Population Viability Analysis of *Astrochelys yniphora* (The Ploughshare Tortoise)?

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**Abstract**

*Astrochelys yniphora,*or the ploughshare tortoise is on the IUCN red list of threatened species as critically endangered. There are currently many conservation tactics that are being employed in order to save this species and have been since the 1960’s when the species became protected in Madagascar (Pedrono 2008). Unfortunately, though, population numbers continue to decrease even with increased conservation efforts over the years. This population decrease is caused by two main factors: habitat destruction due to bushfires and illegal collection for the international pet trade (Currylow et al 2017). In this paper, I complete an elasticity analysis, a reproductive value analysis, and a population viability analysis in order to determine the parameters that are most effecting the population and how variations in those parameters may positively impact the future population. The results from the reproductive value analysis and the elasticity analysis showed that the adults were the most valuable to the future population in terms of reproduction. The population viability analysis showed that at current predation and brushfire rates, the population under the best circumstances would only survive another 27 years. After reducing the frequency of brushfires and reducing predation, there is a chance that the population of ploughshare tortoises can survive long term.

**Introduction**

The ploughshare tortoise is the world’s rarest tortoise and currently considered critically endangered on the IUCN red list (Pedrono and Sarovy 2000). The ploughshare tortoise is endemic to a small area of Northwestern Madagascar concentrated around Baly Bay in five isolated subpopulations (Pedrono et al 2004). Its historic population has always been restricted to this area in Madagascar, but the suitable population in recent years has declined mainly due to bush fires started for agricultural reasons (Pedrono et al 2004). This reduction in habitat size is one of two main stressors on the ploughshare tortoise’s population. The other factor is the increase in illegal collection for the international pet trade (Currylow et al 2017). Pedrono et al (2001) mentions that there is minor predation from African bush hogs, within their research though, it only account for 2.8% of hatchling losses. Life history traits such as: long life span, older age until sexual maturity, and low fecundity are not conducive to a population in need of recovering from almost constant human exploitation, especially when the population size at each individual patch is quite low with no migration between populations (Pedrono et al. 2004). Current and past conservation efforts have focused almost exclusively on captive breeding with reintroduction into the wild either to supplement wild populations or to be introduced into new suitable areas (Pedrono and Sarvoy 2000). Even with these conservation efforts and a fair amount of current research on how to maximize the productivity of the captive breeding programs, we still see a serious and concerning decline in the population of ploughshare tortoises. With this being said, it may be necessary to reevaluate previous conservation efforts such as captive breeding and focus on other forms of conservation.

Due to this disparity between current conservation methods and a consistently declining population, I am interested if conservation efforts can actually save the ploughshare tortoise from extinction. In order to answer this question, I will first find out what parameters are having the greatest effect on the ploughshare tortoise’s population. I will then determine what stage class (hatchlings, small juveniles, large juveniles, or adults) is most valuable in terms of reproduction to the population. I will then conduct a population viability analysis based on the predation level (predation in this case being individuals taken from the population for illegal trade) and habitat loss due to bush fires that current populations are seeing now, and investigate if there are feasible measures that can be taken to save this population from extinction.

**Methods**

For the sensitivity and elasticity analysis and the reproductive value analysis I used a stage based population matrix. I chose to use a stage based population matrix instead of an age based population matrix due to the long life span of the ploughshare tortoise which ranges from 50 to 100 years. I chose to use four different stages: eggs/hatchlings (0 years old), small juveniles (1-3 years old), large juveniles (4-16 years old), and adults (17-death). These different stages were based off previous studies from Pedrono et al. (2004) and O’Brien et al. (2005). The probabilities of surviving and remaining in the same stage and the probabilities of surviving and transitioning into the next stage class were determined using the results from a study conducted by O’Brien et al. (2005) which gave total probability of surviving for each stage class, see Figure 1. The probability of remaining in each stage class and the probability of graduating to the next stage class was determined using the total probability of surviving for each stage class. It was calculated assuming a uniform distribution of the population within each stage class. The hatchling stage class (stage class 1) has no probability of staying a hatchling and therefore the total probability of surviving was that it transitions to the next stage class which is the small juvenile stage class (stage class 2). The small juvenile stage class consists of individuals of ages 1-3 years old. In order to calculate the probability of remaining and the probability of graduating from the total probability of surviving, I assumed a uniform distribution of the population throughout each of the ages and therefore divided the total probability of surviving by three to get the probability of graduating to the next stage. The only way to graduate to the next stage is to be three years old and then transition to the large juvenile stage when the tortoise turns four years old. Therefore, if we assume a uniform distribution, one third of the total population will be three years old and will transition to four years old with probability .749, or the total number of small juveniles will transition to the large juvenile stage class with probability .2497. The probability of remaining in the small juvenile class was then just the probability of graduating into the next stage class subtracted from the total probability of surviving. I used these same methods to obtain the probability of remaining a large juvenile or graduating to an adult. The only difference is that the tortoise spends 13 years as a large juvenile, so I divided the total probability of surviving by thirteen. In order to determine the fecundity of the population, I took the mean clutch size multiplied by the number of clutches laid each year multiplied by the survival rate of the clutches (3.2\*2.45\*.546=4.28) which gives an average fecundity for the adult age class of 4.28 (O’Brien et al, 2005, Pedrono et al, 2008 and Pedrono et al., 2001). Figure 1 shows the initial probability matrix used for the reproductive value analysis and the population viability analysis.

I then constructed another population projection matrix using decreased survival probabilities for more a more realistic setting to be 25% less than values extrapolated from O’Brien et al (2005). The data from O’Brien et al (2005) was based on a 6-month capture and release program from only the Cape Sade patch. This is a short-term program and it would be hard to capture all of the population dynamics involved in that small period of time, especially the stochastic factors that can have large effects on small populations. Also with researchers frequenting this site for this period of time, possible theft may have been decreased due to more human intervention.

In order to determine the number of individuals in each stage class, I used a population estimate of the ploughshare tortoises from January 2016 of approximately 400 individuals (Currylow et al. 2017). In terms of total population size, the ratio of male to female tortoises is assumed to be one to one, so I use a total population size of 200 individuals because females are the only ones laying clutches (Currylow et al 2017). There is no up to date information on how many of those individuals are in each age class, and therefore I used population percentages from Smith et al. (1999). Smith et al. (1999) found that of the total ploughshare tortoises they sampled, 40% had a carapace length that was less than 85mm (corresponds to hatchling and small juvenile stage class), 22% had a carapace length between 86mm and 322mm (corresponding to the large juvenile stage class), and the remaining population, 38%, had a carapace length of greater than 322mm (corresponding to the adult stage class). Since the hatchlings and small juveniles were classified in the same range for this study, I used 20% hatchlings and 20% small juveniles. Initial population sizes for each stage class can be found in Table 1.

Since these tortoises occur in five isolated patches, making migration between patches impossible, it is more appropriate to consider each individual isolated patch on its own with its own total population size. These patches are Capa Sada, Ankasakabe, Behata, Betainalika, and Ambatomainty. These patches (along with other patches that no longer have suitable habitat for ploughshare tortoises) were sampled by Smith et al (1999) from 1993-1995, they found 99, 2, 18, 1 and 4 ploughshare tortoises respectively for the patches listed. Although this data was collected over 20 years ago and populations change, I will be using these proportions to determine a best estimate of how many tortoises of the current population are in each individual patch. Based on these data, we can expect approximately 80.4% of tortoises to be in the Capa Sada patch, 1.6% to be in the Ankasakabe patch, 14.6% to be in the Behata patch, .8% to be in the Betainalika patch, and 3.3% to be in the Ambatomainty patch, see Table 1 for population numbers used in each patch.

*Reproductive Value Analysis*

Reproductive value was calculated using the initial population matrix and the reduced survivorship population matrix. And was calculated by finding the proportion of individuals in each stage class after the population had stabilized and then standardizing it by dividing the reproductive value by the reproductive value of class one. This method allows us to compare each stage classes reproductive value to the first stage class. This was done with the total population of tortoises, and not individual patches.

*Sensitivity and Elasticity Analysis*

The sensitivity and elasticity analysis was done with the reduced survivorship population matrix because it best reflects the wild ploughshare tortoise population. The sensitivity analysis was done only to get the values to conduct the elasticity analysis. The elasticity analysis was also done with the total population of tortoises, not individual patches. The elasticity analysis was done using the stable-stage distribution of the population which is simply the proportion of the population that each stage class makes up and the reproductive value of each stage class (unstandardized). The formula for the analysis is where w is the right eigenvector of the Leslie Matrix (our population matrix) and v is the left eigenvector of the Leslie Matrix. <w, v> is the scalar of the two vectors. Once this sensitivity analysis was done, I used the results to obtain the elasticities of each of the stage classes. This was done by using the formula , where is the original matrix element, is the sensitivity of the given matrix element, and is the asymptotic growth rate.

*Population Viability Analysis:*

For the population viability analysis, I took into account the two largest factors effecting the ploughshare tortoise population: bushfires and theft. Since the populations occur in five distinct patches, I did a population viability analysis for each of the individual patches. Kull (2012) estimated that approximately one quarter to one half of Madagascar’s grasslands are burned each year. I used one quarter as a lower limit estimation and one half as an upper limit estimation for the probability of a bush fire occurring in a given year. This was used in the analysis as a stochastic event because they are not predictable and therefore I used a lower estimation of a bush fire occurring every four years and an upper estimation of a bush fire occurring every two years. There is no published data on the effect that these fires have on the ploughshare tortoise population, just that they reduce suitable habitat. The amount of suitable habitat for the ploughshare tortoises is already quite small, so a bushfire could have a large impact on the population. To determine the growth rate of the population with a bushfire, I decreased each of the stage class survival rates by 10%, 25%, and 40% and calculated the new asymptotic growth rates, Table 2. I set the quasi-extinction rate to two individuals based on the small population sizes that occur in each of the individual patches. I then allowed the predation rate to be set to 19%. I calculated this value based on the number of thefts of the tortoises per year. Keister et al (2013) found that a total of 218 tortoises were found to be illegally held or being sold over the course of 2008-2011. Since this was over three years, I average the total number of tortoises found on these black markets across three years to obtain an average of 73 ploughshare tortoises being taken each year. Since there is a total population of 400 ploughshare tortoises, this is approximately 19% predation rate. This is likely an underestimate because these are just the tortoises that were found to be sold on the black market, there are most likely many more that were not found. The carrying capacity is not discussed in the literature most likely due to the fact that these tortoises have been endangered for the past 30 years. Carrying capacity has most likely not been a concern due to the relatively low success of conservation efforts. For the sake of this analysis, I will set the carrying capacity to 3 tortoises per hectare of land in each patch. That leaves us with a carrying capacity of 450, 150, 600, 1020, and 1500 individuals for Cape Sada, Ankasakabe, Behata, Betainalika, and Ambatomainty respectively. In order to complete the population viability analysis, the population is said to either be extant or be extinct after 100 years. The size of the population is calculated by multiplying the growth rate of the population by the predation rate by the total population size of the previous year. The growth rate for the population will be determined using a random number generator that if a number is less than the average number of brushfires, it will be a year with a brushfire and therefore, the growth rate will be one of the decreased survival growth rates. If it is larger than the average number of bushfires, it will be a year without a bushfire and it will be the growth rate of the population without a bushfire which was based on the initial population matrix. The population cannot exceed the carrying capacity, and if the population drops below the quasi-extinction threshold, it will be considered 0 and the population will go extinct. I ran 10 simulations for each of the scenarios: 10% reduction in survival, 25% reduction in survival, and 40% reduction in survival for 25% chance of a brushfire and for 50% chance of a brushfire. I then chose to vary both the probability of a brushfire and the predation in order to see if the population could survive long term. I chose to decrease the probability of a brushfire to 20% and 10% (one every 5 years and one every 10 years) and to also decrease predation to 10% and 5% to see if the population could survive under either of these parameters long term using a 25% reduction in survival of the population if the brushfire occurs. Each of the population viability analyses was run ten times and the average number of years to extinction was calculated and the proportion of times a population was extant was calculated.

**Results**

*Reproductive Value:*

The results from the reproductive value analysis can be found in Figure 3. From those results, we can see that stage class four, or the adults, has the highest reproductive value for the population for both the initial and the reduced survivorship population matrix being approximately twenty times more valuable to the population in terms of future offspring in both situations. This makes sense because they are the only ones that are capable of reproduction. The values obtained for the asymptotic growth rate, , for both the initial and the reduced survivorship population projection can be found in Table 3. The effect that reduced probability of survivorship has on the asymptotic growth rate and the population total after fifty years can be seen in Table 3 as well. The reduced survivorship population matrix had a clear negative impact on the population totals and the asymptotic growth rate.

*Sensitivity and Elasticity Analysis:*

The results for the elasticity analysis can be found in Figures 4 and 5. The total elasticity values for each stage class can be found in Figure 4, this shows that stage class 4, the adults, has the largest elasticity and therefore a change in this stage class will have the largest proportional impact on the growth of the population. Figure 5 shows the elasticity values for the remaining in the same stage class or graduating to the next stage class for each of the individual stage classes. The probability of surviving in stage class 4 (adults) has the highest elasticity and therefore the greatest proportional impact on the population, but the probability of surviving in stage class 3 (large juveniles) is important as well. For stage classes 3 and 4 (adults and large juveniles), the probability of surviving has a higher elasticity, but for stage class 1 and 2 (hatchlings and small juveniles), the probability of graduating to the next stage class has the higher elasticity and therefore the greater proportional impact.

*Population Viability Analysis:*

The first part of the population viability analysis was to see if the population could survive long term when brushfires occurred every four years and either had a 10%, 25%, or 40% reduction in survival of the ploughshare tortoise. The results for this analysis are in Figure 6. Outside of the Ambatomainty and Ankasakabe patches, the number of years to extinction decreased with an increase in reduction to survival. The patches that had the larger initial population sizes such as Cape Sada survived longer. Even with the lowest reduction in survivorship, and the largest population size from Cape Sada, the population only survived for an average of about 27 years. The next part of the population viability analysis was to see if the population could survive long term when the brush fires occurred every two years with the same reductions in survival. The results of this analysis can also be found in Figure 6. As with the burning every four years, the patches that had the largest initial population had the longer number of years until extinction, and as the reduction in survivorship increases, years to extinction decreased. The greatest number of years to extinction is only 17 years in this case, which also takes place in Cape Sada. The average number of years to extinction decreased when the brushfire rate went from every four years to every two years.

The next part of the population viability analysis focused on changing the brushfire frequency and the predation rate in order to see what values would allow these patches to exist long term. The number of times a population was extant out of 10 for each of the scenarios can be found in Figure 7. The Cape Sada population had extant populations for each of the simulations. At the 5% predation rate, each of the patches had a high percentage of extant populations. At the 10% predation rate, the percentage of extant populations was reliant on the initial population size of the patch with patches that had a larger initial population having a higher proportion of extant populations. The average number of years to extinction for patches under different scenarios that did not have all extant populations was calculated and the results are shown in Figure 8. The number of years to extinction has drastically increased from the initial population viability analysis for all scenarios and patches. Betainalika had an initial population of 1 individual which was below the quasi-extinction rate and therefore it was not included in the population viability analysis.

**Discussion**

Based on my results from the elasticity analysis, the stage group most important to the population in terms of reproductive value are the adults, which is sensible because they are the only stage class that can reproduce. In terms of survival and graduation, survival of the adults had the largest proportional impact on the population in terms of reproduction. Captive breeding and reintroduction has been the main focus of current conservation efforts with a mean introduction age of 10 years old (young juvenile stage) which was shown to be the most effective in terms of cost and population success (Pedrono et al 2004). Due to the continued decrease in population size of this population though, it may be more relevant to investigate other conservation factors that focus on the increasing the survival of the adult ploughshare tortoises in the wild since they the most valuable in terms of reproduction. If conservationists could determine the most pressing threat on the adult ploughshare tortoise population, whether it be brushfires, theft, or something else, then they can make management plans around that threat and hopefully increase the probability of survival of the adult ploughshare tortoises therefore increasing the probability of a successful future population.

The population viability matrix found that with a brushfire frequency of one every two years and one every four years with varying effects on survival from the brushfire, the largest number of years to extinction of the population was only about 27 years and that was for the largest patch of the tortoises in Cape Sada. The outlook for the other populations were much more bleak. Since those conditions did not permit for long term persistence of the population, situations with reduced frequency of brushfires and reduced predation were considered. In these situations, the decreased predation rate had the largest effect even with more frequent bush fires. This shows that if predation can be reduced, which in this case was considered theft, to just 5% of the population and if brushfire frequency can be reduced to once in every 5 years, almost all of the five patches have a chance of producing successful future populations that will persist for greater than 100 years.

Conservation efforts for this species focus almost exclusively on captive breeding with a lot of money and funds in that area, but what this study suggests is that it might be best to work on increasing the survival of the wild populations. Although an increase in population size would be helpful to the current populations, increasing the probability of survival in the adult and the large juvenile classes appears to be more important. The population viability analysis suggests that by decreasing brushfires and theft, these populations can survive long term. In order to decrease the bushfires and decrease theft, funds might be better spent on education and policing of the habitats that the tortoises are found in. A current conservation effort that is tackling the issue of theft is marking the shells of the tortoises in order to make them unappealing to thieves who want to sell them on the black market (Walker et al 2015).

This paper focuses on using reproductive value analysis, elasticity analysis, and a population viability analysis. Although these techniques are used in the field, they have serious drawbacks that can and will effect the plausibility of real life outcomes. The population projection matrices used in all of the analyses assumes density independence, which is hardly the case in real life populations. Since the density of these tortoises is so low, it may not have such a large effect, but still is a downside to the analysis. The reproductive analysis allows for exponential growth of the population, which is simply unrealistic. Since there was no exact data on a number of things, a lot of the data was extrapolated from other studies which can lead to misleading results that may not provide to be true in the future.

Future studies on the ploughshare tortoise should focus on the effects of small population size in individual patches. The lack of genetic variation could be having a serious impact on population dynamics and lead to a faster extinction in the smaller patches. In terms of cost-effective conservation, I think it would be best to focus in on the two patches that have a viable population size: Cape Sada and Behata. Cape Sada has a large population of the ploughshare tortoises which means there is probably a fair amount of genetic variation and the population will be more resistant to stochastic events, which would make it easier to manage. Focusing in on one or two patches could also maximize efforts because the focus will be in a more narrow range.

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| --- | --- | --- | --- | --- | --- | --- |
| Stage Class | Total Population | Capa Sada | Ankasakabe | Behata | Betainalika | Ambatomainty |
| Hatchling | 40 | 32 | 0 | 5 | 0 | 1 |
| Small Juvenile | 40 | 32 | 0 | 5 | 0 | 1 |
| Large Juvenile | 44 | 35 | 1 | 6 | 0 | 1 |
| Adult | 76 | 60 | 2 | 11 | 1 | 2 |
| Total | 200 | 159 | 3 | 27 | 1 | 5 |

Table 1. Shows the number of individuals in each stage class of the total population of all five patches combined, and is then broke down into each individual patch. Number of individuals was rounded always rounded down to the smaller number

|  |  |
| --- | --- |
| Percentage of decreased survival rate |  |
| 0% | .94672 |
| 10% | .84905 |
| 25% | .80813 |
| 40% | .72834 |

Table 2. Asymptotic growth rate for each of the decreased survival rates due to a bushfire.

|  |  |  |  |
| --- | --- | --- | --- |
| Population Matrix |  | Years to Stabilization | Population After 50 years |
| Initial | 1.141118 | 28 | 343,127 |
| Reduced Survivorship | .946720 | 29 | 32 |

Table 3. The asymptotic growth rate (), number of years until the population is stabilized, and the total number of individuals after fifty years of the initial population projection matrix and the reduced survivorship population projection matrix for the total population of ploughshare tortoises.

Figure 1. Gives the initial population matrix used for the sensitivity analysis. The 1 corresponds to hatchlings (stage class one), the 2 to small juveniles (stage class two), the 3 to large juveniles (stage class three), and the 4 to adults (stage class four). The probability of remaining in each stage class is given by where i=1,2,3,4. The probability of graduating into the next stage class is given by where i and j= 1, 2, 3, 4 and ij. is the fecundity of age class i, where i= 2, 3, 4.

Figure 2. Gives the reduced survivorship (reduced by 25%) population matrix used for the reproductive value and sensitivity analysis. The 1 corresponds to hatchlings (stage class one), the 2 to small juveniles (stage class two), the 3 to large juveniles (stage class three), and the 4 to adults (stage class four). The probability of remaining in each stage class is given by where i=1,2,3,4. The probability of graduating into the next stage class is given by where i and j= 1, 2, 3, 4 and ij. is the fecundity of age class i, where i= 2, 3, 4.

Figure 3. The standardized reproductive value for each stage class for the initial population matrix and the reduced survivorship population matrix. Stage class one corresponds to hatchlings, stage class to corresponds to small juveniles, age class three corresponds to large juveniles, and age class four corresponds to adults.

Figure 4. The elasticity for each of the individual stage classes. Stage class one corresponds to hatchlings, stage class to corresponds to small juveniles, age class three corresponds to large juveniles, and age class four corresponds to adults.

Figure 5. The elasticity values for remaining in a stage class (surviving) or graduating to the next stage class. Stage class one corresponds to hatchlings, stage class to corresponds to small juveniles, age class three corresponds to large juveniles, and age class four corresponds to adults.

Figure 6. Years to extinction of each individual patch based on the frequency and the impact of bushfires. The Q in front of the percentage represents a bush fire frequency of every four years, and an H in front of the percentage represents a bushfire frequency of one every 2 years. The percentages represent the percent reduction in survival of each stage class of the population.

Figure 7. The percentage of extant populations out of ten simulations under different brushfire rates and predation rates for each of the different patches. Betainalika only had one individual and therefore was under the quasi-extinction rate and did not survive through the first year.

Figure 8. The average number of years to extinction for each of the different brushfire and predation scenarios for each patch. Patches that every simulation provided an extant population are not represented, because the average years to extinction is greater than 100. Betainalika is once again not represented because the initial population number was one, which is less than the quasi-extinction rate for this population.