Module- Models in Conservation Biology

Report by- Mukund Nagpure

The Last population of Asiatic cheetah in Iran: Impact of car collisions and prey population

Abstract

Asiatic cheetahs (*Acinonyx jubatus venaticus*) are an endangered subspecies of cheetah, with only a few remaining in the wild areas of Iran. The decline in cheetah population in Iran is partly attributed to car collisions and the decrease in prey population. This report aims to investigate the impact of these factors on cheetah populations. We used a modification of the Lotka-Volterra prey-predator model to simulate the population dynamics of cheetahs and their prey and implemented it in R using the DeSolve package. Our results showed that both car collisions and a decrease in prey populations had a substantial impact on the population of cheetahs, with the car collision being the primary factor affecting their survival. The findings of this report highlight the urgent need for conservation efforts to preserve cheetahs and their natural habitats.

Introduction

The Asiatic cheetah, *Acinonyx jubatus venaticus* is a cheetah subspecies that is now critically endangered. They flourish in open spaces, modest plains, semi-arid regions, and other open habitats where prey is present. The Asiatic cheetah used to live throughout Iran's arid and semi-arid regions, as well as the Arabian Peninsula, the Near East, Central Asia, Afghanistan, and South Asia (Nowell and Jackson, 1996). Its number was estimated to be 200 individuals in the 1970s, and the rapid loss of the population persisted; by the 1990s, it was between 50 and 100 individuals (Jourabchian and Farhadinia, 2008). As per the statement of the deputy environment minister of Iran, only 12 individuals are left in Iran (www.rferl.org, 2022; France 24, 2022; Staff, 2022).

Currently, the survival of Asiatic cheetahs is threatened by two main threats: direct and indirect (Farhadinia et al., 2016). In direct threats, cheetahs are directly targeted things like poaching and road collisions. Whereas in indirect threats, changes in the surrounding environment cause lower prey availability and habitat suitability. The overlap between cheetah range and livestock in some places has caused an aggressive approach by herders; between 2002 and 2016, at least 21 cheetahs were killed by herders in the reserves (Farhadinia et al., 2016). Poaching of Asiatic cheetahs is also a main concern, although the amount of evidence is very low and may not necessarily represent the actual threat level (Farhadinia et al., 2016).

Historically, the cheetah range in Iran overlapped with the distribution of gazelles, and these animals were considered as their main prey (Heptner and Sludskii, 1972). But in the mountainous range of Asiatic cheetahs in Iran, where gazelles (Jebeer gazelle and Persian gazelle) are rare, wild sheep (*Ovis orientalis*) and Persian ibex(*Capra aegagrus*) have been the main prey species for Asiatic Cheetahs (Harrington, 1977; Farhadinia, 2004; Hunter et al., 2007). But these primary prey species for Asiatic cheetah are currently listed as vulnerable by the IUCN (Hemami and Groves, 2001). The disappearance of the prey species is suspected as a key indirect threat to the Asiatic cheetah's survival in Iran (Farhadinia, 2004; Hunter et al., 2007; Ziaie, 2008).

Car collisions are another major threat to cheetah populations in Iran (Mohammadi et al., 2018). Many major highways and national roads in Iran traverse the cheetah range, including through or next to many protected areas where the species is located, and this road network is growing day by day. At least 1–2 cheetahs are killed by cars on roadways per year (Hunter et al., 2007). There is currently a very small population of Asiatic cheetahs left in Iran; therefore, even one of them dying on the road might have a significant impact on this critically endangered subspecies.

As the population of any species decreases, the gene pool becomes smaller and the chances of mating with a close relative increase, which is called inbreeding. Continuous inbreeding for several generations may cause an increase in homozygosity, which might lead to the expression of recessive deleterious genes. This phenomenon is known as inbreeding depression. This can lead to a decrease in fitness and an increase in the incidence of genetic disorders within the population. In a study of mountain lions (*Puma concolor*) in inbred individuals, various physical deformities were found (Huffmeyer et al., 2022). As the population of Asiatic cheetah is very small, inbreeding can cause various physical deformities, which might decrease their agility and make them more susceptible to road accidents.

In this report, we investigated the effects of prey populations and car accidents on cheetah population survival. We also attempted to establish a link between inbreeding depression and the individual's susceptibility to vehicle collisions. We modified the Lotka-Volterra prey-predator model to comprehend the effects of these variables on the survival of cheetah populations. The model assumes that there is a link between the numbers of predators and their prey, and that the prey population size determines the predator population size.

My main question for this report is, "What are the effects of prey population growth and car collisions on the survival of the cheetah population?" The small, dwindling population of Asiatic cheetahs is on the verge of extinction, with car collisions and a declining prey population being two of the major threats to its survival. Studying these threats could give some new insights that could help in better conservation efforts to save these last remaining cheetah subspecies.

Methods

Model:

Equation 1:

$$\frac{dN_{prey}}{dt} = r \times \left(1 - \frac{N_{prey}}{K}\right) \times N_{prey} - \left(\frac{aN_{prey}}{N_{cheetah} + ahN_{prey}}\right) \times N_{cheetah}$$

Equation 2:

$$\frac{dN_{cheetah}}{dt} = f \times \left(\frac{aN_{prey}}{N_{cheetah} + ahN_{prey}}\right) \times N_{cheetah} - (q + c\_m) \times N_{cheetah}$$

Equation 3:

$$c = \frac{cmax}{1 + e^{-k(x - x0)}}$$

Parameters:

Symbol	Parameter	Explanation	Default values
r	prey's intrinsic growth rate	It represents the per capita birth rate minus the per capita death rate for the prey population	0.3
K	prey carrying capacity	It is the maximum number of individuals of a prey species that the environment can carry and sustain	1200
a	predation or attack rate	the proportion of prey killed per predator per unit of searching time	0.6
f	conversion efficiency of killed prey into predators	It is the ecological efficiency with which prey consumed are converted into predator biomass	0.4
q	death rate (from natural and other reasons) of cheetah	Deaths due to reasons other than car collisions	0.1
h	handling time	Time spent by the predator handling each prey encountered	3
c_m	Predator's average collision rate per individual	-	Calculated using parameters below
x	loss in agility due to inbreeding	-	12 normally distributed random variables with mean 1 and variance 0.5
k	slope	The slope of the curve at the midpoint	10

x0	sigmoid midpoint	Determines the value of x at which cheetahs have half the maximum collision rate	1
cmax	max value of c	corresponds to selection coefficient	0.1

The values of all the parameters are random.

Assumption-

The primary prey species (gazelles, wild sheep, and Persian ibex) are grouped together as a single population. The predator (Asiatic cheetahs) only eats these prey species. The prey population grows logistically with a growth rate of r until the carrying capacity K. The predator population is driven by the availability of prey, and the predator population growth rate is proportional to the predator attack rate. The predator attack rate is influenced by handling time, which is the amount of time that the predator spends capturing, handling, and consuming its prey. There is intraspecific competition (interference) among the predators for the predation of prey.

Explanation of the model-

The above equations are a modification of the Lotka-Volterra predator-prey model. Lotka developed the standard predator-prey model in 1925 in the book Elements of Physical Biology, and Volterra developed his model independently from Lotka in 1926 (Bacaër 2011). Since the development of this standard predator-prey model, it has been modified several times to overcome its limitations. We took one such modification of the model given in the book "How Species Interact: Altering the Standard View on Trophic Ecology" by Arditi and Ginzburg (2012). In order to include the deaths of predators (Asiatic cheetahs) due to car collisions, we added a parameter c_m with the death rate q.

The first equation of rate of change of prey population has two components: first, growth of the prey population with intrinsic growth factor r but limited by K carrying capacity of the ecosystem, second, decline in the prey population due to predation, with predation rate a which can be interpreted as the proportion of prey killed per predator per unit of searching time, and this predation is affected by handling time h, which means time spent by the predator handling each prey encountered, and during which it stops searching.

The second equation of the rate of change of the cheetah population has two components as well. First is the growth in the cheetah population due to predation; the cheetahs hunt with a predation rate of a and convert the hunted biomass of prey into offspring with an efficiency of f. The second component is the decline in cheetah population due to deaths from car collisions with collision rate c_m and deaths due to other reasons with rate q, q+ c_m overall death rate.

The parameter c_m is calculated using the following equation :

Equation 3:

$$c = \frac{cmax}{1+ e^{-k(x-x0)}} \qquad c\_m = \text{mean of c}$$

This equation shows the relation between individual susceptibility to car collisions *c* and loss in agility due to inbreeding *x.* This relation is affected by *cmax,* which corresponds to the selection coefficient (chance of death of an individual if it has a homozygous deleterious allele) of inbreeding depression models, and *x0* is the sigmoid midpoint, which determines the value of *x* at which cheetahs have half the maximum collision rate.

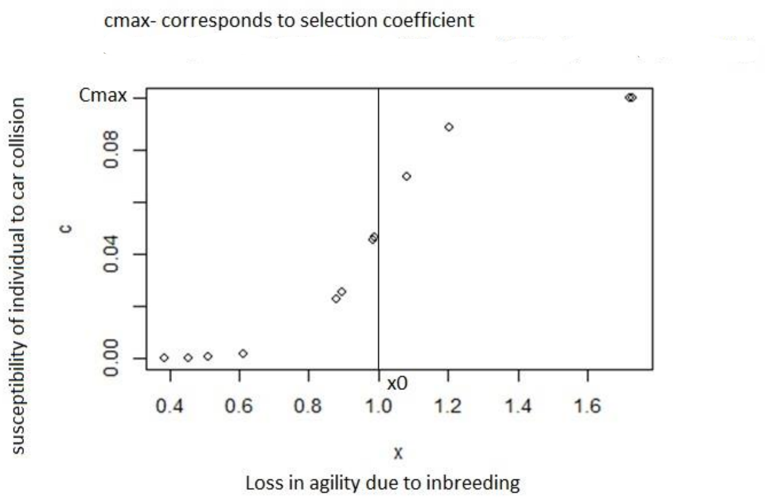


Figure 1. Plot between loss in agility due to inbreeding *x* on the x axis and individual susceptibility to car collision *c* on the y axis

Running the Model in R-

The differential equations are solved in R with the help of the DeSolve library (Soetaert et al., 2010), where the right-hand side of the equations is a function passed along with the initial conditions and other parameter values. This gives us a table that has values of *Ncheetah* and *Nprey* over a period of time.

To test the effect of different values of different parameters on the survival probability of the cheetah population, a range of values for a parameter to be tested was defined, and the simulation was repeated 1000 times (repnum) for each value of the parameter in the defined range. At the end of each simulation, if the population year of cheetah at the 200th is greater than or equal to 1, then it is considered to have survived. The number of simulations where the population survived is divided by the total number of simulations (repnum) to give the survival probability of the cheetah population.

To introduce some stochasticity, the values of *x* are 12 (the initial Cheetah population) normally distributed random variables with a mean of 1 and a variance of 0.5. So, the value of *x* changes every time the simulation runs, hence changing the value of c_m for every simulation as well. The value of c_m stays constant over the course of one simulation run; it does not change with time.

Results

1. Change in Population of cheetah and prey over 200 years for the given values of parameters

a)The initial conditions were Nprey= 1000, Ncheetah= 12 with default values of parameter.

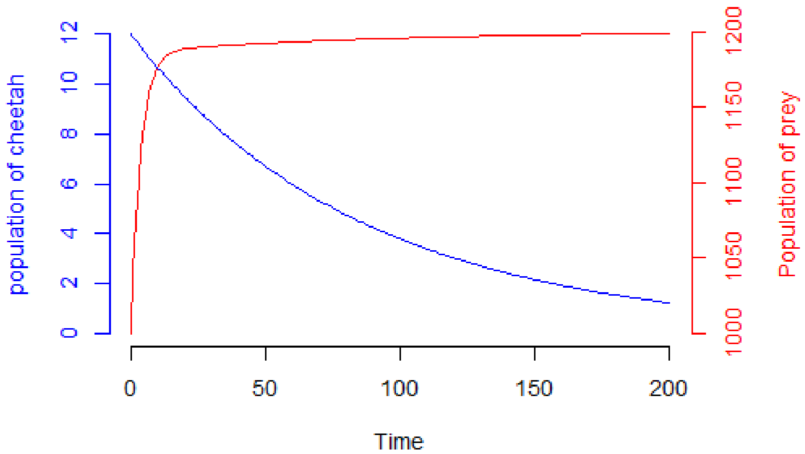


Figure 2. Time series plot of population of cheetah (*Acinonyx jubatus venaticus*) and prey for time period of 200 years. Blue line represents the population of cheetah and red line represents the prey population.

b) When *c_m* = 0 (no deaths due to car collisions are), third equation of the model is not involved. Other parameter values are same.

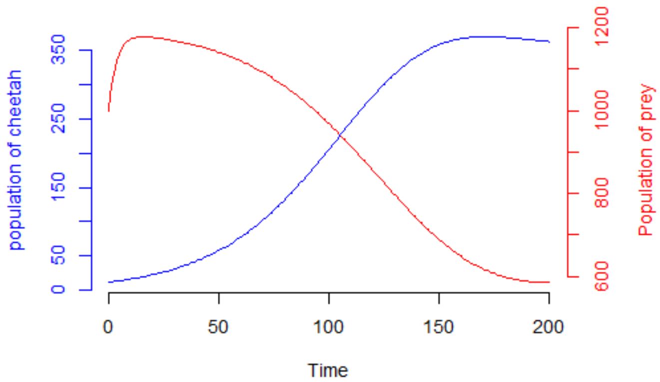


Figure 3. Time series plot of population of cheetah and prey for time period of 200 years. Blue line represents the population of cheetah and red line represents the prey population.

2. Effect of different parameters on survival probability of cheetah's population after 200 years

a) Effect of intrinsic growth rate of prey on survival probability of cheetah's population

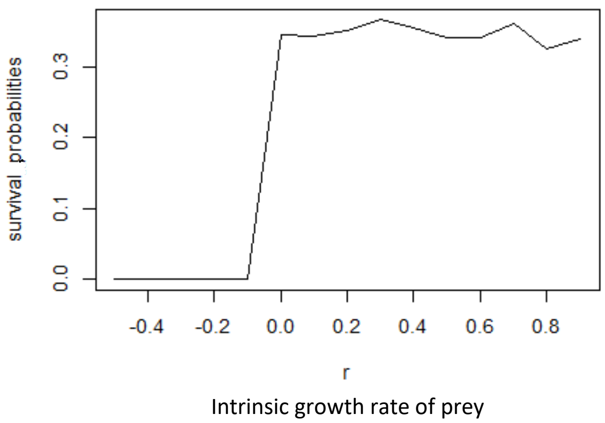


Figure 4. Plot between Intrinsic growth rate of prey r on the x axis and survival probability of cheetah's population on y axis

b) Effect of collision rate on survival probability of cheetah's population

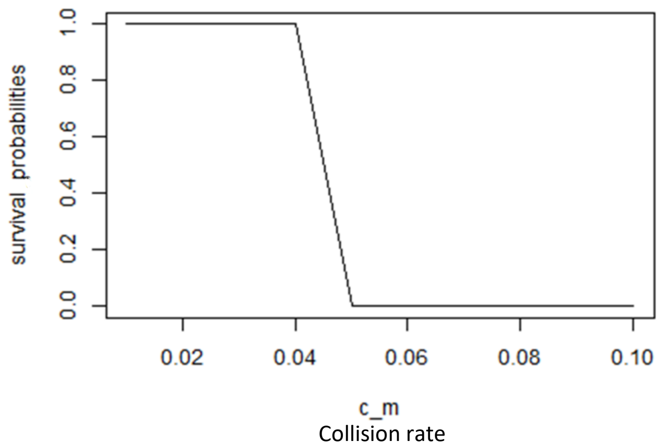
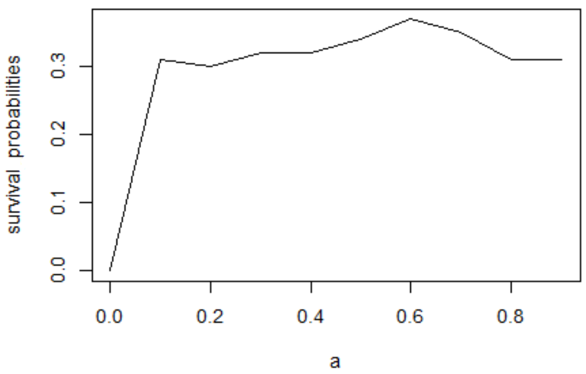


Figure 5. Plot between collision rate c_m on the x axis and survival probability of cheetah's population on y axis, number of replicates= 1000

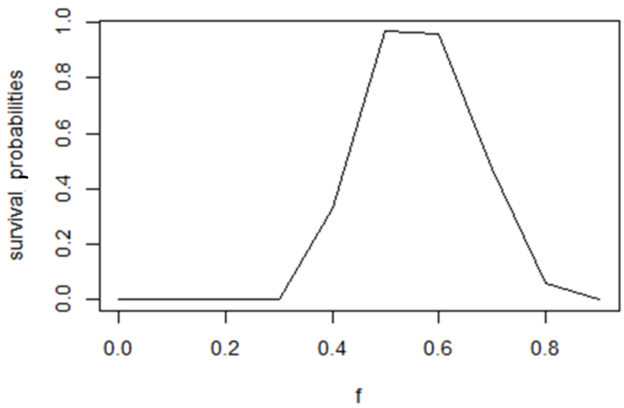
c) Effect of predation rate *a* on survival probability of cheetah's population



Predation rate

Figure 6. Plot between predation rate *a* on the x axis and survival probability of cheetah's population on y axis. Number of replicates= 1000

d) Effect of conversion efficiency of killed prey into predators *f* on survival probability of cheetah's population



conversion efficiency of killed prey into predators

Figure 7. Plot between conversion efficiency of killed prey into predators *f* on the x axis and survival probability of cheetah's population on y axis . Number of replicates= 1000.

e) Effect of rate of deaths reasons other than car accident *q* on survival probability of cheetah's population

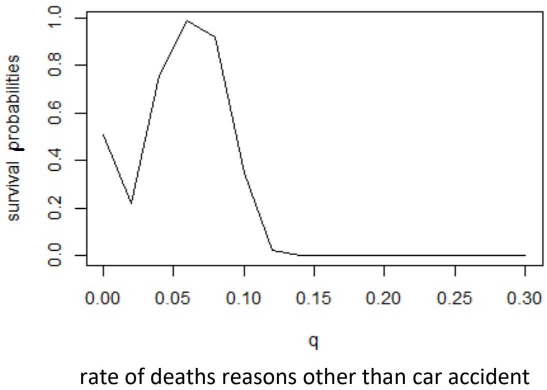


Figure 8. Plot between rate of deaths reasons other than car accident *q* on the x axis and survival probability of cheetah's population on y axis . Number of replicates= 1000.

f) Effect of handling time *h* on survival probability of cheetah's population

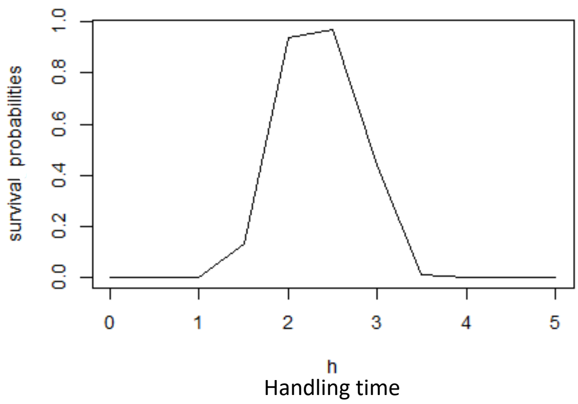


Figure 9. Plot between handling time *h* on the x axis and survival probability of cheetah's population on y axis. Number of replicates= 100.

g) Effect of *cmax* which corresponds to selection coefficient on survival probability of cheetah's population

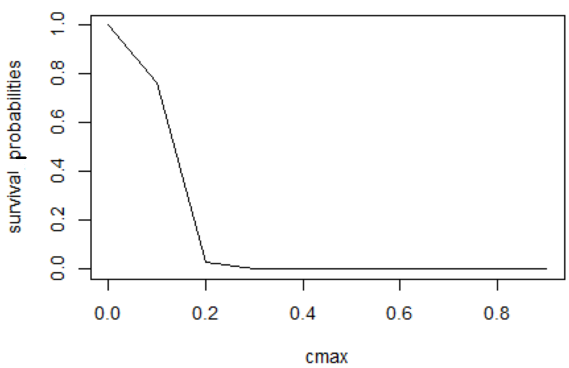


Figure 10. Plot between *cmax* on the x axis and survival probability of cheetah's population on y axis. Number of replicates= 100

Discussion

The small population of cheetahs is facing a lot of challenges and is very close to extinction. According to the model, if the trends continue, after 200 years only two individuals will remain, which almost guarantees extinction in nature. But somehow, if there is a way to reduce the deaths due to car accidents to zero and other parameters remain constant, there will be a positive growth in the cheetah population and the cheetah will survive.

The deaths due to cheetahs in car accidents are a major threat to the population, and according to my model, there is even a threshold collision rate (c_m= 0.05). If the collision rate exceeds this threshold, the cheetah population has no chance of survival.

The decreasing population of prey is another major threat to the small population of cheetahs. The population growth of prey heavily depends on their intrinsic growth factor. When the intrinsic growth factor is positive, there is some survival probability for the cheetah population. But if the intrinsic growth factor is negative, there is zero survival probability for the cheetah population. So, anthropogenic factors that affect the prey's intrinsic growth factor and push it to a negative number will also push the cheetah population to the brink of extinction.

There are other parameters that also affect the survival of the cheetah population in the future, like predation, handling time, the conversion efficiency of killed prey into progeny by cheetah, and natural deaths. But these parameters depend on cheetahs themselves and cannot be influenced directly by anthropogenic activities.

These parameters have a nonmonotonic relationship with the survival probability. When the value of these parameters is low, the survival probability is low, but for a certain range of values, the survival probability rises. But again, the survival probability drops when the value of the parameter is high. The reason being the nature of the model, which assumes that the predator population grows with the availability of prey but also that the rate of predation decreases as the predator population becomes larger. Thus, there is a trade-off between the growth rate of the predator population and the consumption rate of the prey population. If the values of parameters h (handling time) and q (deaths rate due to reasons other than car accidents) are low, the predator population grows too fast, which can cause the prey population to decline, which in turn can lead to a decline in the predator population. If the value of the parameter is too high, the prey population grows too fast, it can lead to overconsumption by the predator population, which in turn can cause the predator population to crash. This is vice versa for the parameters a (attack rate) and f (conversion efficiency of killed prey into predators).

Aside from these factors, the models include a third equation that attempts to link the effects of inbreeding depression to the car collision. So, inbreeding depression can cause various deformities in animals, and these deformities, according to my assumption, negatively affect cheetah agility, making them more vulnerable to car collisions.

Similarly, cmax in figure 10 is directly proportional to selection coefficient, so higher the selection coefficient, higher will be the value of cmax and this will result in a higher value of c (higher susceptibility to car collisions) for individuals, ultimately causing a higher c_m and more deaths of cheetah due to car collisions.

The main effect of inbreeding depression is the increased chance of death for offspring with a deleterious homozygous allele. Mean individual viability is the chance for a given number of offspring to survive in the population. The higher the inbreeding (more deleterious alleles), the lower the individual viability. The values of mean individual viability were calculated by teammate Afeen Rafiq in her model. It could be integrated into the cheetah's growth rate part of my model. In my model, the amount of prey eaten by the predator is converted into offspring with an efficiency of f, which means all the offspring survive. But if we incorporate inbreeding into the model, the survival of offspring will be determined according to their individual viability. The death of offspring due to inbreeding will negatively affect the cheetah's growth. However, because the model is made up of differential equations, it is extremely difficult to integrate another parameter whose value is taken from another model and changes with each generation.

The value of the average collision rate (c_m) is considered constant in all generations of one simulation. It should change every generation, as the population of cheetah changes with every generation. But due to the way the model was solved (without loops), I failed to find a way to vary the average collision rate with time.

Due to all the assumptions, I have made and the inclusion of only certain parameters in the equations of the model, it might not translate well in real life. In my model, I have the differential equations, and due to their nature, solving them gives us population values in decimals, which is not possible in reality. Introducing demographic stochasticity in a continuous time model is pretty difficult as well. In survivorship curves, survival probability of 1 does not mean that cheetah population is out of danger of extinction, the reason is at the 200th year even if the cheetah population is more than 1,it is considered as population survived but in reality, population of one or two means it will go extinct soon.

As for future improvement, more parameters can be included in the equation, and the use of a discrete time model can be closer to reality because then we could introduce demographic stochasticity.

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