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Management of a Geometric Tortoise (*Psammobates geometricus*) Population in a High-Risk, Fire-Prone Landscape

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Abstract. – We began developing our Geometric Tortoise Ecosystem Preserve in 2015. At the same time, we began a mark–recapture study to detect changes in the population size through time to inform our management practices. We now have data through 2021. Mark–recapture analysis gives a population size of between 800 and 1200 individuals. It is the last remaining substantial population. Using Lande's classification of 1933 of stochastic influences on demography, we find that 1) demographic stochasticity is not a problem, as the population is large enough and consists of individuals whose home ranges overlap; 2) environmental stochasticity is important mainly through variations in annual rainfall, including severe droughts; and 3) catastrophes occur in the form of wildfire that can destroy a local population. Taken together, these environmental effects can cause large changes in population size, making this species at risk of local extinction. If it were to go extinct, there are no other adjacent populations that could be used to recolonize our preserve. Therefore, we conclude that head starting is necessary to safeguard the population.

Key Words. – tortoise population management; mark–recapture; head-starting

Loveridge and Williams (1957) were correct in that the geometric tortoise (*Psammobates geometricus*) was not exterminated but was very rare. In the 1960s and 1970s, workers in South Africa began a serious effort to save this species from extinction. W.H. Archer (1960, 1967), R. Rau (1969, 1971, 1976), J.O. Juvik (1971, 1972), A. Eglis (1965), and J.C. Greig (1982, 1984) all worked to understand geometric tortoise biology and implement conservation measures, mostly involving the creation of protected areas to save it. The modern era began with CapeNature's management of the species and the work of E.H.W. Baard (1990, 1993) and M. Hofmeyr, whom we honor here.

In 2015, the Turtle Conservancy and its affiliated Southern Africa Tortoise Conservation Trust purchased 87 ha of geometric tortoise habitat in the Breede River Valley of the Western Cape Province in South Africa, creating the private Geometric Tortoise Ecosystem Preserve. This land and population were previously identified by Baard (1997) as a possible location for a protected area. Further purchases of neighboring land have brought the total protected area up to 485 ha by 2021. At the same time, a mark–recapture study was started on a subset of the property. Here we present the results of this study from 2015 to 2021 and analyze the demography of this population and the impact of various threats that could lead to its extinction.

The geometric tortoise is a diminutive species with females ranging from 400 to 600 g in weight and males smaller at 200–400 g. As noted in the opening quotes, it is one of the most beautiful tortoises anywhere, with bright yellow and black radiating lines on their carapaces. In the field, this pattern provides extraordinary camouflage in their shrubland fynbos habitat, making them extremely difficult for people to find unless they are out and active. This species is listed as critically endangered on the International Union for Conservation of Nature Red List (Hofmeyr and Baard 2018), and its total wild population in now estimated to be fewer than 2000 individuals. Unlike other very rare tortoises, geometric tortoises do not typically survive, let alone reproduce, in normal captivity (M. Hofmeyr, *pers. comm.*, October 2017). Other tortoises that are effectively extinct in the wild, such as the angonoka or plowshare tortoise (*Astrochelys yniphora*) and the Burmese star tortoise (*Geochelone platynota*), do well in captivity and are the beneficiaries of successful captive breeding efforts. This makes the geometric tortoise likely the most endangered tortoise of all.

Geometric tortoises occur primarily in 2 vegetation types, alluvium fynbos and shale renosterveld, forming part of the Fynbos Biome, 1 of 9 plant biomes in South Africa. The Fynbos Biome is an integral and important part of the Greater Cape Floristic Region, considered one of the world's 6 distinctive plant kingdoms. The Fynbos

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Biome is known for its extreme biodiversity, especially of plants. It hosts over 7000 species in 46,000 km^2 (Allsopp et al. 2014; Esler et al. 2014). It is a fire-dependent ecosystem, and the resulting fires are a critical threat to the geometric tortoise. Fynbos is a Mediterranean ecosystem with a pronounced wet and dry season, with rains occurring primarily in the austral fall and winter. Annual rainfall at the preserve typically varies between 350 and 600 mm/yr with significant droughts occurring every few decades (Richard et al. 2001; Masih et al. 2014). Most of the geometric tortoise habitat of renosterveld and alluvium fynbos has been converted through intensive human use into urban areas, wheat fields, fruit orchards, and vineyards, with the result that over 97% of the original fynbos is now lost to development (Baard 1995a; Hofmeyr and Baard 2018). In addition to dramatic habitat loss, the tortoise is impacted by 4 major threats (Baard 1995a):

1. Invasive plants species. The Australian Port Jackson acacia (*Acacia saligna*) is an ongoing existential threat because it forms monocultures within the fynbos and other landscapes in the Western Cape that exclude all other species and transforms the soil to be more nitrogen rich and thus unfavorable to fynbos.
2. Fire. Although the fynbos, including renosterveld, normally recovers from fire rather quickly, geometric tortoise populations are significantly impacted by wildfires. In the past, populations thus lost could be replaced by immigrants from outside the burned areas. This replacement is no longer possible, as there are no other neighboring populations.
3. Drought and climate change. South Africa is a region of occasional severe drought (Richard et al. 2001; Masih et al. 2014) that affects tortoises in ways not yet understood. Rapid warming climate change is also occurring in the Western Cape with modeling of future fynbos habitat dynamics suggesting further fragmentation and restricted distribution effecting the endemic, native wildlife (Mokhatla et al. 2015; Du Plessis and Schloms 2017).
4. Subsidized predators. We now know that large corvids (ravens and pied crows) prey on small tortoises in South Africa (Fincham and Lambrechts 2014; Hofmeyr and Baard 2018). Increases in the number and distribution of these corvids in and adjacent to human-altered ecosystems are a serious threat to isolated tortoise populations.

A key effort in conservation biology is to identify the factors that can lead to population extinction. Lande (1993) synthesizes this work by developing models that help estimate the probability of extinction for 3 classes of stochastic threats: demographic stochasticity, environmental stochasticity, and catastrophes. Here we examine mark–recapture data for this species to understand the importance of these threats.

METHODS

Study Area. — Our study area is made up of 2 separate parcels that add up to a 75-ha subsection of the original 2015 preserve parcel. The vegetation type is Breede alluvium fynbos. This land has a history of fire, grazing by sheep, and some agriculture that has resulted in indistinct rows of furrows. It last burned completely in 1993 with smaller fires in 2002 and 2015. A fire covered 15 ha in 2017 and killed approximately 40 tortoises.

Weather. — Because rainfall in patchy in this region and decreases to the east (3–5 km) where official municipal and airport records are monitored, it is important to have weather data immediately adjacent to the preserve. Our rainfall data were provided by a neighbor who used an automated rain gauge to collect daily data from 1999 to 2021. The rain gauge is less than 200 m from our preserve.

Tortoise Capture and Processing. — Tortoises were found through the use of CapeNature conservation detection dogs (Hudson et al. 2020). These dogs find tortoises that have been active by smell and track them to where they are active or hiding. The dogs were equipped with GPS devices so that their route over the study area could be determined to make sure coverage was more or less even. Multiday detection dog surveys were conducted twice annually—in spring (September–October) and fall (March–May)—for the 7 yrs 2015–2021. The dogs were not effective during the dry season or times of drought, as the tortoises remain hidden. Adult tortoises so captured were marked using a file or a Dremel tool with Honegger's number system (Honegger 1970). Tortoises were sexed, weighed, and measured, and health and shell abnormalities were noted. Tortoises larger than approximately 125 mm were sexed as described in Boycott and Bourquin (2000, p. 9).

Population Estimation. — Estimates of population size were obtained from the *Rcapture* program in R (Baillargeon and Rivest 2007) using methods for open populations. We used the *openp* function of *Rcapture* that implements the log-linear recapture method of Cormack (1989).

Movement Data. — GPS capture locations were recorded in decimal degrees to 5 decimal digits of precision, allowing a spatial resolution of 1.1 m in latitude and 0.9 m in longitude at our site. Using the mark–recapture data, we calculated the distance between successive captures. We did not otherwise adjust the data so that the pairs of capture points can be regarded as a haphazard sample of 2 points from the home range. Home range itself was not calculated due to lack of data.

RESULTS

The Western Cape experienced a severe drought in 2017 that affected our ability to find animals. Figure 1 shows the annual rainfall for our site from 1999 to 2021.

Population Size. — Figure 2 shows the annual counts of the number of tortoises encountered in our mark–

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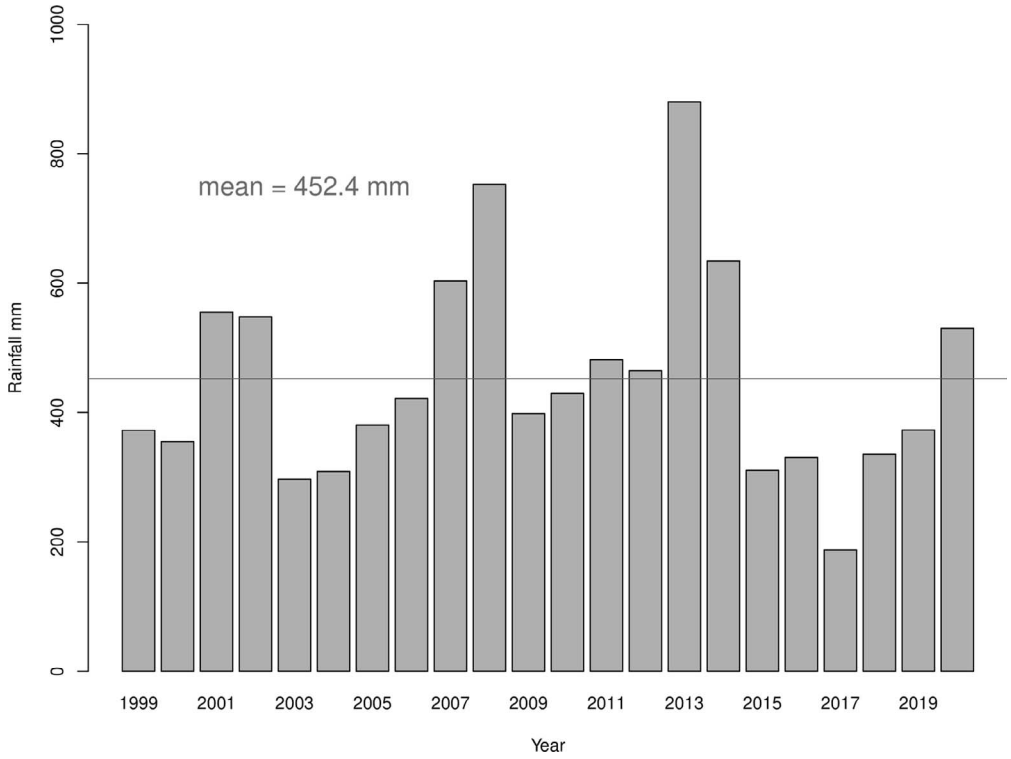


Figure 1. Annual rainfall (1999–2020) at the Geometric Tortoise Ecosystem Preserve study site.

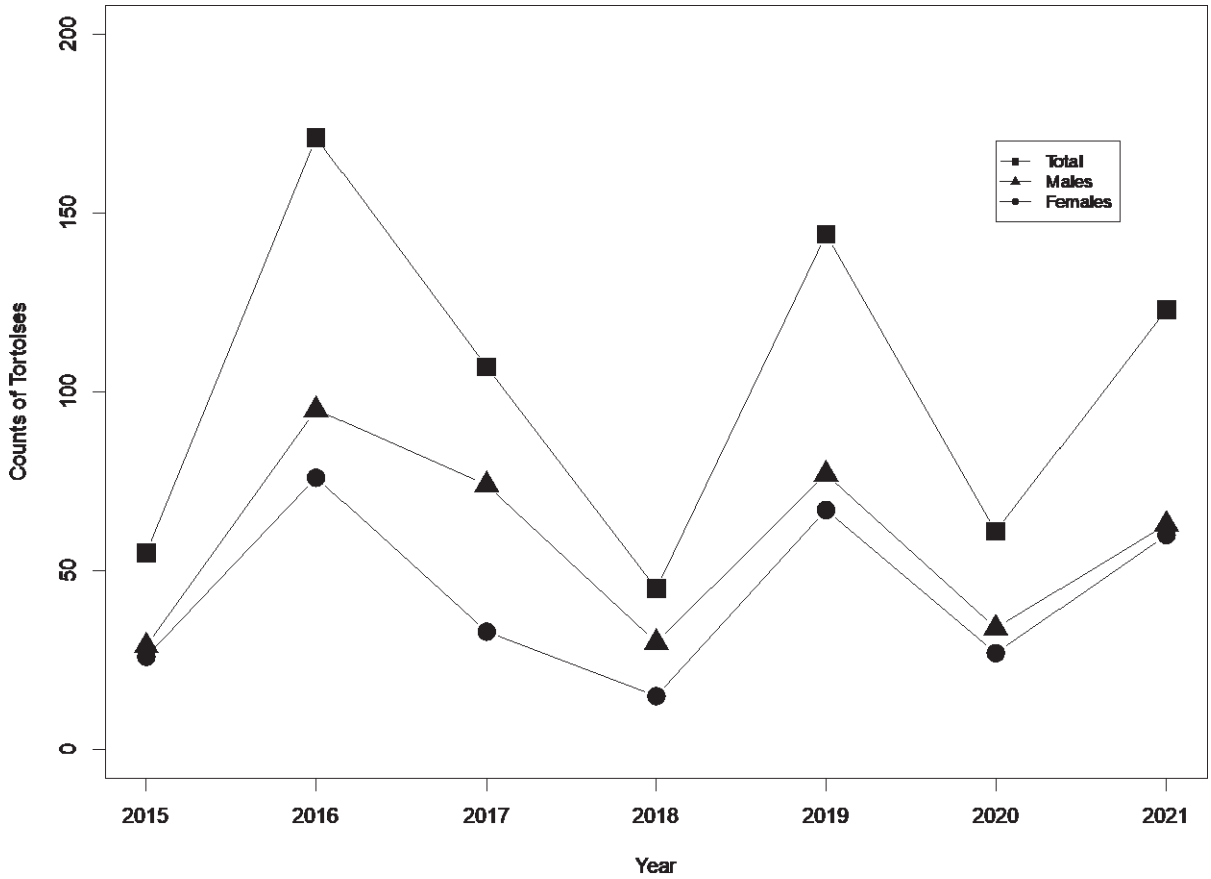


Figure 2. Annual counts of individual geometric tortoises encountered.

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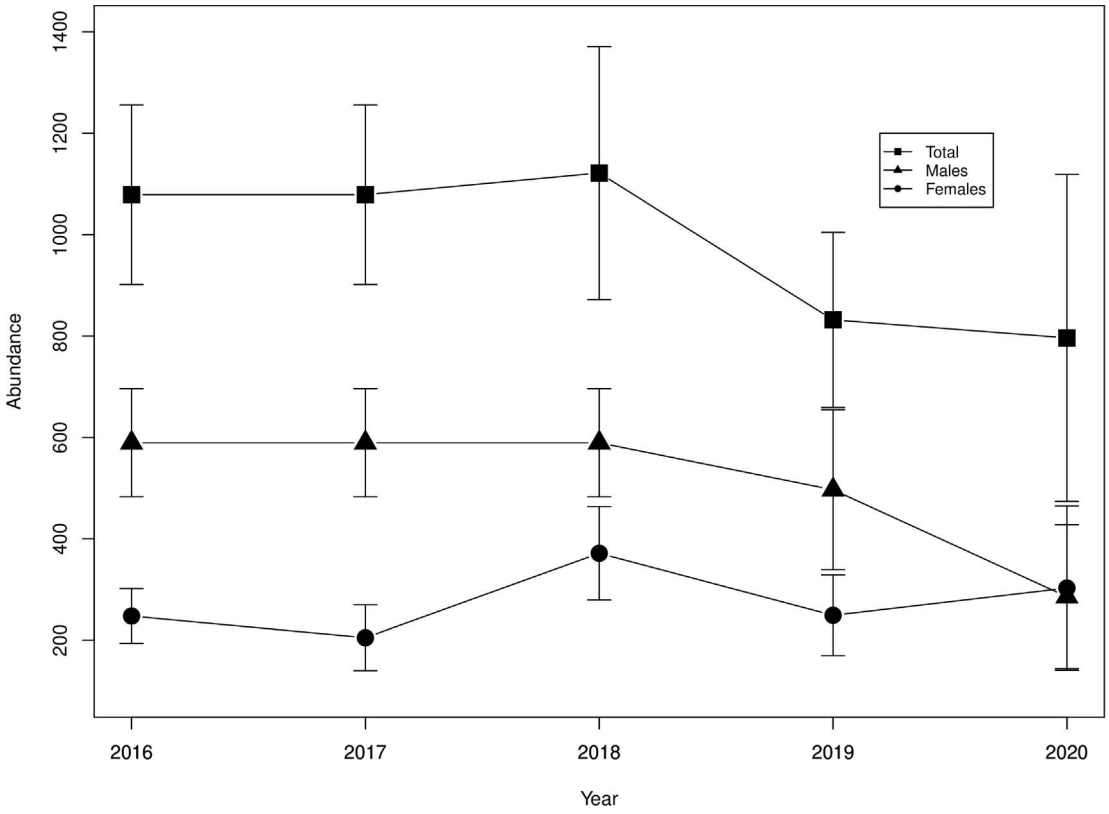


Figure 3. Estimated annual abundance of geometric tortoises using *Rcapture openp*.

recapture survey. A total of 706 captures makes up the basis for our estimates of population size and their standard errors. Within the study area, the frequency of counts was high at 55–171 per year. These capture histories were used by the *openp* function of the *Rcapture* package (Baillargeon and Rivest 2007) to estimate the number of animals in our study area with corresponding error bars. The model fit for all animals gave a deviance = 56.606, degrees of freedom (df) = 113, and Akaike information criterion (AIC) = 219.935. Females and males were also analyzed separately with females giving a deviance = 46.778, df = 114, and AIC = 167.499 and males a deviance = 52.561, df = 114, and AIC = 184.413. Figure 3 shows these estimates for the sexes and for the total. The estimates show flatter trajectories than the counts that are expected, as the *openp* program is estimating the total population and the population of each sex somewhat independent of the counts. These estimates show that our population is likely between 800 and 1200 tortoises, resulting in densities of 10.6–16.0 tortoises per hectare. It is clear that we have a large population with no obvious large changes in abundance during the monitoring period. These densities are much larger than the estimates of 2.7 $\pm$ 0.7 individuals reported by Baard (1990) using human searchers at Elandsberg. This work is the only other study of this species that estimated population size.

The male:female sex ratio varied from 1:1 to 2.2:1. Males were found more often than females. We believe that the difference in encounter rates is partly a function of the fact that males move around more and thus are more likely to lay down scent trails that our dogs can find.

Biometric Data. — Figure 4 represents the relationship between tortoise weight and length for all captures. The graph indicates that females are larger than males as previously reported by Baard (1995b).

Movement Data. — GPS data could be attributed to 111 recaptures enabling an estimate of movement between captures. Figure 5 shows the distribution of distance moved for males and females. These distributions are not significantly different by the Wilcoxon test in R ($p = 0.01$) although there is a slight tendency for males to move farther. Hofmeyr et al. (2012) found that males moved more than females. Henen et al. (2017) found that female displacement per day did not differ between seasons but that males displaced farther per day in autumn than in spring. In each season, males displaced farther than females.

DISCUSSION

The high density of tortoises on this part of our preserve is exceptional. We are not sure why this is the case, but there may be methodological issues with comparing our results to those of others due to the different detectability using dogs versus humans (Gardner et al. 1999). Further data may help us understand this result.

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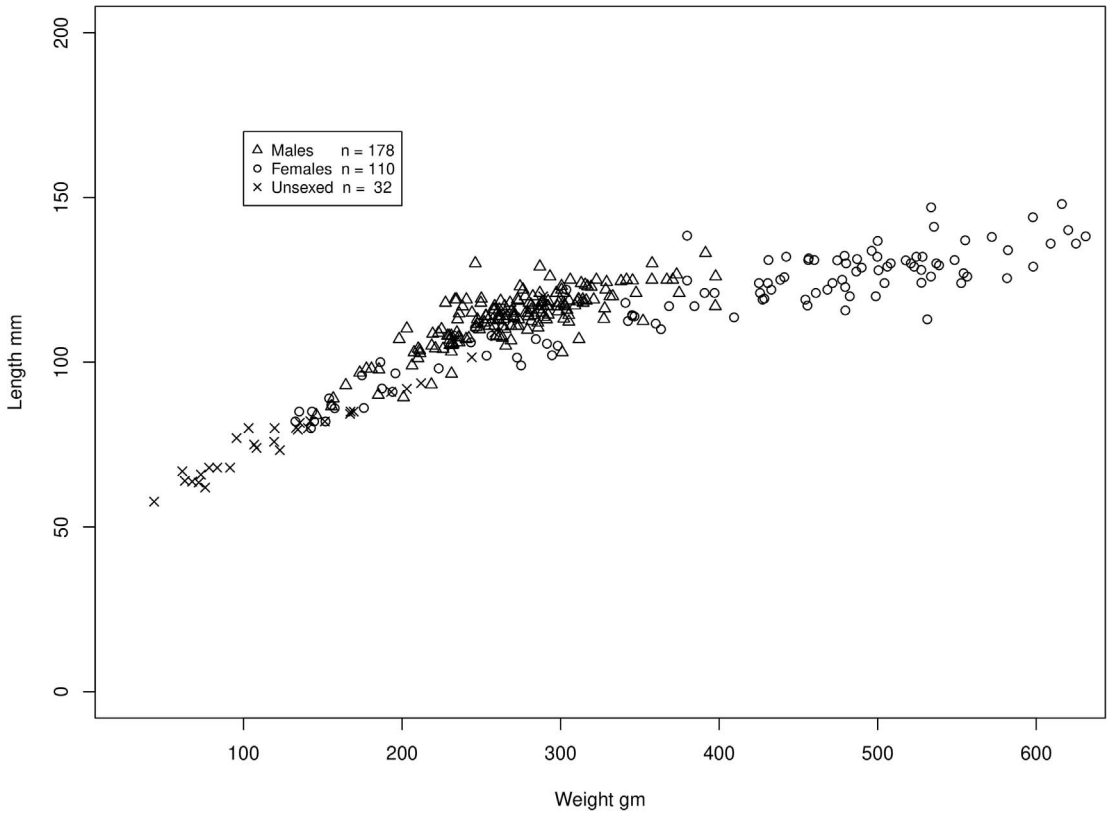


Figure 4. Length by weight of encountered geometric tortoises.

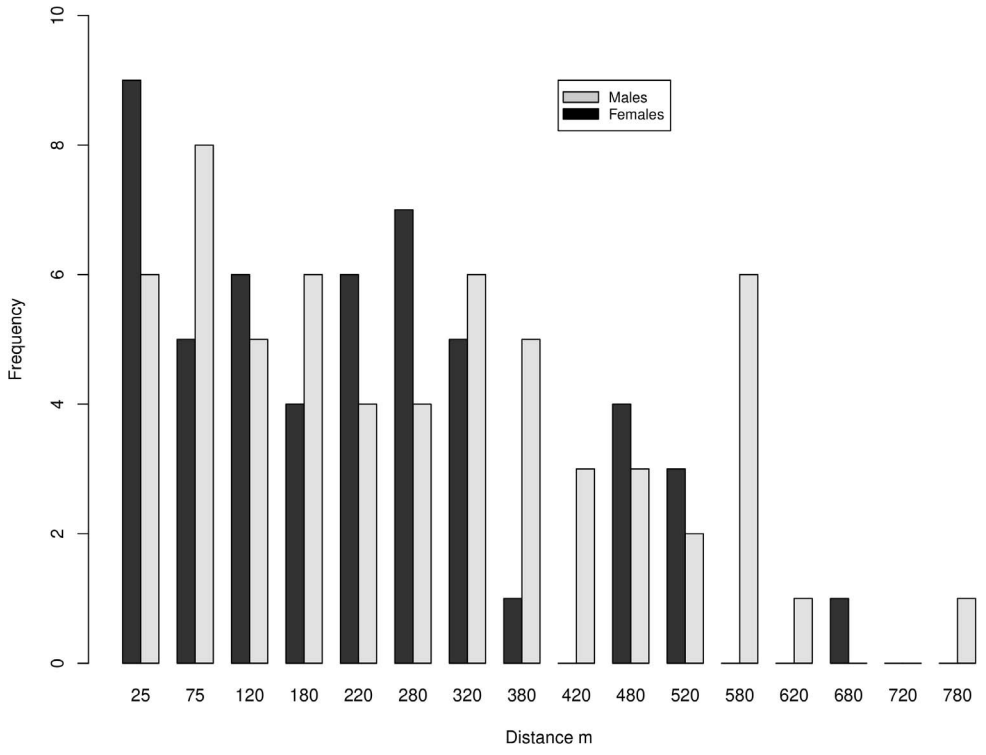


Figure 5. Distance moved by sex between recaptures of geometric tortoise individuals.

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Clearly, we have the last remaining large population. Many of the reserves for geometric tortoise conservation described by Baard (1993) no longer support the species. Elandsberg has perhaps 200 wild tortoises that survived the fire of 2012 (Goode et al. 2012). That population is being augmented with captive-bred animals and should recover over the next 10 yrs.

Understanding the threats to tortoise demography that could lead to extinction enables better planning and adaptive management. Using Lande's (1993) classification to better understand our results, we find the following:

1. Demographic stochasticity. When populations are small, random variation may prevent successful reproduction and recruitment, as individuals may be unable to find a mate. This process must be important in small remnant tortoise populations. The reported density of the preserve population is likely to buffer against this threat.
2. Environmental stochasticity. Rainfall in the Western Cape is variable and is probably the most important source of environmental stochasticity. Our limited data show that tortoises can survive a drought year, but the effects of drought on reproduction are not known, although it is likely that tortoises do not reproduce in dry years. We need to plan for global change that is likely to produce more extreme weather events, including droughts.
3. Catastrophes. Fire can eliminate an entire population virtually overnight. We have had a small fire on the preserve that killed about 40 tortoises. A large fire would be devastating. Fires can be managed through controlled burns and by working closely with our neighbors to prevent fires from spreading.

There is a trade-off between obtaining more accurate estimates of the postulation and undertaking all of the other management tasks to respond to threats. Both mark–recapture studies and general management (to say nothing of land purchase) are expensive. Most funders of tortoise conservation want to see proof that populations are increasing or at least stable, so mark–recapture studies are usually part of any proposal. Being able to show that our population is both large and sustainable does help attract funding. At this time, we are comfortable with the mark–recapture results and their standard errors. However, the threat of catastrophic summer fire means that we must manage for fire prevention through the use of active firebreaks, removing fire-prone alien plants, and maintaining adequate fire suppression equipment. Further, we need to be proactive in the manner that has been developed at our sister geometric reserve at Elandsberg, where an innovative semicaptive geometric tortoise breeding and head-starting facility was developed over the past 7 yrs by Margaretha Hofmeyr and colleagues (Juvik 2020). Eggs are incubated naturally and hatchlings head-started for 6 yrs in predator-protected natural habitat and released back into the wild after reaching a shell length of 80 mm. The protected semicaptive tortoises provide potential replacements for animals lost. Equally important is that head-started animals can be used to create new populations of tortoises in areas where suitable habitat still exists but where tortoises have been lost. We are now undertaking similar head-starting efforts at our preserve.

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