicated as a cause of SSD (Vargas-Salinas 2006). McGarrity and Johnson (2009) observed that SSD decreased at higher latitudes across the state and hypothesized that the differences observed were a result of physiological stress due to more stochastic environmental conditions in northern latitudes. Currently, studies using introduced amphibians and reptiles as a means for testing ecological trends in morphological variation have been limited, and therefore this study seeks to take advantage of another introduced species, the Mediterranean House Gecko (*Hemidactylus turcicus*), as a model to determine larger trends of the effects of varying environmental conditions on phenotypic expression of non-indigenous species.

Hemidactylus turcicus is an introduced lizard native to the Middle East and Asia that has become well established in the extreme southeastern United States over the last century (Fowler 1915; Smith and Kohler 1977; Knight 1993; Kraus 2008). Like many squamate species, *H. turcicus* displays male-biased SSD in head size, which is thought to be attributed to sexual selection or resource defense where males with larger heads are more successful during intrasexual encounters (Saenz and Conner 1996; Smith et al. 1997; Olsson et al. 2002; Johnson et al. 2005; Gifford and Powell 2007). Recent work by Johnson et al. (2005) suggested that male-biased head dimensions are a result of continued somatic

growth after post-reproductive age. Continued post-reproductive growth likely represents a metabolically costly process that may be potentially limited in environments with unfavorable conditions. The combination of an extensive introduced geographic range covering a broad spectrum of latitudinal gradients, and the physiologically demanding post-reproductive somatic growth in males make *H. turcicus* a good model for exploring both larger trends in Bergmann's scaling patterns, and whether climatic variability (as represented by latitude in this study) influence SSD in herpetofauna.

In this study, we explore variation in SSD in *H. turcicus* across a broad latitudinal and longitudinal gradient to determine environmental effects on morphological variation. We hypothesize that environmental conditions at higher latitudes place a metabolic constraint on post-reproductive growth and male-biased SSD and overall body size will be lower at higher latitudes. We expect to find no indication of morphological variation along a longitudinal gradient due to relatively more stable environmental conditions compared to latitudinal gradients.

MATERIALS AND METHODS

We examined preserved specimens (n = 186; 69 males, 117 females) of *H. turcicus* from the Florida

TABLE 1. Mean (\pm SD) snout-vent length (SVL), head length (HL), head width (HW), and head depth (HD) in mm of male and female Mediterranean House Geckos, *Hemidactylus turcicus*, from the southeastern United States.

Sex	SVL	HL	HW	HD
Male	51.53 \pm 2.91	14.97 \pm 0.95	10.36 \pm 0.75	6.19 \pm 0.54
Female	50.03 \pm 3.43	14.32 \pm 1.03	9.50 \pm 0.80	5.84 \pm 0.64

Museum of Natural History and the North Carolina Museum of Natural Sciences (Appendix 1). We measured only adults (≥ 44 mm snout-vent-length [SVL]; Selcer 1986; Saenz and Conner 1996; Johnson and McBrayer 2005) because it is difficult to differentiate between males and females at smaller sizes without dissection and destructive sampling and differences in SSD in head shape do not appear until after maturity (Johnson et al. 2005). Males were differentiated from females based on the presence of well developed pre-cloacal pores. We measured head length (HL; from the base of the quadrate to the tip of the premaxilla), head depth (HD; at the deepest part of the head), head width (HW; from the widest part of the head around the quadrate), and SVL on each specimen using Tresna Instrument IP 67 Digital Calipers (Guilin Guanglu Measuring Instrument Co., Guangxi Province, China; ± 0.03 mm).

Our sample represents both a broad latitudinal (24°33'21"N–35°57'40"N) and longitudinal (79°3'17"W–98°9'48"W) portion of the introduced range of *H. turcicus* (Fig. 1). We tested for differences in HL, HW, HD, and SVL between male and females using a student's t-test or a non-parametric Mann-Whitney U test (Sokal and Rohlf 2012). We tested all data for normality with either a Shapiro-Wilk or Kolmogorov-Smirnov test.

We used regression analyses to evaluate the potential significance of latitudinal and longitudinal trends on SVL, HL, HW, and HD. Longitude and latitude was expressed in decimal degree notation rounded to the nearest 0.1°. If latitude or longitude had some predictive relationship with the morphological variables of interest, we performed a t-test to compare the slopes of males and females using an F-test to determine significance differences in slopes (Sokal and Rohlf 2012). We used JMP Pro Ver. 11 (SAS Institute Inc., Cary, North Carolina, USA) for all tests and we determined statistical significance with an $\alpha = 0.05$.

RESULTS

We found significant differences in SVL ($U = 3018.5$; $P < 0.01$), HL ($t = 4.27$; $P < 0.01$), HW ($t = 7.23$; $P < 0.01$), and HD ($t = 6.14$; $P < 0.01$) between male and female *H. turcicus* (Table 1). While significant differences were observed in SSD between males and

females across the entire sample range, there were no significant relationships observed between latitude and any of the morphological variables (Fig. 2). Similarly, we did not find significant relationships between HL and longitude for either sex (Fig. 3). In contrast, male HD significantly decreased ($F_{2,184} = 5.33$; $P = 0.02$) as longitude decreases towards the prime meridian (although the relationship was weak; $r^2 = 0.07$), but there was no significant relationship in females (Fig 3). Male HW was not significantly different across longitude, although female HW increased significantly as longitude decreases towards the prime meridian ($F_{2,184} = 4.09$; $P = 0.05$), also a very weak relationship ($r^2 = 0.03$; Fig 3). Total SVL increased significantly in both males ($F_{2,184} = 7.31$; $P < 0.01$; $r^2 = 0.10$) and females ($F_{2,184} = 5.81$; $P = 0.02$, $r^2 = 0.05$) as longitude decreases towards the prime meridian (Fig 3), but there was no significant difference between the slopes of males and females ($t = 0.11$; $P = 0.91$).

DISCUSSION

Hemidactylus turcicus exhibited significant male-dominated SSD in head shape across its nonindigenous range in the southeastern United States. This is in accordance with previously conducted studies (Saenz and Conner 1996; Johnson et al. 2005), and is thought to be attributed to sexual selection or resource defense where males with larger heads are more successful during intrasexual encounters (Saenz and Conner 1996; Smith et al. 1997; Olsson et al. 2002; Johnson et al. 2005; Gifford and Powell 2007). The consistency of this finding suggests that selection for male-biased SSD in head shape is a phenotypically constrained feature that does not appear to vary among local populations. This does not appear to be the case for overall body length. As suggested by Saenz and Conner (1996) and Johnson et al. (2005), *H. turcicus* demonstrates male-biased SSD in head shape, but not SVL. While this finding is generally consistent within squamates, the sample used by Saenz and Conner (1996) and Johnson et al. (2005) was from a highly localized population in Texas (campus of Stephen F. Austin State University, Nacogdoches, Texas; 31°37'21"N, 94°38'63"W). Our analysis of a much larger geographic range suggests that *H. turcicus* demonstrates male-biased SSD in body length as well as overall head shape, potentially

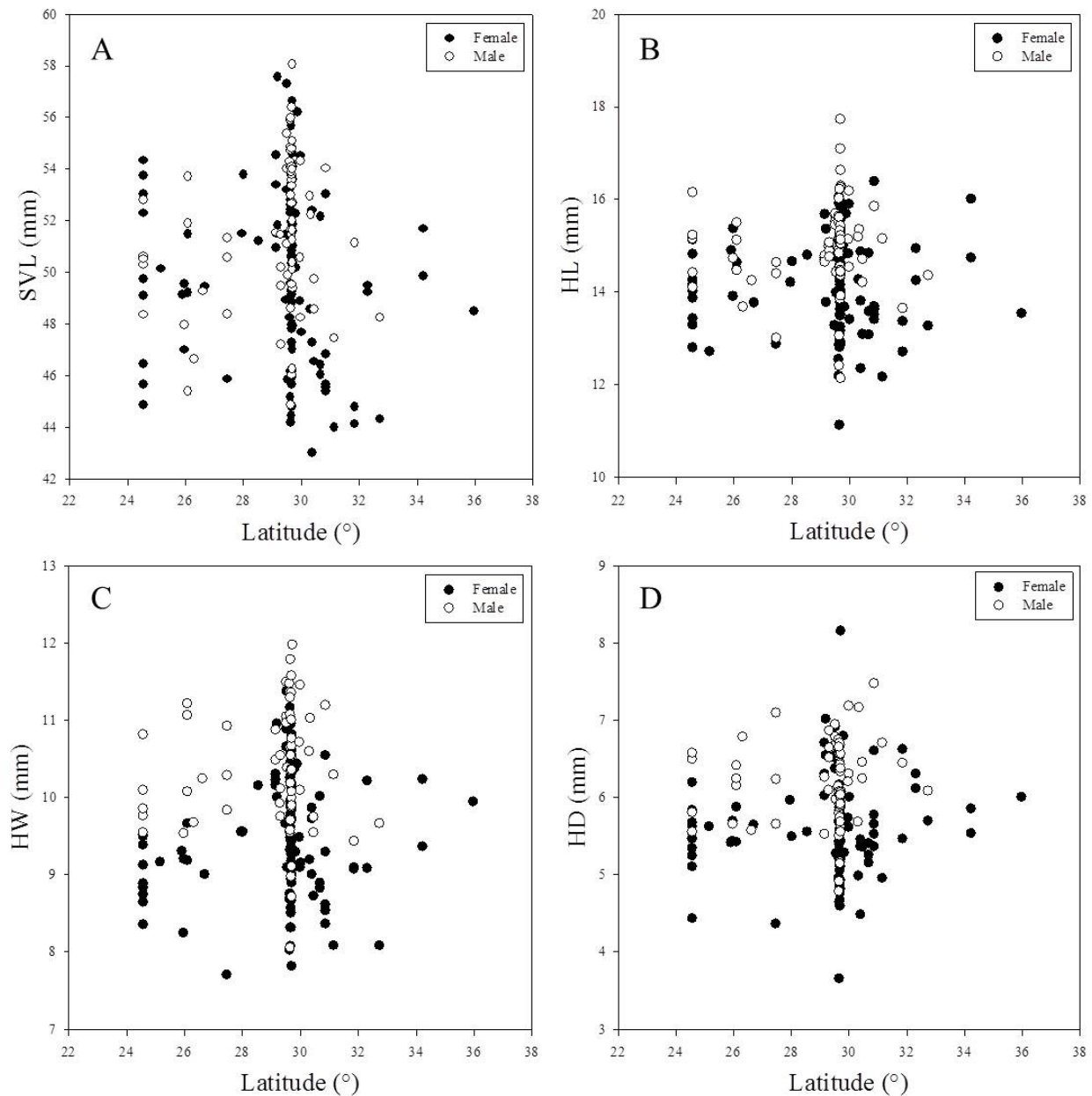


FIGURE 2. Relationship of snout-vent length (A), head length (B), head width (C), and head depth (D) of the Mediterranean House Gecko (*Hemidactylus turcicus*) to latitude (°) in the southeastern United States.

suggesting differences in morphology between local populations. A future analysis between this dataset and that of Saenz and Conner (1996) and Johnson et al. (2005) may prove valuable to test this hypothesis.

The patterns of longitudinal variation observed in this study likely represent either patterns of local variation, or unforeseen bias within the sample, rather than actual geographic trends. This conservative interpretation is based on the high degree of morphological variation observed within a very small longitudinal range,

suggesting that the patterns we are detecting are statistically significant but are unlikely to be biologically meaningful. Our data show that: (1) western males have deeper heads than eastern males; (2) eastern females have wider heads than western females; and (3) both males and females are longer in the east than in the west), but these findings should be interpreted with caution. A more detailed study incorporating more specimens from the western extent of the introduced range may elucidate these patterns further. There was no

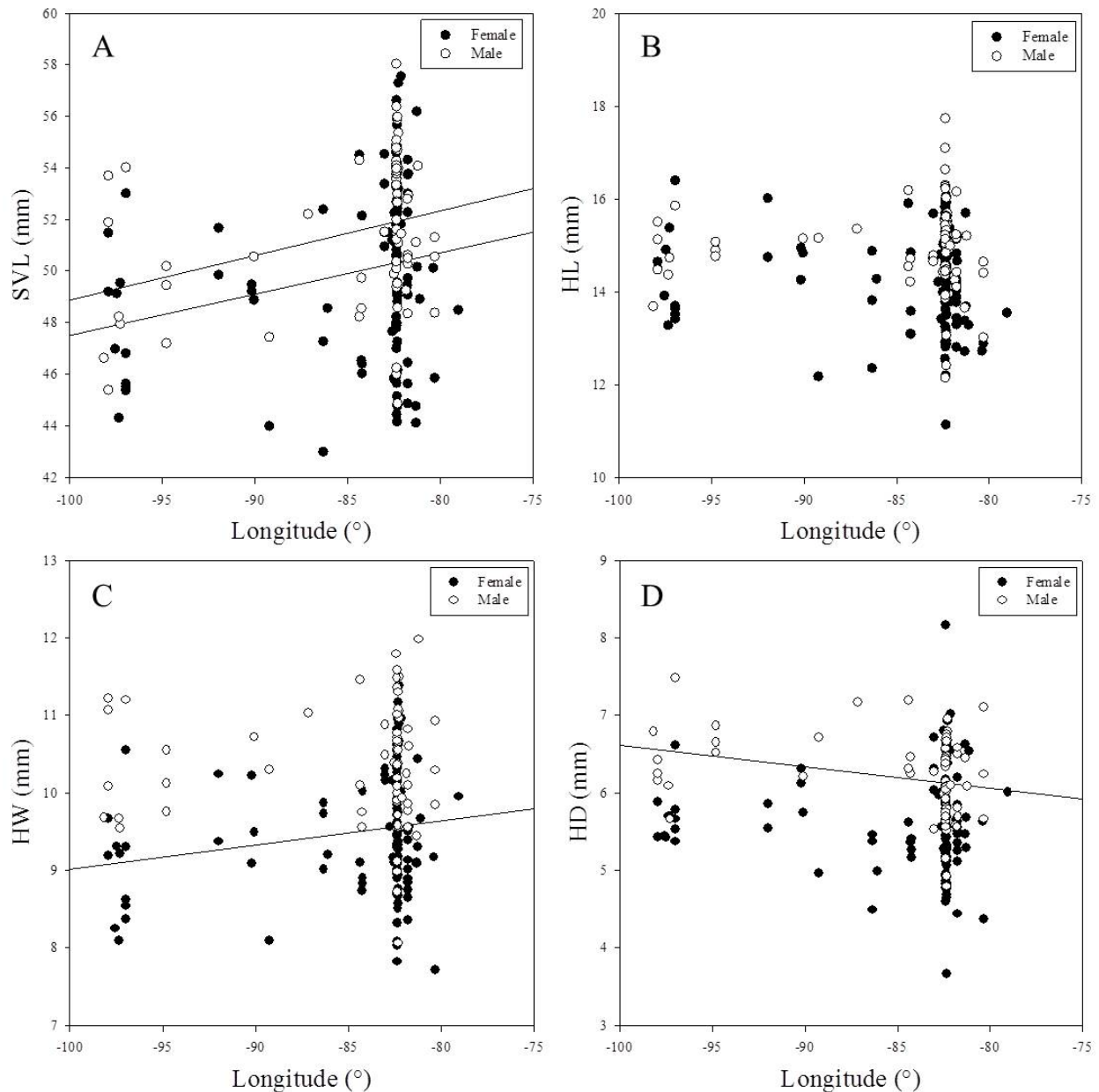


FIGURE 3. Relationship of snout-vent length (A), head length (B), head width (C), and head depth (D) of the Mediterranean House Gecko (*Hemidactylus turcicus*) to longitude (°) in the southeastern United States.

significant relationship between SSD and geographic latitude. These data provide no evidence for patterns associated with Bergmann's rule. Some animals seem to follow this rule or the inverse, and the type and degree of concordance with this rule can vary within families (Ashton and Feldman 2003; Meiri and Dayan 2003; Angilletta et al. 2004; Blackburn and Hawkins 2004; Olalla-Tárraga et al. 2006). Our data are in accordance with work by Newman (1953), Geist (1987), Ashton et al. (2000), Meiri and Dayan (2003), Millien et al. (2006),

and Adams and Church (2008) that suggest that certain taxa do not strictly follow the predictions of Bergmann's rule, and caution should be exercised when making broad interpretations about the patterns of morphological change across geographic gradients. The lack of any correlation between SSD and latitude in *H. turcicus* may stem from a variety of reasons. *Hemidactylus turcicus* is a hardy and virulent species and morphological variation in SSD may not be affected by colder climatic conditions. Also, the necessity for male *H. turcicus* to

maintain larger body proportions to successfully reproduce may limit energy allocation towards other life-history variables (i.e., longevity, fecundity, offspring survivorship, etc.). In addition, the native range of *H. turcicus* corresponds to a much larger latitudinal gradient (see Moravec et al. 2011 for a recent taxonomic revision) than does the non-native range and the non-native range may have more favorable climatic conditions for *H. turcicus* than does the native range, suggesting that the introduced populations may be under lower metabolic stress than their native counterparts. Finally, the introduction of *H. turcicus* into the southeastern United States is a relatively recent introduction, and patterns of morphological variation may not yet be visible. Further studies should be conducted to explore the causal agents of this study's findings.

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MICHAEL C. GRANATOSKY is a Doctoral Candidate at Duke University in the Department of Evolutionary Anthropology. His research interests focus on animal locomotion, specifically how an animal adjusts when switching from one form of locomotion to another. Additionally, Michael has a keen interest in exotic ecology and trying to determine aspects of the biology of invasive species that make them more virulent in their introduced range. Michael began herpetological research at the Florida Museum of Natural History where he worked on projects related to exotic ecology, taxonomy, and functional morphology. His work has led to the discovery of several new introduced species in Florida, a more detailed analysis of the diet of the invasive Burmese Python (*Python bivittatus*) and the description of two new species of alligator snapping turtles (*Macrochelys suwanniensis* and *M. apalachicola*; Thomas et al. 2014). Upon moving to Duke University, he has worked closely with the North Carolina Museum of Natural Sciences reporting on and collecting newly introduced reptile and amphibian species within the state. His eventual goal is to further this partnership by creating an early detection program to help limit the spread of exotic herpetofauna within North Carolina. (Photographed by David Haring).



KENNETH L. KRYSKO (center, holding the fish) is a Research Scientist in the Division of Herpetology, Florida Museum of Natural History, University of Florida (UF). He also holds courtesy faculty appointments in the departments of Wildlife Ecology and Conservation as well as the School of Natural Resources and the Environment at UF. He teaches Invasion Ecology, Herpetology, and related courses when he feels like it. His students think that he is tough on them at times, but he believes it is for their own good. On many occasions he would rather be on the shallow crystal clear water flats fishing in remote areas of The Bahamas or Florida Keys. He loves his wonderful wife and appreciates that she enjoys being in the hot sun conducting field work with him. (Photographed by Claudia Mackenzie-Krysko).

APPENDIX I. Specimens examined for in this study. Specimens provided by the North Carolina State Museum (NCSM) and the Florida Museum of Natural History, University of Florida (UF-Herpetology).

State	Accession Number
Arkansas	UF 141606-07
Florida	NCSM 17972, 52968, 70667, UF 616, 7096, 9283-01, 9283-03, 9283-06-08, 9283-10, 9283-13-14, 9283-17, 9283-19, 9283-22-24, 9283-26, 9283-28, 9283-32-34, 40647-48, 40650, 66941, 69311, 69313, 71520-21, 71523, 73734, 73736-37, 74994, 82821, 86816, 86875-76, 86879, 86881-82, 87703-06, 87725-29, 87818-20, 87830, 87833, 87835-38, 87840, 89632, 89634, 89636, 89640-41, 89646, 89654, 91969, 98749, 99770, 104899, 115970, 117754, 120792, 121185-86, 124750, 126835, 126838, 127130, 128025, 128028, 133844-46, 133934, 138218, 139397, 141253, 141618, 141643, 143207-08, 143209, 144188, 151216, 153460-61, 158564-65, 158567-68, 158570-77, 158581-90, 158592-93, 158597-99, 158602, 158604, 158607-08, 158611, 158613, 158615-16, 158619-22, 158624-25, 158628, 158631, 158634, 158636-37, 162963-65, 165652
Georgia	UF 168506-08
Louisiana	NCSM 7304-05
Mississippi	NCSM 73769-70, UF 133859-60
North Carolina	UF 171920
Texas	NCSM 5017-22, 70776, 70779-80, UF 74995, 48540-41, 126840-41, 126843-45, 126847-48, 126851-52