Herpetological Conservation and Biology 17(2):370–377.
Submitted: 20 May 2021; Accepted: 24 June 2022; Published: 31 August 2022.

Assessing Population Density of Radiated Tortoise (*Astrochelys radiata*) in Southwest Madagascar

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Abstract.—**The Radiated Tortoise (*Astrochelys radiata*) is a critically endangered species endemic to southern Madagascar. Their populations are in decline due to human harvesting and anthropogenic deforestation; however, current population densities have not been assessed in over a decade. This study focused on a population of *A. radiata* in Lavavolo, Madagascar, one of the last remaining strongholds of the species. We made surveys in the dry and wet seasons across six parallel transects on three soil types present in Lavavolo (sandy, ferruginous, calcareous). We identified 289 live tortoises. Based on distance sampling, there were significant seasonal differences in density between the wet season (14.5 ± 1.1 individuals/ha) and dry season (9.6 ± 0.9 individuals/ha). We also found significant differences in population densities between soil types, with a mean of 17.5 individuals/ha found on ferruginous soils, 15.8 individuals/ha on sandy soil, and 12.0 individuals/ha on calcareous soil during the wet season. Activity of poachers near the transects on calcareous soil, however, may have contributed to lower numbers in this habitat. The higher densities of *A. radiata* around Lavavolo in comparison to other parts of its range suggest that a combination of protective taboos and conservation initiatives in the area may be effective.**

Key Words.—calcareous soil; ferruginous soil; Lavavolo; population density; sandy soil; seasonality

Introduction

The critically endangered Radiated Tortoise (*Astrochelys radiata*; Fig. 1) is endemic to the dry spiny thicket of southern Madagascar (Glaw and Vences 2007; Leuteritz and Rioux-Paquette 2008). Historically, its natural distribution extended across southern Madagascar, from the Onilahy River in the north to the bay of Ranofotsy in the south within about 40 km of Tolagnaro (Decary 1950; Fig. 2). Local people from the Tandroy and Mahafaly tribes have taboos (*fady*) that prohibit them from eating or touching *A. radiata*, thus providing a form of protection for the species in some areas (Raxworthy and Nussbaum 2000; Lingard et al. 2003). Human populations in the northeastern and southeastern range of the tortoise, however, as well as immigrant populations from other regions of Madagascar that have moved into the southwest, do not have these protective beliefs (Raxworthy and Nussbaum 2000). As such, *A. radiata* is exploited as a source of food or for the international pet trade even within their protected range (Raxworthy and Nussbaum 2000; O'Brien et al. 2003; Irwin et al. 2010). In addition to anthropogenic harvesting, the natural habitat of this species continues to come under pressure from forest clearing for agricultural use, overgrazing, and charcoal production (Raxworthy and Nussbaum 2000). On average 1.2% of remaining forests are lost every year, negatively impacting most all native fauna (Harper et al. 2007), especially *A. radiata*, with a 20.9% decrease in its geographic range between 1975 and 2000 (Juvik 1975; O'Brien et al. 2003).

These anthropogenic factors have caused a decline in the distribution of the tortoise, which now only stretches from the Onilahy River to Cap Sainte Marie (Fig. 2), reducing the overall population size and creating isolated groups in the east as far as Andohahela National Park (O'Brien et al. 2003; Pedrono 2008). Unfortunately, accurate assessments of the overall population decline cannot be achieved as data prior to the observed population decreases are not available (Leuteritz et al. 2005). Instead, we are reliant on monitoring current population trends to assess the status of the species. The last estimate was over 10 y ago and suggested a population size of 6.3 million tortoises, with the largest populations limited to Lavavolo, Cap Sainte Marie Special Reserve, and Lavanono (Rafeliarisoa et al. 2013). In other places, particularly those near urban centers in

Figure 1. Captive Radiated Tortoise (*Astrochelys radiata*). (Photographed by Andrée Nambinina).

the south such as Toliara and Tolagnaro, populations have been extirpated (Hudson 2013; Rafeliarisoa et al. 2013), and many more were fragmented, such as those to the east of Cap Sainte-Marie (O'Brien 2002). Indeed, of the 64 sites surveyed by Rafeliarisoa and colleagues (2013), 23 of them were devoid of tortoises.

As the conservation status of a species is extrapolated from site-specific data, regular monitoring at different localities will be valuable for conservation management of *A. radiata*. Density data are available for multiple sites from 1995 (Richard Lewis, unpubl. report as published in Leuteritz et al. 2005), 1999 (Leuteritz et al. 2005), and 2009 (Castellano et al. 2013). For example, at Lavavolo, one of the remaining strongholds for *A. radiata* (Castellano et al. 2013; Rafeliarisoa et al. 2013), density was estimated to be 602 tortoises/km^2 in 1995 (Richard Lewis, unpubl. report as published in Leuteritz et al. 2005), sharply increasing to 4,908 (95% confidence interval 2,749–8764) tortoises/km^2 in 1999 (Leuteritz et al. 2005) and falling to 948 (average of two transect densities of 925 and 970) tortoises/km^2 by 2009 (Castellano et al. 2013). These fluctuations occurred in a decade or less, highlighting the need for continued data collection to determine the population trend.

Population counts and density estimates are valuable to ascertain the stability of a population, though ecological factors such as seasonality and soil type can affect these values (O'Brien et al. 2003; Pedrono and Smith 2003; Leuteritz et al. 2005; Rasoma et al. 2010). *Astrochelys radiata* are generally more active during the wet season, November to April (Ranaivoharivelo 2013), when rainfall increases plant biomass production, which is favorable for tortoise feeding making them easier to observe. During the dry season, May to October, they aestivate to avoid dehydration (Pedrono and Smith 2003).

The earliest density estimate for *A. radiata* at Lavavolo was established by Richard Lewis (unpubl. report) during the wet season. Subsequently, Leuteritz

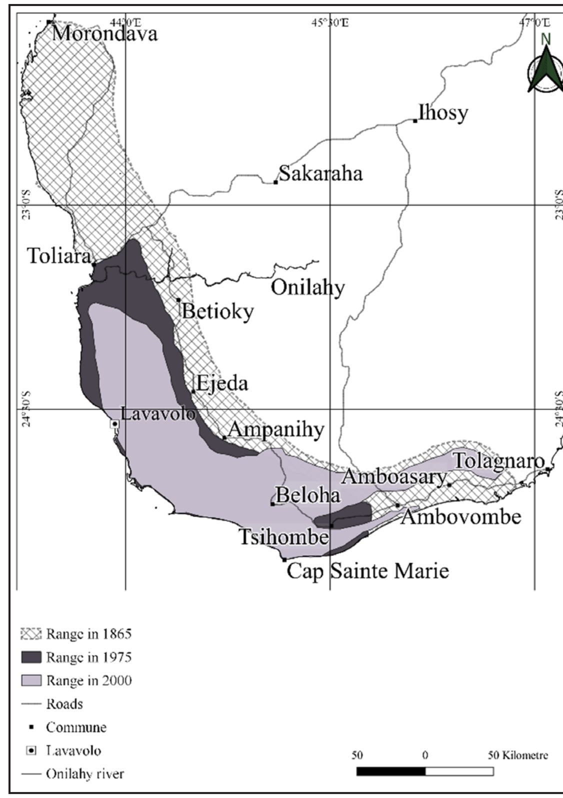

Figure 2. Map of southern Madagascar showing historical and recent distribution of the Radiated Tortoise (*Astrochelys radiata*) in 1865, 1975, and 2000 (modified from O'Brien et al. 2003 with permission from Oryx, License number: 5062600418112).

et al. (2005), using the same transects as Lewis, also collected data during the wet season, specifically January and February 1999. The most recent estimate for Lavavolo was based on data collected at the end of the dry season into the beginning of wet season, October and November 2009 (Castellano et al. 2013). Though density estimates are anticipated to be higher during the wet season, dry season estimates are a valuable minimum threshold for assessing stability, particularly as southern Madagascar is predicted to experience the greatest increase in annual temperatures based on climate change models (Tadross et al. 2008).

Though it is difficult to establish a relationship between population size and soil type, previous studies found that *A. radiata* population densities are higher on sandy soil than ferruginous or calcareous soils in Tsimanampetsotsa National Park (Rasoma et al. 2010; Marzec 2013). It was proposed that this difference has to do with taller vegetation cover on sandy soil; however, this variance has not been confirmed (Rasoma et al. 2013). Though all the previously mentioned studies reported data from the wet season, none of them acknowledged the presence of different soil types in Lavavolo. At Lavavolo, there are three soil types that *A. radiata* can occupy: sandy, ferruginous, and calcareous.

These can be clearly distinguished on site and via satellite imagery. By mapping the starting points of transects surveyed by both Richard Lewis (unpubl. report) and Leuteritz et al. (2005), they would have crossed through habitat on calcareous soils, possibly reaching ferruginous soils. Castellano et al. (2013) did not report GPS locations or soil types. A more recent survey conducted from 2010–2011 (Rafeliarisoa et al. 2013) only traversed the calcareous soil but did not provide a density estimate for Lavavolo. These reported coordinates suggest that sandy soils were never assessed and soil type, and related habitat differences, have been overlooked in Lavavolo.

Conservation management dictates that accurate estimates of population densities are fundamental to protecting any species (Gelatt and Siniff 1999). Given that environmental factors can alter tortoise activity and, therefore, density estimates (Pedrono and Smith 2003; Rasoma et al 2010, 2013), it may be necessary to conduct surveys across seasons and soil types, especially in places with a history of long-term monitoring (O'Brien 2002). The aim of our study is to better understand the effect of seasonality and soil types on the *A. radiata* population in Lavavolo.

Materials and Methods

Study area.—Lavavolo (24°38'26.91"S, 043°56' 03.48"E; Fig. 3) is located in the rural commune of Itampolo, approximately 150 km south of Toliara, and is the driest region in Madagascar. A coastal region along the Mozambique Channel, Itampolo encompasses part of the Mahafaly Plateau, a limestone feature about 100 m above sea level (Guyot 2002). The climate of southwestern Madagascar is dry or sub-arid (Morat 1969) with two distinctly marked seasons: a dry season (May-October), and a wet season (November-April; Ranaivoharivelo 2013), which is often erratic and precipitation is always < 600 mm/year (Office National de l'Environnement 2008). The vegetation is dominated by baobab (*Adansonia* sp.), *Alluaudia ascendens* (no common name), Octopus Tree (*Didierea trollii*), spurge (*Euphorbia* sp.), Nettlespurge (*Jatropha mahafalensis*), and Velvet-leak (*Kalanchoe beharensis*; Leuteritz 2002). Lavavolo contains three soil types similar in definition to those identified in Tsimanampetsotsa with dry forest on both sandy and ferruginous soils, while calcareous soils supports open xerophytic bush (Rasoma et al. 2010).

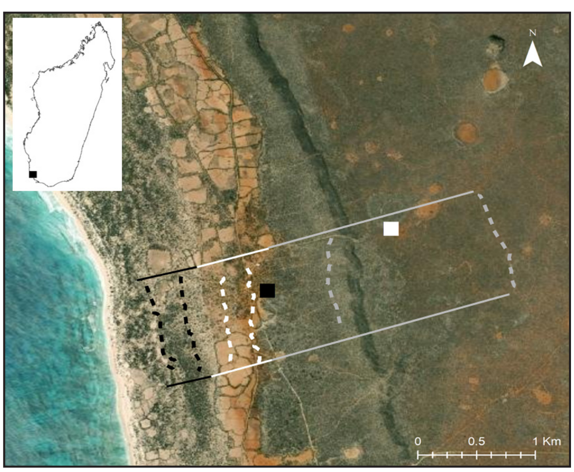

Figure 3. Location of the transects in Lavavolo, Madagascar. The solid lines delineate the soil types while the dotted lines indicate the 1 km transects. Black lines are in the sandy soil, white lines are in the ferruginous soil, and grey lines are in the calcareous soil. The black square indicates the beginning of transect T084 of Rafeliarisoa et al. (2013), which extended 1 km east. The white square indicates the beginning of the Lavavolo transect surveyed in Richard Lewis (unpubl. report) and Leuteritz et al. (2005), which extended along a northwesterly bearing.

Survey methods.—To survey for tortoises, we employed distance sampling (Buckland et al. 1993). This method employs a series of linear transects assuming that the detection on the transect center line is certain, there is no movement of individuals in response to the observer, and the distances of individuals from the transect center line are accurately measured. Because tortoises aestivate underground (Pedrono and Smith 2003), tortoise density, in this instance, is a measure of active, above-ground tortoises within our sampling area. We analyzed transect data using the distance sampling model of Royle et al. (2004) to determine tortoise density.

The surveys were carried out during both dry and wet seasons between July 2018 and April 2019. We established six transects oriented north-south, two on each soil type. Each transect was 20 m wide (10 m left and right of the center line) and 1,000 m in length. In sandy soil and ferruginous soil, we spaced these transects approximately 200 m apart, while in the calcareous soil, one transect was set below an escarpment that separates the ferruginous and calcareous soils while another transect was 1,400 m east of it (Fig. 3). We conducted surveys from July-September (dry season), November-December (wet season), and March-April (wet season; Table 1).

Astrochelys radiata are known to be most active from 0630–1000 and 1500–1830 daily (Pedrono 2008); thus, we walked transects twice daily, once in the morning and again in the afternoon, to maximize potential observations. We treated each daily survey as an independent sample for the analysis. For observed tortoises in each soil type, we measured the perpendicular distance between the tortoise and the transect line using a 15 m tape measure. We recorded the exact location of each tortoise with a Garmin Map64S GPS handheld unit (Garmin International, Inc., Olathe, Kansas,

Table 1. Counts of the Radiated Tortoise (*Astrochelys radiata*) individuals encountered on each transect in the dry and wet seasons in Lavavolo, Madagascar, from July-September 2018, November-December 2018, and March-April 2019.

Soil type	Transect	Dry	Wet
Sandy	t1	27	31
	t2	20	32
Ferruginous	t3	22	34
	t4	23	36
Calcareous	t5	12	22
	t6	11	19

USA). During transect surveys, we also enumerated the carapaces of dead tortoises along the transect. To determine the potential cause of death, we checked the shell for traces of dog tooth marks, fire, and breakage.

Statistical analysis.—For all tests, α = 0.05. We used the unmarked v. 1.1.1 (Fiske and Chandler 2011) package in R (R Core Team 2020) to estimate tortoise density based on season and soil. Specifically, we used the distance sampling model, using season and soil type as covariates on density and a half-normal detection function. The half-normal detection function and hazard-rate detection function had equal Akaike Information Criterion values (209.5), so we used half-normal detection function as it was appropriate for non-numerical covariate data. Lastly, we used Analysis of Variance tests to compare densities between seasons and soils, and a Tukey test to compare densities on soil types.

Results

We recorded 289 tortoises with 115 tortoises on ferruginous soil, 110 tortoises on sandy soil and 64 tortoises on calcareous soil (Table 1). Observed tortoise densities were significantly different seasonally ($F_{1,2}$ = 53.54, P = 0.018) and between soil types ($F_{2,2}$ = 21.34, P = 0.045). We observed significantly more tortoises during the wet season, with a mean population density of 14.5 ± 1.1 (standard error) individuals/ha, than the dry season (9.6 ± 0.9 individuals/ha).

During the wet season, the mean density estimates were 17.5 ± 2.1 individuals/ha in the ferruginous soil, 15.8 ± 2.0 individuals/ha in the sandy soil, and 12.0 ± 2.7 individuals/ha for calcareous soil. For the dry season, the mean population densities were 11.3 ± 1.7 individuals/ha in the ferruginous soil, 11.8 ± 1.7 individuals/ha in the sandy soil, and 5.8 ± 1.2 individuals/ha in the calcareous soil. There was a significantly greater density of tortoises on the ferruginous soil than the calcareous soil (Tukey HSD, P = 0.049; Fig. 4), though there were no significant differences between sandy soil and calcareous (Tukey HSD, P = 0.061) or sandy and ferruginous soil (Tukey HSD, P = 0.798).

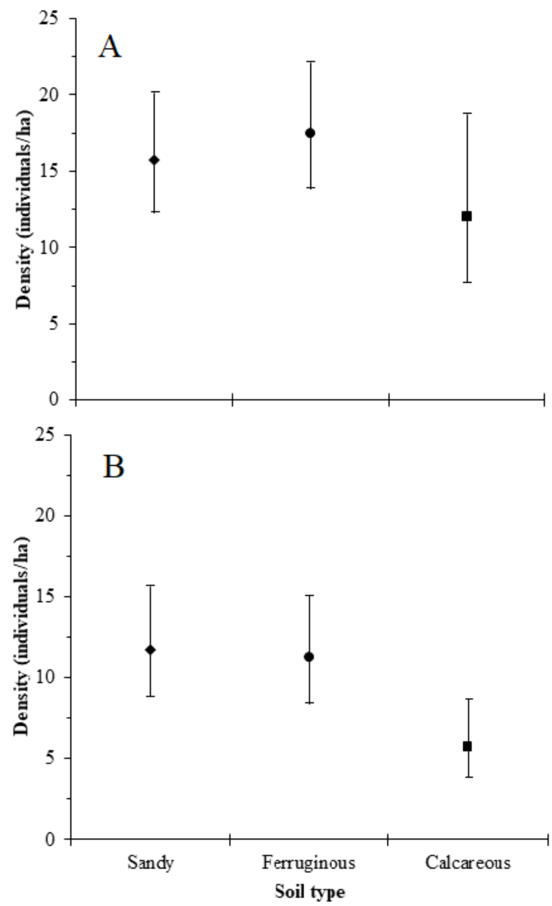

Figure 4. Predicted covariate relationships in the wet season and dry season in Lavavolo, Madagascar. (A) Wet season and (B) dry season predicted covariate relationships.

Discussion

Applying the wet season density estimate, the Lavavolo population has increased from 948 individuals/km^2 (Castellano et al. 2013) to 1,460 individuals/km^2 (this study). The estimate reported by Castellano et al. (2013), however, was based on data collected at the cusp of the dry and wet seasons (October-November) and is consistent with the density estimate we acquired based on the dry season (950 individuals/km^2). While the estimates from our study do not reach the peaks reported from 1999 (4,908 individuals/km^2; Leuteritz et al. 2005), in comparison to estimates from 1995 (602 individuals/km^2; Richard Lewis, unpubl. report) and 2009 (Castellano et al. 2013), there does appear to be an upward trend in the Lavavolo population. At a minimum, based strictly on comparisons with our dry season data to Castellano et al. (2013), our estimates indicate the Lavavolo population has been stable for the last decade.

Our observed densities of *A. radiata* were significantly higher in the wet season compared to the dry season. This was expected, given seasonal behavioral changes of tortoises (Raxworthy and Nussbaum 2000; Pedrono and Smith 2003; Hammer and Ramilijaona 2009; Rasoma et al. 2013). As an example, the Speckled Cape Tortoise (*Homopus signatus signatus*) aestivates and moves less often during the dry season, decreasing its metabolism and conserving energy (Loehr et al. 2009). Comparatively, during the wet season when herbaceous plants have new growth and food becomes more abundant (Ratovonamana et al. 2011), *A. radiata* are more active, searching for food and water (Leuteritz 2003). In addition, the wet season coincides with the breeding season of *A. radiata* (Leuteritz and Ravolonaivo 2005; Pedrono 2008), presumably resulting in increased activity as tortoises search for reproductive partners, as seen in Egyptian Tortoise (*Testudo kleinmanni*; Geffen and Mendelssohn 1988). This is not to say that the actual density of the population decreases during dry seasons, rather the aestivating tortoises are not observed and thus density estimates may be underrepresented during this time.

As with other studies that identified habitat-dependent densities (Hammer and Ramilijaona 2009; Rasoma et al. 2010; Marzec 2013), we found some differences in tortoise densities based on soil type. We did not identify any significant difference between densities on sandy or ferruginous soils; however, there was a significant difference between calcareous and ferruginous soil, while densities between sandy and ferruginous approached significance. The higher density on ferruginous compared to calcareous soil may be due to the floral composition of the habitats. For example, average canopy heights and percentage cover of vegetation are greater on sandy soil and ferruginous soil than calcareous soil (Ratovonamana et al. 2011), potentially providing more optimal conditions for tortoises.

Alternatively, the lower density on the calcareous soil may be due to human poaching. We identified 170 adult carapaces, all of which were found on the calcareous soil in a tortoise graveyard, or a poaching camp containing remains of carapaces. These individuals had their carapace and plastron separated with visible signs of hatchet marks and their heads and limbs were absent, characteristic signs of human predation (Walker 2010; Castellano et al. 2013). In addition, many of the carapaces found were old, which indicates that this area has a long-term use for bushmeat collection. This tortoise graveyard is situated along the eastern edge of our study area, the farthest point, approximately 2 km, from the village of Lavavolo. It is possible the lower canopy cover and shorter canopy height of vegetation on the calcareous soil compared to the sandy soil and ferruginous soil (Ratovonamana et al. 2011) make it easier for poachers to identify tortoises. On the other hand, the vicinity of tortoises to conservation facilities and Lavavolo village, where people adhere to the protective *fady*, may deter poaching. Despite poaching pressure, *A. radiata* in Lavavolo have a higher population density compared to other sites such as Itampolo (5.13 tortoises/ha), Andranomasy (3.22 individuals/ha), Besasavy Avaratra (1.96 individuals/ha), Bevala (2.80 tortoises/ha), and Andranovao (0.58 individuals/ha; Rakotondrainy 2008; Rasoma et al. 2010), which have likely declined in the last decade.

While Lavavolo may contain one of the larger populations of *A. radiata* across its range, there are still conservation needs within this region. Indeed, Lavavolo is in a zone (between the Onilahy and Linta rivers) where the poaching threat level is only moderate (Walker 2010), likely why *A. radiata* still persists here. *Astrochelys radiata* populations closer to Lavavolo village appear to be less exploited by human populations than those further away from it, as evident from the discarded carapaces *in situ* found in the western part of our study site. Though this finding seems to run counter to previous studies where population numbers were lower near human settlements (O'Brien et al. 2003; Leuteritz et al. 2005; Rasoma et al. 2010), the *fady* of the Mahafaly and Atandroy tribes against harming these tortoises has been invoked to explain this seeming paradox (Lingard et al. 2003). Unfortunately, poachers from the Vezo and Antanosy groups, who travel into the region do not share this belief and are the main culprits in tortoise harvesting in the region (World Wildlife Fund 2010). This represents a conservation conundrum with regards to where to focus efforts.

Local community members have expressed that the presence of conservation-oriented Non-Governmental Organizations like Madagascar Biodiversity Partnership, Conservation Fusion, and Turtle Survival Alliance, help to dissuade poaching around Lavavolo. Yet, further away from these protective communities poaching is ongoing. We suggest that conservation initiatives for this species focus on helping community members with the advantageous *fady* to promote protection of *A. radiata* in areas where the population density is highest, i.e., on the sandy and ferruginous soils. Personnel of agencies should also strive to conduct surveys and patrols in the more remote areas around their facilities to help maintain the remaining populations, i.e., on the calcareous soil. Lastly, as populations in protected areas continue to decline, we recommend regular survey efforts be conducted in wet and dry seasons to acquire an accurate census of the current population trends of

A. radiata. Determining the role of soil types on *A. radiata* population density also needs to be achieved to help guide conservation initiatives.

Acknowledgments.—We would like to thank Madagascar Biodiversity Partnership (MBP) and Omaha's Henry Doorly Zoo and Aquarium of Nebraska, USA, for their financial support of this project. The IACUC (12-101) was approved by Omaha's Henry Doorly Zoo and Aquarium. We are extremely grateful for all the help from Tonosoa, MBP guide, and the community of Lavavolo. Many thanks to the Direction de la Gestion des Ressources Naturelles Renouvelables et des Ecosystèmes Antananarivo and the Direction Régionale de l'Environnement et du Développement Durable Atsimo Andrefana for granting permission for this research referred to the authorization 128/18/MEEF/SG/DGF/DSAP/SCB.Re. For their support and helpfulness, we wish to thank the University of Toliara, Madagascar, and the members of the Center for Conservation and Research Conservation Genetics Department of Omaha's Henry Doorly Zoo and Aquarium.

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