Project Title: Bonobos Life

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1 Introduction

Bonobos, with their intricate social structures and cognitive capabilities, present an interesting puzzle for researchers. However, studying them in their natural habitats can be very difficult because of geographical constraints, ethical considerations, and the unpredictability of wildlife. This is where simulation emerges as a powerful tool, enabling us to replicate and observe the activities of chimpanzee life within a digital environment.

Exploiting the capabilities of simulation, we can meticulously recreate the bonobos' physical surroundings and the factors influencing their lives. This allows us to manipulate variables, test hypotheses, and explore scenarios that would otherwise be difficult to replicate in the real world.

Moreover, simulation enables us to compress time, accelerating the pace of observations and experiments. What might take years or even decades in the field can be simulated and observed within a fraction of that time, facilitating a deeper understanding of long-term trends and emergent phenomena. This acceleration of knowledge acquisition empowers researchers and conservationists to make informed decisions and predictions, thereby contributing to the preservation of these monkeys and their habitats.

2 Model

The chosen paradigm for developing this simulation model is the agent-based approach, where each agent within the system possesses its own logic and operates accordingly to its individual interests. To virtually replicate the environment in which bonobos live, we have developed the following agents and logic:

- Male Bonobo: In the early stages of life, it is nourished through nursing by a female bonobo and sleeps. In adulthood, it explores the environment, searches for food in the trees and mates through interaction with a female bonobo.

- Female Bonobo: It performs the exact same activities as a male bonobo. In addition to these activities, in adulthood, it nurses, goes through pregnancy, and gives birth to new bonobos.
- Tree: Trees are the source of food in this simulation, as their diet is primarily fruit-based. Every day, each tree will produce a certain amount of food. The trees provide berries to the bonobos, who wait in line, based on their level of hunger.
- Human predators: The main danger to the life of a bonobo is human predators. In this simulation, they will be generated at a variable rate and will attempt to kill the bonobos. Adult bonobos can counterattack and kill their predators.

Furthermore, bonobos will face mortality from natural causes or diseases, occurring with varying frequency.

3 Implementation

In this section, we will provide information about the model's implementation. Specifically, in this project, we utilized AnyLogic to conduct the simulation.

3.1 Male Bonobo

Initially, bonobo monkeys are in the infant state, which is maintained until a certain age determined by a discretized normal random variable (with parameters: mean = 6; std = 1), measured in years. In the infant state, bonobos can be in the following states.

- Want to be Fed: In this state, the infant bonobo searches for food due to hunger (this state is activated when hunger reaches or exceeds a level of 5). To be fed, it sends FeedingRequests to female bonobos in the exploring state (when they are not engaged in significant activities). These messages are sent at an hourly rate determined by a Poisson random variable (with parameter: lambda=6).
- Being Fed: When a female bonobo accepts the feeding request, the infant bonobo passes to the being fed state. The state will be kept for a number of minutes defined by a truncated Normal random variable (with parameters: min = 5; max = 20; shift =10; stretch= 4). Once the state is left, the hunger of the infant bonobo will be set to 0 and a message to the female feeder will be sent.
- Sleeping Infant: This state is the second priority after being fed and is activated when tiredness reaches or exceeds a level of 5. The state is maintained for a number of hours equal to the bonobo's tiredness, and when the state is left, the tiredness is reset to 0.

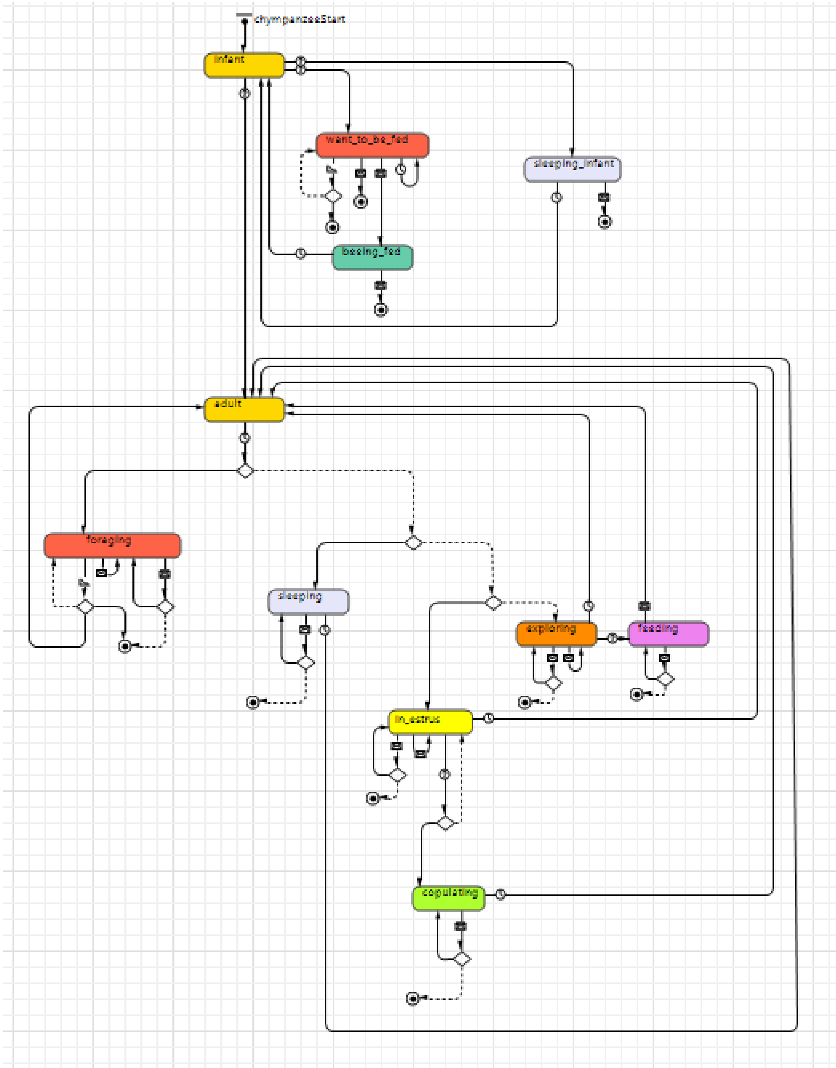

Figure 1: State chart describing female bonobos' states and activities.

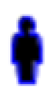

Figure 2: Male bonobo icon.

Once the monkeys have grown up, they will be in the adult state and subject to standard dynamics. Specifically, they can be in the following states.

- Foraging State: In this state, the bonobo searches for food because it is hungry (the state is activated when hunger reaches or exceeds a level of 5). To locate food, a message is sent to a random tree at an hourly rate determined by a Poisson random variable (with parameter: lambda=6). The tree may or may not have available berries. In the case of availability, the tree will provide a certain number of berries depending on the bonobo's hunger. This state takes precedence over the others. If the monkey is hungry and thus at risk of starvation, this state is maintained until food is found or the bonobo succumbs.

- Sleeping State: In this state, the bonobo will locate a random place in the environment, go there, and remain in the sleeping state for a duration equal to its tiredness in hours. This state is the second priority after foraging and is activated when tiredness reaches or exceeds a level of 5. When the state is left, the tiredness is reset to 0.

- In Estrus State: In this state, the bonobo is sexually aroused and, as a result, is searching for a partner to copulate with. To find a partner, the males will send a message to a randomly selected female bonobo in the Estrus state. If the male receives a positive response, they will enter the copulating state. When the male bonobo is in this state, it will send messages at an hourly rate defined by a Poisson random variable (with lambda=5). The state will be kept for a specific duration, determined by a truncated normal random variable (with parameters: min = 10; max = 60; shift = 10; stretch = 20) in minutes.

- Copulating State: In this state, the bonobos are copulating and will maintain the state for a certain number of minutes, as defined by a truncated normal random variable (with parameters: min = 10; max = 60; shift = 10; stretch = 20). When the state is left, the tiredness and hunger increase by 1.

- Exploring State: In this state the bonobo is exploring the environment, it selects a point randomly and go there exploring the area. When the state is left, the tiredness and hunger increase by 1.

In each of the previous states, the bonobo can be attacked by a human predator, and the attack is delivered in the form of a message. The bonobo can either be killed by the attack with a variable probability depending on the state it is in (there are certain states in which the monkey is more vulnerable) or survive and counterattack the predator.

The parameters that characterize each male bonobo are:

- Is Infant: A boolean value indicating whether the bonobo has reached adulthood or not.

- Age: Representing the number of years the monkey has been alive. The initial population consists solely of 6-year-old bonobos, and their age increases by one year per year.

- Tiredness: Indicating how tired the bonobo is on a scale from 0 to 10. This parameter determines the number of hours the bonobo will sleep in the sleeping state. It increases by 1 three times a day and also after experiencing certain states such as exploring and copulating.

- Hunger: It represents the level of hunger that a bonobo has at a certain moment, increasing by 1 three times a day and also after experiencing certain states such as exploring and copulating.

The last three parameters are associated with events that increase their values with certain rates.

The variables that characterizes each male bonobo is:

- Timer: This variable is used to calculate the time (in hours) that bonobos spend in each state. It is initialized to `time(HOUR)` when a certain state is entered and is subsequently used when the state is left.

- Enemy: This variable contains a reference to a `HumanPredator` that attacked it, which is useful for responding to the attack.

- Feeder: This variable contains a reference to a `femaleBonobo` that is feeding the bonobo, which is useful for sending a message when the bonobo is full and doesn't want any more food.

- Adult Age: This variable represents the age at which the bonobo reaches adulthood, determined by a discretized normal random variable (with parameters: mean = 6; std = 1).

3.2 Female Bonobo

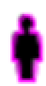

Figure 3: Female bonobo icon.

Female bonobos have the same states of males, the only two differences are:

- In Estrus: When a female is in estrus state, it receives copulation proposals and places them in a waiting list. Subsequently, it decides, following the FIFO scheme, whether each partner is suitable or not based on a Bernoulli random variable with a parameter of 0.6. It's important to note that this assumption simplifies the process, as bonobo sexual behavior is complex and influenced by various dynamics and factors.

- Feeding: When a female is in the exploring state (not engaged in any significant activity), it can receive `FeedingRequests` from infant bonobos. This state is activated when the waiting list length exceeds 1. The list is emptied using a FIFO scheme, with the female sending a message to the selected infant, transitioning into the Feeding state, while the infant enters the Being Fed state.

The parameters characterizing a female bonobo are the same as those for males, with the addition of:

- Pregnancy: An integer value (initially set to 240) representing the days remaining before the birth of a new bonobo.

In addition to the variables characterizing male bonobos, female bonobos have the following variables:

- Waiting partners: A queue of male bonobos who wish to copulate with the female, evaluated using a FIFO scheme.
- Partner: A reference to the last male bonobo with whom the female has been copulating. It is useful for interrupting the sexual act by sending a message.
- Waiting to be fed: A queue of infant bonobos who want to be fed by the female, emptied using a FIFO scheme.

3.3 Tree

Figure 4: Tree icon.

Trees have two primary states, primarily designed to respond to food requests from bonobos. When a hungry bonobo sends a `FoodRequest` to the tree, including information about their hunger and a pointer to themselves, the request is placed in a waiting list. The tree's states are as follows:

- Rest: This state is where trees spend most of their time and is only left when there are waiting `FoodRequests` to fulfill.
- Serving: This state is entered when the waiting food requests list has a length greater than 1. The queue is emptied using a FIFO scheme. Each request contains the hunger level, so the tree responds by sending as many berries as the hunger level divided by 3. If that quantity of berries isn't available, the tree sends as many berries as it has.

The parameter that characterizes a tree is:

- Berries: It is an integer value (initially set to 0) that represents the number of berries available at a certain moment. This value increases depending on the `foodAvailability` parameter.

The variable that characterizes a tree is:

- Waiting Food Requests: A queue of waiting food requests to be served, emptied using a FIFO scheme.

3.4 Human Predator

Figure 5: Human predator icon.

Human hunters pose the primary threat of predation to bonobos, as their main objective is to attack and kill them. They have only one state, called the Attacking state, in which they repeatedly (2 times per hour) select a bonobo, move toward it, and initiate an attack in the form of a message. The survival probability of the attacked bonobo depends on its current state. If the bonobo survives the attack, it will retaliate against the human hunter, who, in turn, has a 0.4 probability of survival.

3.5 Simulation Environment

The simulation takes place in a jungle environment (Figure 6). The bonobos and human predators move at a speed of 0.5 meters per second on land, but only at a speed of 0.1 meters per second in the river.

4 Key System Parameters (KSPs) and Key Performance Indicators (KPIs)

The research questions that will be investigated in this study are as follows:

- How does the growth trend of the bonobo population change with varying available food?
- Do bonobos spend more time in other activities when there's more food available?
- How does the population growth trend vary based on the initial population size of females and males?

To address these questions, we will use the following Key System Parameters and Key Performance Indicators.

Figure 6: Simulation Environment

4.1 Key System Parameters

The key system parameters are fundamental variables that govern the bonobo population and their environment in the simulation. These parameters include factors like disease incidence rate, food availability, and initial population sizes. By adjusting these parameters, researchers can directly impact the key system indicators, such as population size, mortality rates, and behavioral patterns. This flexibility allows for in-depth exploration of various scenarios, helping us understand the dynamics of bonobo populations under different conditions.

Specifically, the following parameters were considered.

- `newPredatorsPerMonth`: This parameter represents the monthly introduction of new predators to the simulation. It dictates the rate at which potential threats (predators) enter the bonobos' environment. Higher values indicate more frequent appearances of new predators, which can impact the bonobo population. Valid values for this parameter range from 0 to 10.

- `foodAvailability`: The `foodAvailability` parameter operates within a range of values from 1 to 10. It plays a crucial role in influencing the `increaseBerries` event. This event pertains to the availability of berries as a food source for the bonobos. When the `foodAvailability` parameter is set, it has a dual impact on the `increaseBerries` event.

On one hand, it determines the initial number of berries produced by multiplying the value of `foodAvailability` by 3. This means that a higher `foodAvailability` value will lead to a greater initial berry yield, thus providing more sustenance for the bonobos.

On the other hand, the `foodAvailability` parameter also functions as a limiting factor. It sets an upper threshold for the maximum number of berries that can be generated in the simulation. This maximum limit is calculated by multiplying the `foodAvailability` value by 10.

In essence, the `foodAvailability` parameter dynamically governs both the quantity of berries generated and the upper limit of berries that can be present at any given time. This parameter's range of values from 1 to 10 allows to fine-tune the simulation's depiction of food availability and its impact on the bonobo population.

- `monthlyDiseaseIncidenceRate`: The `monthlyDiseaseIncidenceRate` parameter represents the likelihood of bonobos contracting diseases and experiencing mortality on a monthly basis. It defines the probability of individual bonobos becoming infected with diseases and subsequently succumbing to them within a given month. A higher value for this parameter indicates a greater probability of disease spread and associated fatalities among the bonobo population, while a lower value suggests a reduced risk of diseases affecting the bonobos and causing deaths.

  The `spreadDisease` event operates by randomly selecting a bonobo, with its occurrence rate determined by the `monthlyDiseaseIncidenceRate` parameter. Subsequently, the event draws a Bernoulli random variable with a parameter obtained from a truncated normal distribution (with parameters: min=0, max=1, shift=0.1, stretch=0.2). If the Bernoulli random variable equals 1, the selected bonobo is killed.

- `initial_number_females`: This parameter represents the initial number of female bonobos present at the beginning of the simulation. It serves as the foundation for the female bonobo population, shaping the growth and interactions that will evolve over time.

- `initial_number_males`: Similar to the `initial_number_females` parameter, this one pertains to the initial number of male bonobos present at the beginning of the simulation. These parameters play a key role in shaping the initial composition of the bonobo population in the simulation, enabling the study of their interactions, behaviors, and demographic changes over time.

4.2 Key Performance Indicators

In order to answer the research questions and have additional insight about the simulation we consider the following KPI.

- `newBorns`: This KPI represents the number of new bonobos born from the begin of the simulation. It provides insight into the reproductive success and growth of the bonobo population.
- `killedBonobos`: This KPI quantifies the total number of bonobos that have been killed by human predators within the simulation. It specifically reflects the instances in which bonobos have fallen victim to human-induced threats.
- `deadBonobos`: This KPI indicates the total number of bonobos that have been killed by various factors in the simulation, such as predators, diseases, or other causes. It reflects the level of mortality and the challenges faced by the bonobo population.
- `deadForDiseaseBonobos`: This KPI focuses specifically on the number of bonobos that have died due to diseases within the simulation.
- `deadForStarvationBonobos`: This KPI represents the number of bonobos that have died due to starvation or lack of food resources. It provides insights into the influence of food availability on the survival of the bonobos.
- `averageAgeOfDeath`: This KPI calculates the average age at which bonobos in the simulation typically die. It gives an indication of the average lifespan and longevity of the bonobo population.
- `hoursSpentCopulating`: This KPI measures the total amount of time that bonobos spend engaging in copulation or mating activities. It provides insights into the reproductive behavior and patterns within the population.
- `hoursSpentForaging`: This KPI tracks the cumulative time bonobos spend searching for and gathering food resources. It offers insights into their foraging behavior and strategies for acquiring sustenance.
- `hoursSpentSleeping`: This KPI represents the total hours that bonobos spend sleeping. It gives an idea of their resting patterns and sleep habits.
- `hoursSpentExploring`: This KPI measures the total time bonobos dedicate to exploring their environment. It offers insights into their curiosity within the simulation.
- `sampledPopulation`: This KPI is an array that captures the evolving number of bonobos over time, as tracked by the `samplePopulation` event. This event periodically takes a snapshot of the bonobo population, storing

the count of bonobos at that particular moment. The `sampledPopulation` array thus presents a dynamic record of the population's growth trajectory throughout the simulation. By visualizing this data, researchers can gain insights into trends, fluctuations, and patterns in the bonobo population's size, enabling them to analyze demographic changes and their potential drivers over time.

5 Experimental Analysis

In order to answer the research questions listed above, we designed some simulation experiments with the goal of analysizing the connection between the KSPs and the KPIs of the system.

5.1 How does the growth trend of the bonobo population change with varying available food?

Firstly, we analyzed the relation between food availability and the growth trend of the population. Specifically, we grouped the data obtained from the simulation by the `foodAvailability` parameter and average them using sample mean. The results, Figure 7, show that the growth trend improves drastically when more food is available. The population survive more years, reaching a peak of 17.5 years; while the number of new borns increases.

Simultaneously, we can observe some counter intuitive effects: an increase in the number of deceased bonobos and a decrease in the average age of death. These effects can be explained by the higher birth rate of new bonobos and the extended survival time of the population when more resources are available, resulting in more bonobos experiencing death (especially at younger ages).

5.2 Do bonobos spend more time in other activities when there's more food available?

In Figure 9 we show the time (number of hours) spent in various activities based on the food availability. As it easy to guess, when less time is dedicated to foraging more time is dedicated to second order priorities.

5.3 How does the population growth trend vary based on the initial population size of females and males?

Thirdly, we analyzed the relationship between the composition of initial population (Male/Female rate) and the growth trend statistics.

In Figure 10 we can notice that an initial population with a prevalence of females (specifically 15 males and 35 females is the better) is producing a better growth trend: the bonobos live more years and there are more newborns.

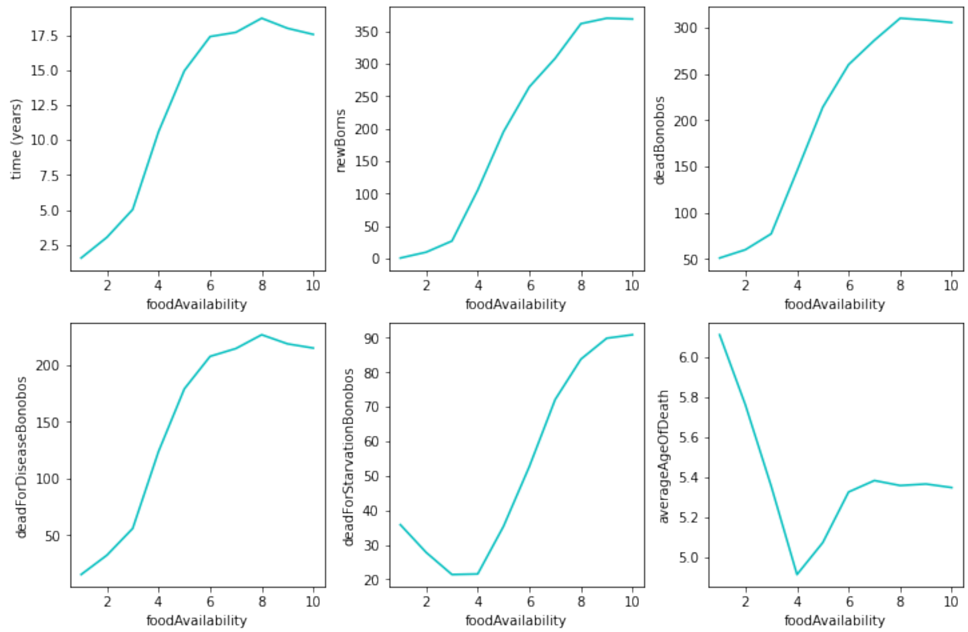

Figure 7: Growth Trend Statistics vs Food Availability

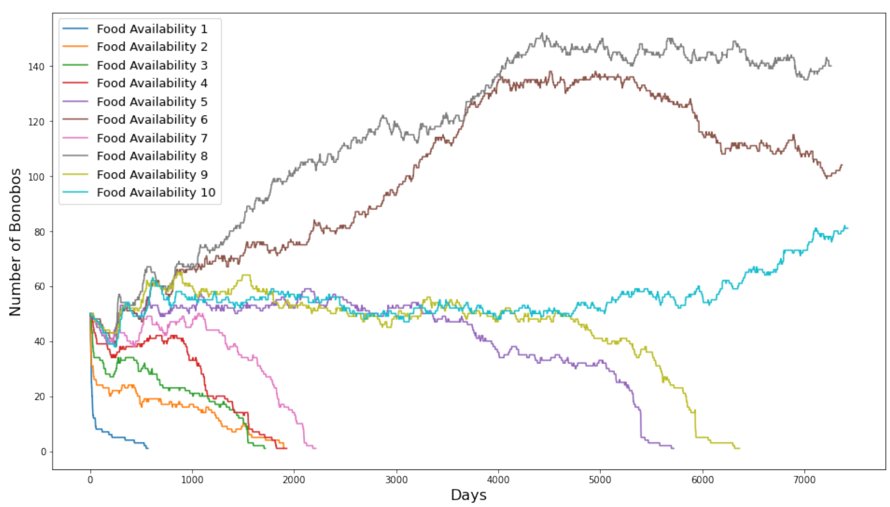

Figure 8: Growth Trend vs Food Availability

Also in this case we experience the counter intuitive effects caused by the increased number of new borns: more bonobos experience death and the presence of young chymps lowers down the average age of death.

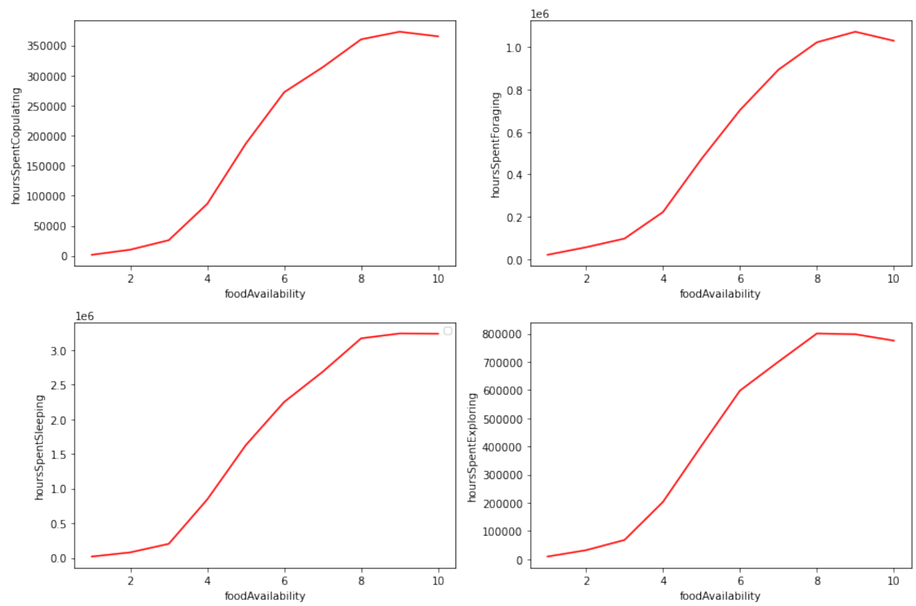

Figure 9: Time Spent in other activities vs Food Availability

The positive effects of the prevalence of females can be seen also in Figure 11.

5.4 How does the population growth trend vary based on the disease incidence rate?

The trend in population growth is significantly influenced by the diseases present in the environment. As illustrated in Figure 12, we observe a dramatic decrease in the survival time of the population and the number of newborns when the monthly disease incidence rate increases. Furthermore, we can identify a counter intuitive effect when analyzing the number of deceased bonobos and the average age of death. Interestingly, the number of deceased bonobos appears to decrease as the monthly disease incidence rate increases. This phenomenon is attributed to the lack of time for the population to grow, as the initial bonobos are quickly succumbing to the diseases. The same rationale can be applied to the average age of death.

5.5 How does the population growth trend vary based on the number of new predators introduced every month?

In this case, the population growth trend is also heavily influenced by the number of new predators per month (Figure 13). The same reasoning that we applied

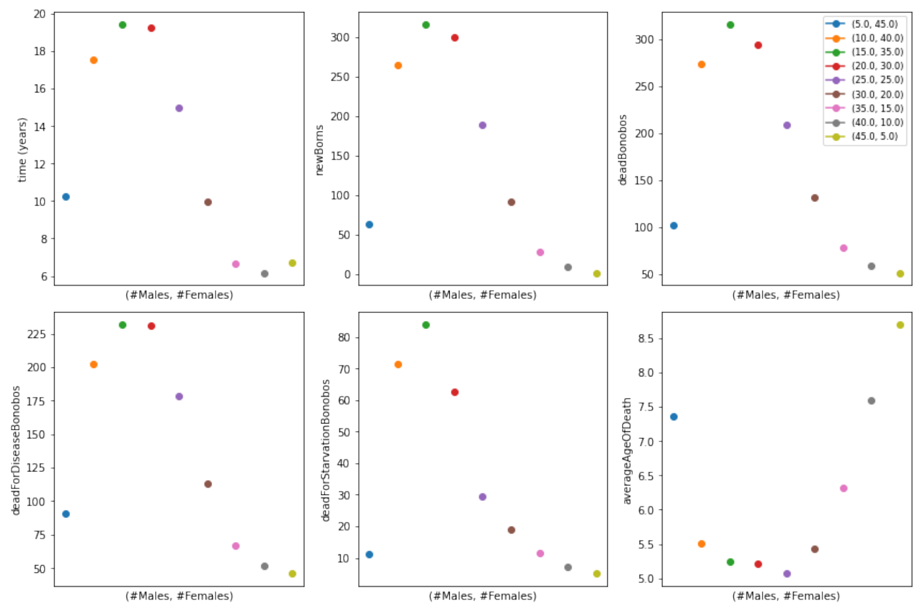

Figure 10: Growth Trend Statistics vs Males/Females rate

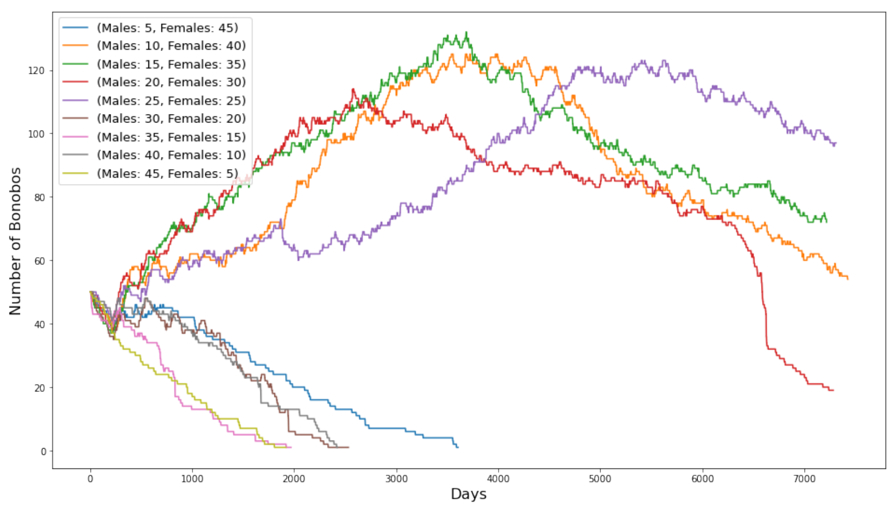

Figure 11: Growth Trend vs Males/Females rate

to the disease incidence rate can be applied here as well.

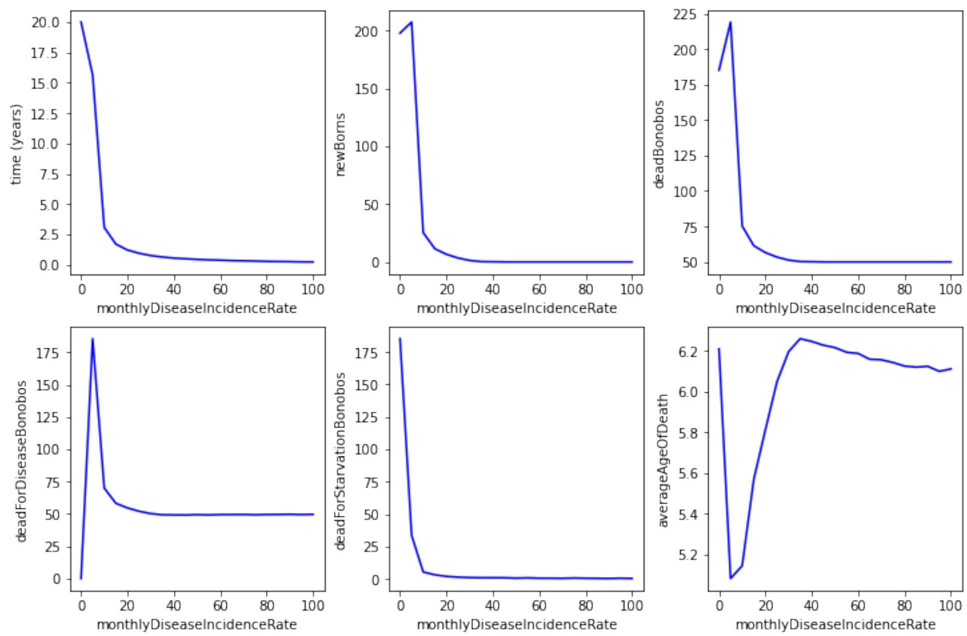

Figure 12: Growth Trend Statistics vs Disease Incidence Rate

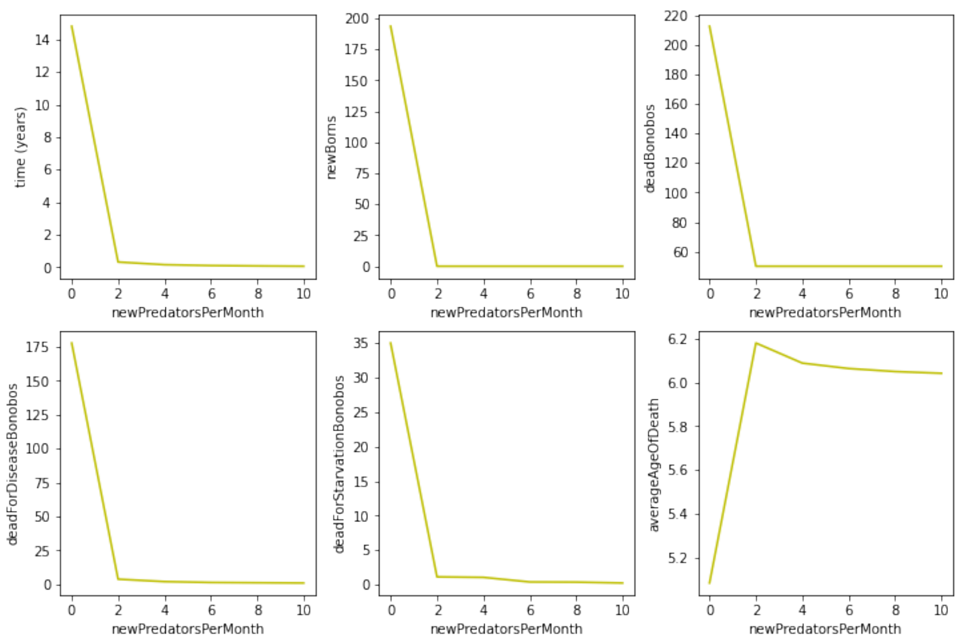

Figure 13: Growth Trend Statistics vs New Predators Per Month