

Evolutionary Models with a Large Number of Genes

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1 Introduction

Have you ever asked yourself how humanity has reached its current state of being? Have you ever wondered how some species (including humans) survived throughout centuries of changing environment, while others went extinct? The answer to these and many other questions lie in the broad study of evolution.

According to Cambridge Dictionary, evolution is defined as *"the way in which living things change and develop over millions of years."* Living things inevitably change over time due to multiple reasons. For example, a long-term food shortage caused by the change in the environment can force a given species to eat less, which over time will affect the next generations of the same species. The new generations might become more and more resistant to starvation and require less nutrition to survive. During this transition, many representatives of the species might die, and in some cases the species might fail to adapt and go extinct. However, if it **evolves** successfully, then the species will continue its existence in the new environment, which might once again change in the future.

A more scientific definition to the term evolution was given by Douglas Futuyma in his popular textbook.

[biological evolution] is change in the properties of groups of organisms over the course of generations. . . it embraces everything from slight changes in the proportions of different forms of a gene within a population to the alterations that led from the earliest organism to dinosaurs, bees, oaks, and humans.

Evolution can occur by different means, such as natural selection, genetic drift, mutation, migration and so on. This report will simulate the process of species evolving over time by adapting to their environment through mutations and natural selection. It will explore scenarios with different starting conditions, where diverse creatures with unique genes inhabit varying environments. The study will examine how these genes mutate over time and determine which mutations dominate in each specific setting.

2 Glossary

Let one first establish some notions which are being discussed throughout this report. These definitions will help the reader more easily grasp the material of this paper, including terms related to biology and mathematics.

2.1 Natural Selection

Elena Racevska defined natural selection as follows.

Natural selection is a process by which organisms that are better adapted to specific pressures of their environment tend to survive longer and produce more offspring, thus ensuring the preservation and multiplication of those favorable traits through generations, at the expense of the less advantageous ones.

If there were no limitations on any species, then it would boundlessly grow. The nature is preventing this by imposing various limitations and creating an environment where species need to survive by adapting to the realities around them. Such limitations may include food limitations, disadvantageous climate conditions, diseases, natural disasters, rival species and so on. In this way, the nature "selects" those species which will be able to reproduce and hence create an evolutionary change. The article published at Stanford University makes an interesting analogy.

Much like breeders choose which of their animals will reproduce and thereby create the various breeds of domesticated dogs, pigeons, and cattle, nature effectively "selects" which animals will breed and creates evolutionary change just as breeders do.

2.2 Mutation

A mutation is a change in a genetic sequence. In biology, it is usually discussed as a negative alteration of a creature's genetic code, which causes various genetic diseases. In the scope of this paper, a mutation is the change in the genome of an offspring compared to genome of its parent. That is, when a creature reproduces, the genes of its offsprings might be slightly modified (also called somatic mutation). Some traits of the offspring might remain the same, others might change.

2.3 Asexual Reproduction

The species which is being simulated in this report reproduce asexually. The Journal of Evolutionary Biology put the definition of asexual reproduction in the following manner.

Asexual reproduction occurs when an individual produces new individuals that are genetically identical to the ancestor at all loci in the genome, except at those sites that have experienced somatic mutations.

In simpler terms, each representative of a species reproduce on its own and copies itself, with a chance that the offspring (copy) will have a slightly mutated, modified genome.

2.4 Manhattan Distance

For any two points $p, q \in \mathbb{R}^n$, the manhattan distance (also called taxicab distance) is defined as

$$d_T(p, q) = \|p - q\|_T = \sum_{i=1}^n |p_i - q_i|$$

In particular, for a plane ($\mathbb{R}^2$) the manhattan distance between two points is $d_2(p, q) = |p_1 - q_1| + |p_2 - q_2|$.

3 Simulation Setting

Let one first define the simulation setting. Each simulation is a collection of time steps. First, the environment and all of its components are being initialized, then the generated entities iterate through a predefined number of steps, and finally at the end the data is being collected, analyzed and visualized.

3.1 Creature

A creature is a single representative of the species one is observing. Each time step, a creature is looking around in search for food, goes towards the food if it sees any, and eats the food if the food is nearby. The creature can also decide to battle another creature if they are in the same location and eat them in case of victory. If in a favorable position, the creature will reproduce, creating an offspring.

Each creature has a genome, a position in the environment and an energy level. Let one discuss each of these separately.

3.1.1 Genome

The genome of a creature is what defines the characteristics (traits) of that creature. It resembles the DNA of the creature which is predefined by nature. The genome and its change through generations is how evolution is observed, and it is the primary focus of this study.

The genome consists of 5 individual genes, each of which depicts a certain trait. Here are the general descriptions of the traits. Note the possible values taken for each trait are only integers.

1. **Speed** - determines the maximal distance that the creature can travel in a single time step. Takes values between 1 and 4.
2. **Eyesight** - determines the area which is visible to the creature. It is mostly used to locate food and move towards it. Takes values between 0 and 7.
3. **Aggression** - determines if the creature will engage in a fight or not. A higher aggression value means that the creature is more likely to start a battle, while a lower value means the creature is more likely to avoid contact and mind its own business. Takes values between 0 and 7.
4. **Strength** - determines the physical abilities of the creatures in case of a fight. A creature with a higher strength value is more likely to win the battle against a creature with a lower strength value. Takes values between 1 and 16.
5. **Stamina** - determines the endurance of the creature, how long can the creature last without resources and at most how much energy it can store in itself. Takes values between -7 and 8.

3.1.2 Position

The position of a creature describes the location of the creature in a given environment. Position has different meanings depending on different environments. For example, the position of a creature on a plane is a coordinate pair (x, y) , on a line its a single number, in space its a coordinate triple (x, y, z) and so on. For each environment, the position will be separately defined, which majorly affects on how creatures move, hence affecting the evolution.

3.1.3 Energy

The energy of a creature showcases the physical power left in the creature to continue surviving. A non-positive value for the energy means that the creature has no power left and hence dies. Each time step, every creature loses energy on moving and supporting their physical existence (see section 3.1.5). Creatures gain energy by eating food or other creatures if they win in a battle. The energy is also used to reproduce, since a certain threshold of energy must be satisfied so that the creature is able to reproduce.

Each creature has maximal energy. It is showing the energy capacity of the creature, how much energy can the creature store in itself. The maximal energy is defined as

$$ME(\text{gene}) = 8 + \text{stamina}$$

3.1.4 Memory Optimization

In order to make the simulation possible to run for relatively big populations in a reasonable time frame, the creatures were designed to take as less space as possible. In the current implementation, each creature is an unsigned 32-bit integer, where (starting from the left) the first 16 bits represent its genome, the next 12 bits represent its position and the last 4 bits represent its current energy. The figures below visualizes the structure of an individual creature more vividly.

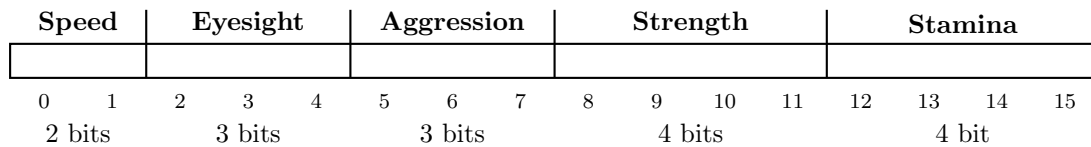


Figure 1: Gene storage

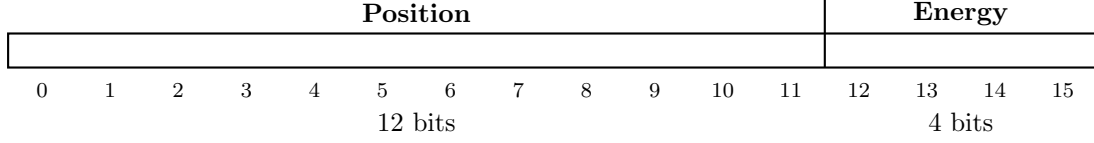


Figure 2: Position storage

This makes a huge impact on memory usage. Let one compare this approach with the one where each trait, position and energy is stored in a separate 32 bit integer. If one has n creatures at a given time step, then the implementation described above will require $32n$ bits for storing all the creatures. On the contrary, if one uses 32 bit numbers for each parameter of the creature, then it would require at least 224 bits to store one creature and $224n$ bits for storing the whole population, 7 times more than with bit manipulations. For example, let $n = 100$, a number which was exceeded by the simulations many times, so it is not a very high number to consider. With bit manipulations, the total memory required is 3200 bits, that is 400 bytes. Without bit manipulation one looks at 22400 bits, which is roughly 2.73 kilobytes.

3.1.5 Energy Loss

The energy loss is a function which determines how much energy does the creature lose in order to support itself. For the purposes of this paper, the energy loss function has been chosen to be the following.

$$EL(\text{gene}) = \left[0.35 \left(\text{steps} + \left\lfloor \frac{\text{eyesight}}{3} \right\rfloor + \left\lfloor \frac{\text{aggression}}{5} \right\rfloor + \left\lfloor \sqrt{\text{strength}} \right\rfloor + \left\lfloor \frac{\text{stamina}}{7} + 1 \right\rfloor \right) \right]$$

$$0 \leq \text{steps} \leq \text{speed} \in \{1, 2, 3, 4\}$$

$$\text{eyesight} \in \{0, 1, \dots, 7\}$$

$$\text{aggression} \in \{0, 1, \dots, 7\}$$

$$\text{strength} \in \{1, 2, \dots, 16\}$$

$$\text{stamina} \in \{-7, -6, \dots, 8\}$$

The steps in the energy loss function is the number of steps taken in the given move. For example, the creature might have speed with value 4 but only do 2 steps to reach the food nearby, so it only spends 2 units of energy, but not 4. Other traits makes the creature constantly use energy to support them.

It is important to understand that the energy loss function is specific to the purpose of the simulation. Depending on what simulation one is doing and what the environment is, this function can have a completely different form. This function is good enough for the purposes of this paper. The differences in constants tries to showcase how some traits are "cheaper" to maintain, while others require more energy. However, it is to be noted here that if some trait is easier to maintain that doesn't mean that creatures are going to always favor it in any environment, the simulations and results are much more complex than that.

3.2 Food

As already discussed above, one of the means for creature to gain energy and support their further survival is through finding and consuming food. Food is a naturally generating unit. After each time step, food is being updated based on the food cap set at the beginning of the simulation. Usually, it is set to meet a certain percentage of available area. During every time step the missing food is naturally replenished to keep the environment as constant as possible.

3.3 Reproduction and Mutations

The species in question reproduce asexually. If a creature's energy level increases more than 80% of its maximal possible energy, it reproduces, gives 1 offspring, and loses 50% of its current energy because of it. Reproduction is the only way a creature can spawn in naturally in the simulation. The only exceptions are the initially generated creatures at the beginning of the simulation.

Each individual trait of the gene has an 8% chance of mutating and increasing/decreasing its value by 1 unit. If one denotes M as the event of getting mutations, then the probability of getting at least one mutation happening in an offspring is

$$\mathbb{P}(M \geq 1) = 1 - \mathbb{P}(M = 0) = 1 - 0.92^5 \approx 0.341$$

One can argue that this percentage is quite high and would have a point. However, each additional step in a simulation exponentially adds the waiting time for that simulation, hence the mutation percent is high so that meaningful results can be obtained in a reasonable amount of time.

4 Results and Future Development

All the code written and used for the simulations is available at <https://github.com/suren2003ah7/EvolutionaryModel>.

4.1 Grid Environment

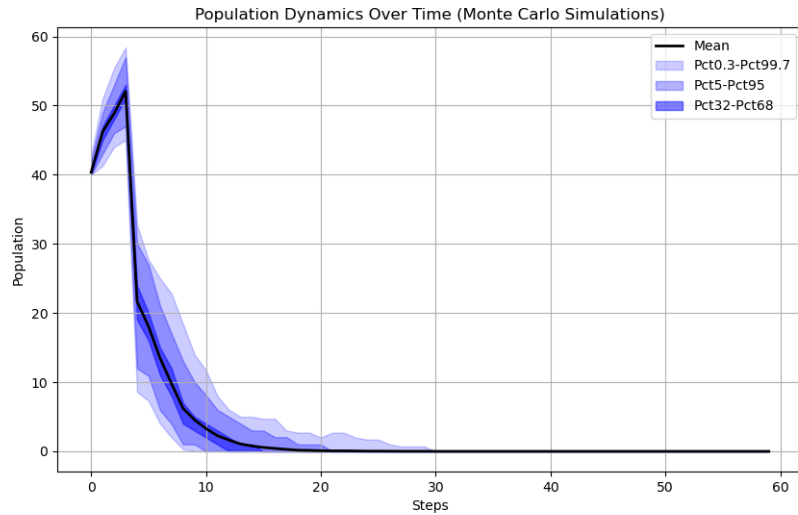
The grid environment is a plane where the values on each axis are integers. The position of the creatures is expressed by two coordinates: x and y . Since there are 12 bits to store the position of the creature, the first 6 bits will store x and the other 6 will store the value of y . This means that $0 \leq x, y \leq 63$, since one can have 64 values with 6 bits for each coordinate. That also fixes the size of the grid: 64×64 , 64 possible values for each coordinate.

The notion of distance in this environment is expressed by the Manhattan distance discussed earlier. The movement and everything which is related to moving is calculated by the Manhattan distance. This especially affects what eyesight and speed mean in this environment.

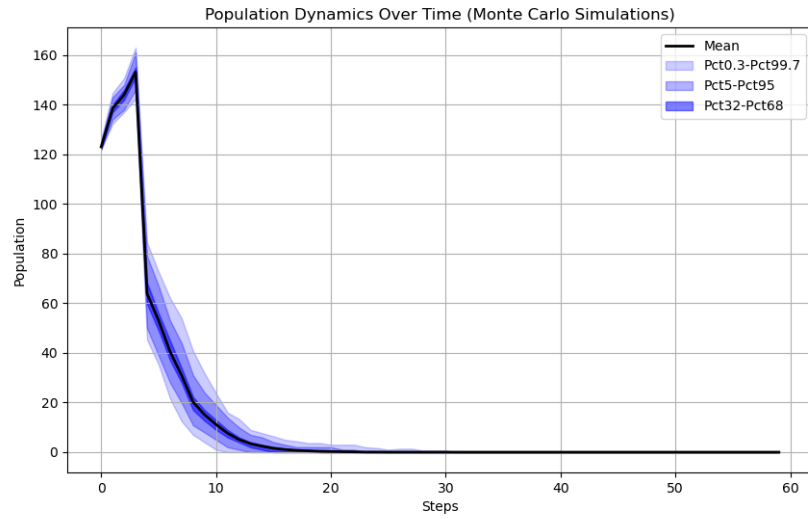
4.1.1 Scenario 1: Average Gene

In this scenario, the starting gene for all creatures is set to be a gene with average traits. More specifically, the gene is represented by the following 16 bits: 0101101110001000, which means 2 speed, 3 eyesight, 3 aggression, 8 strength and 1 stamina.

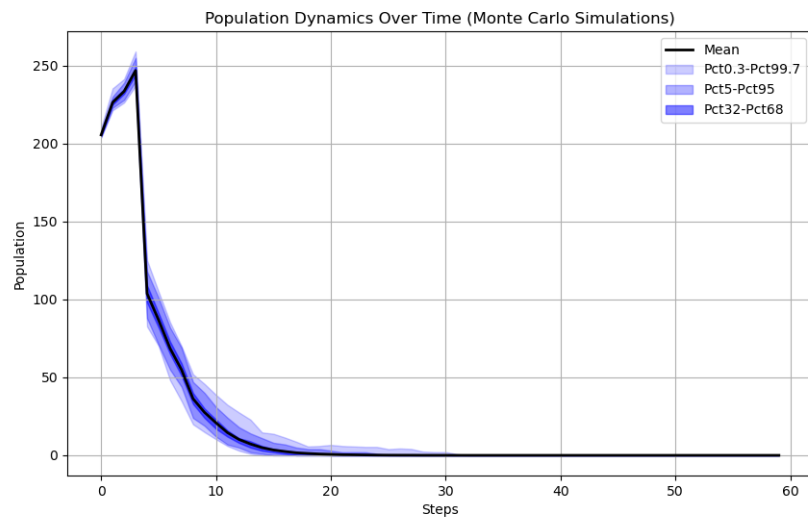
Simulation 1 - 1% Food, 1% Creatures



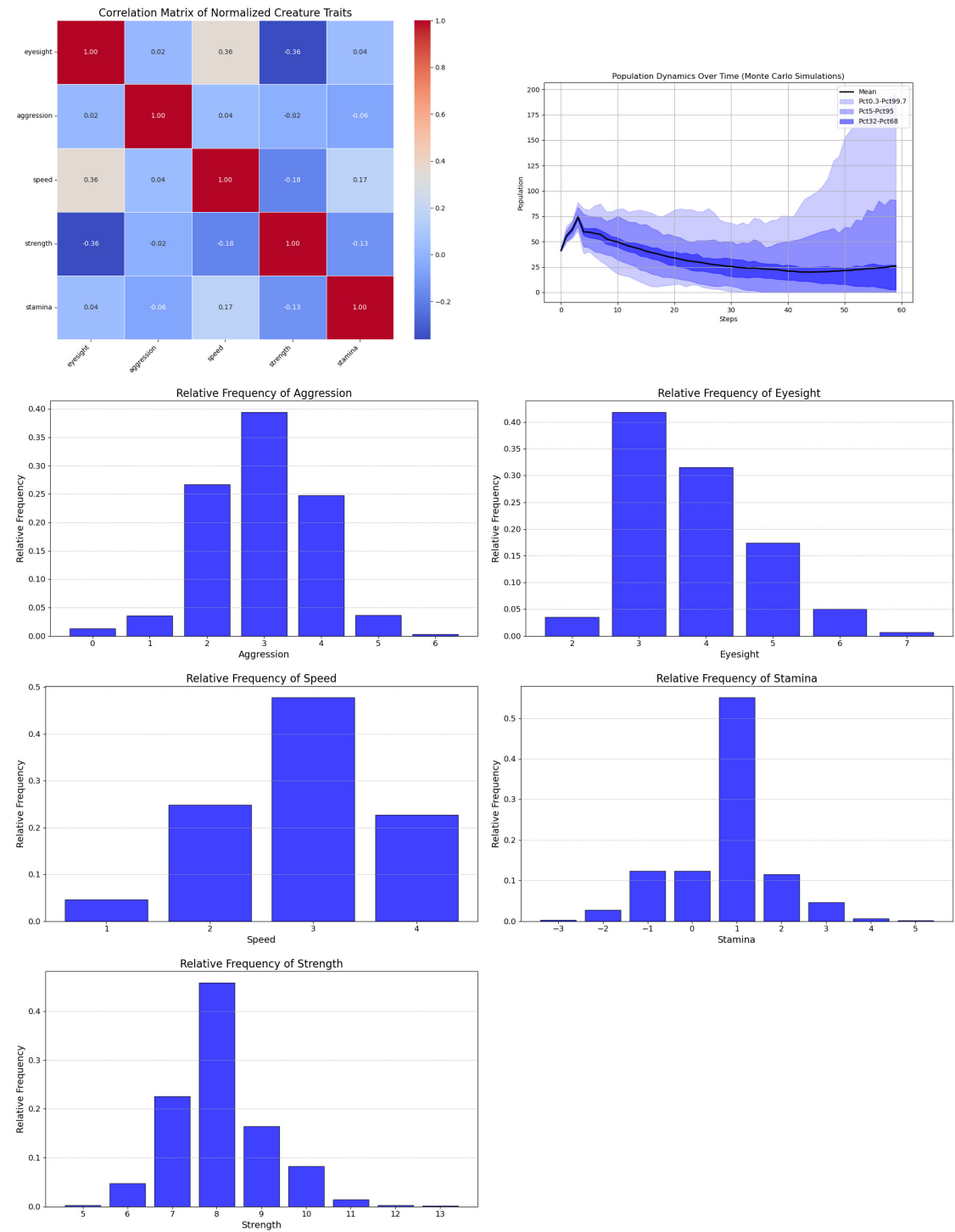
Simulation 2 - 1% Food, 3% Creatures

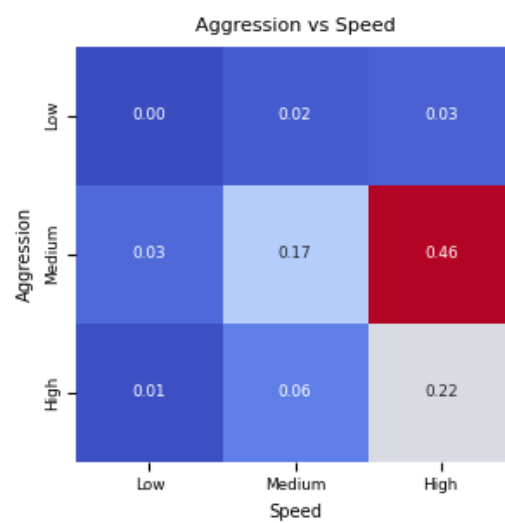
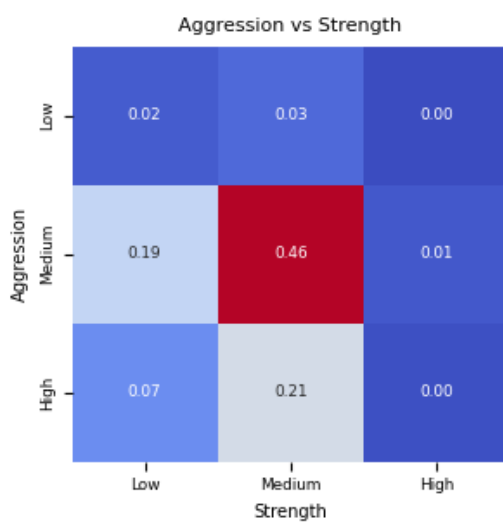
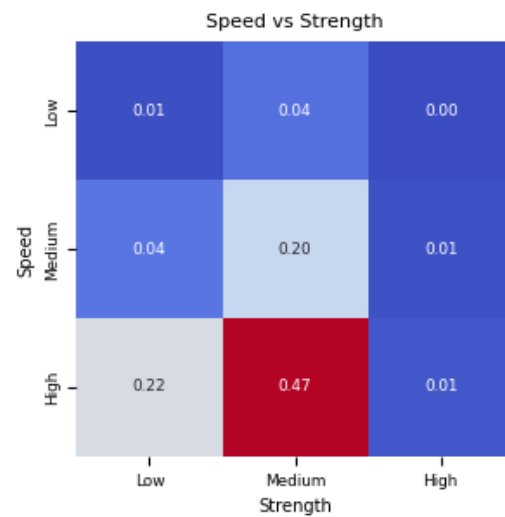
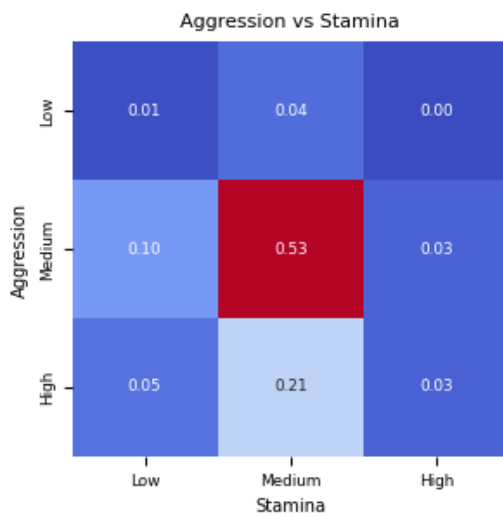
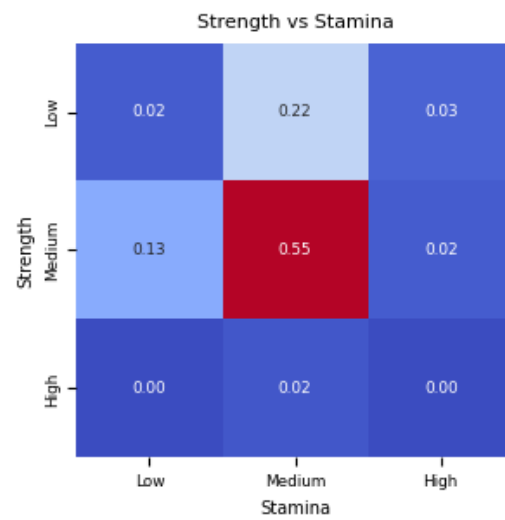
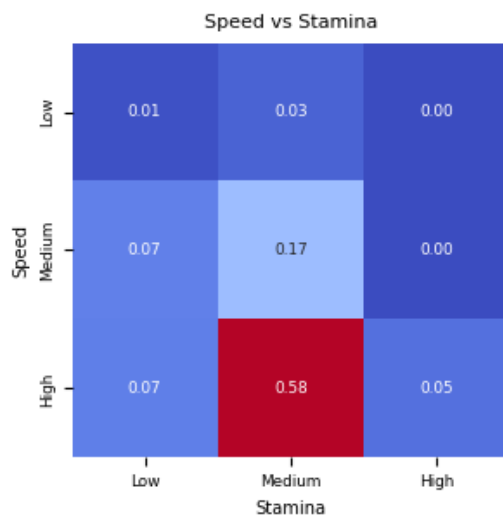


Simulation 3 - 1% Food, 5% Creatures

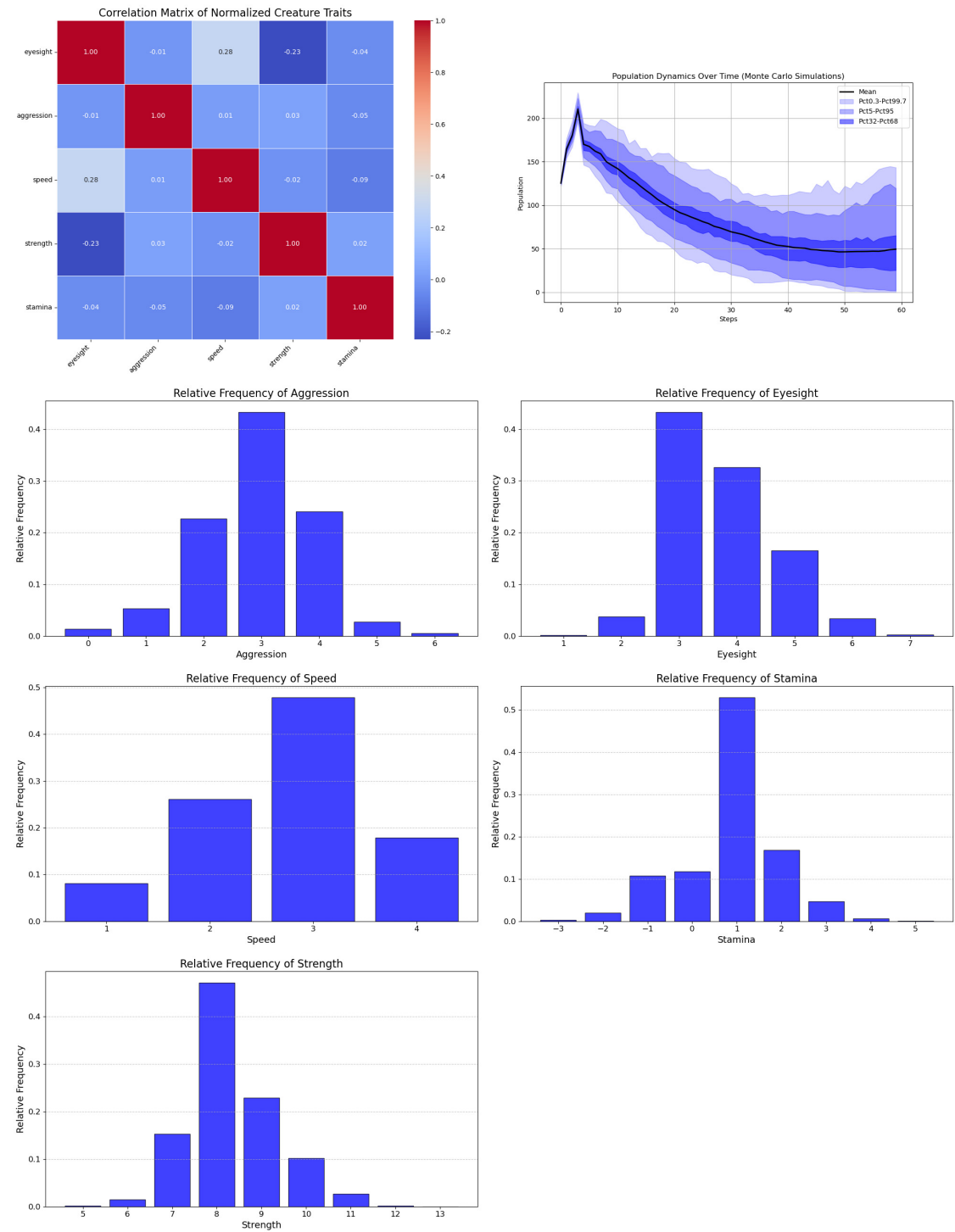


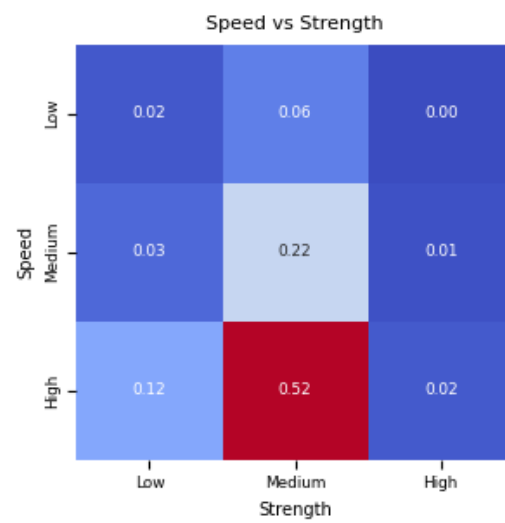
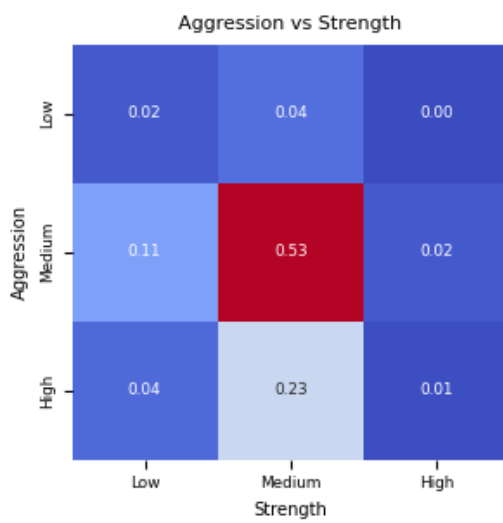
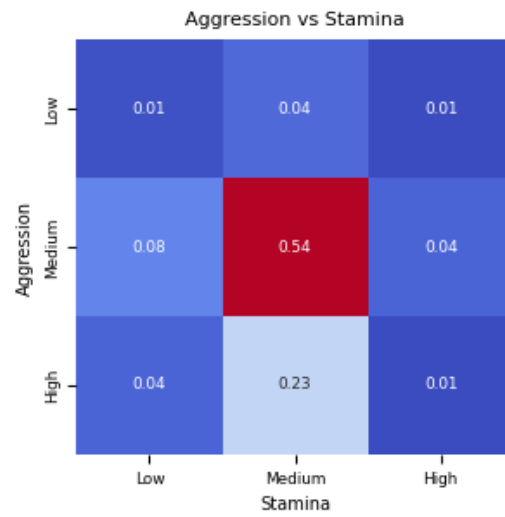
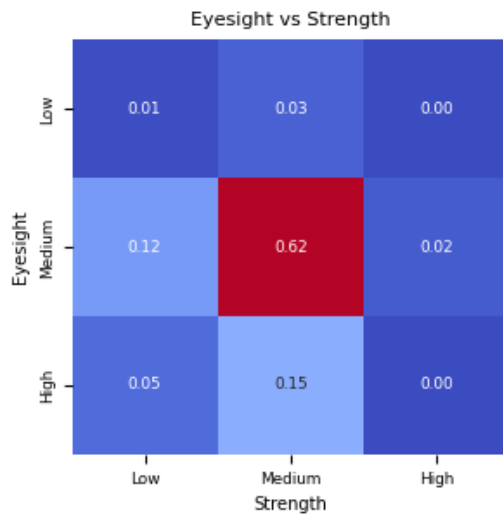
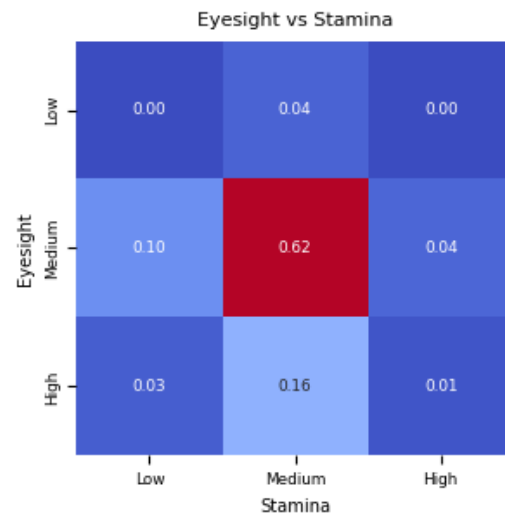
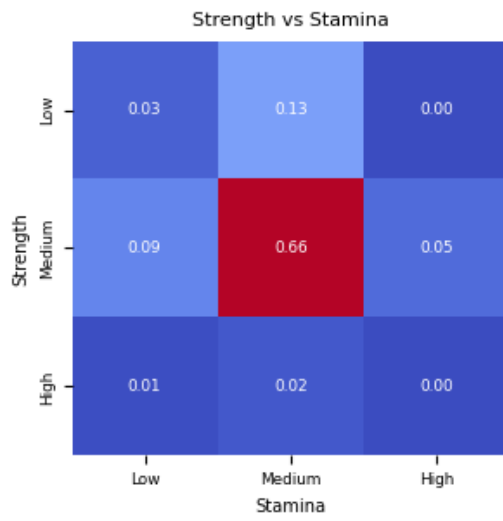
Simulation 4 - 3% Food, 1% Creatures



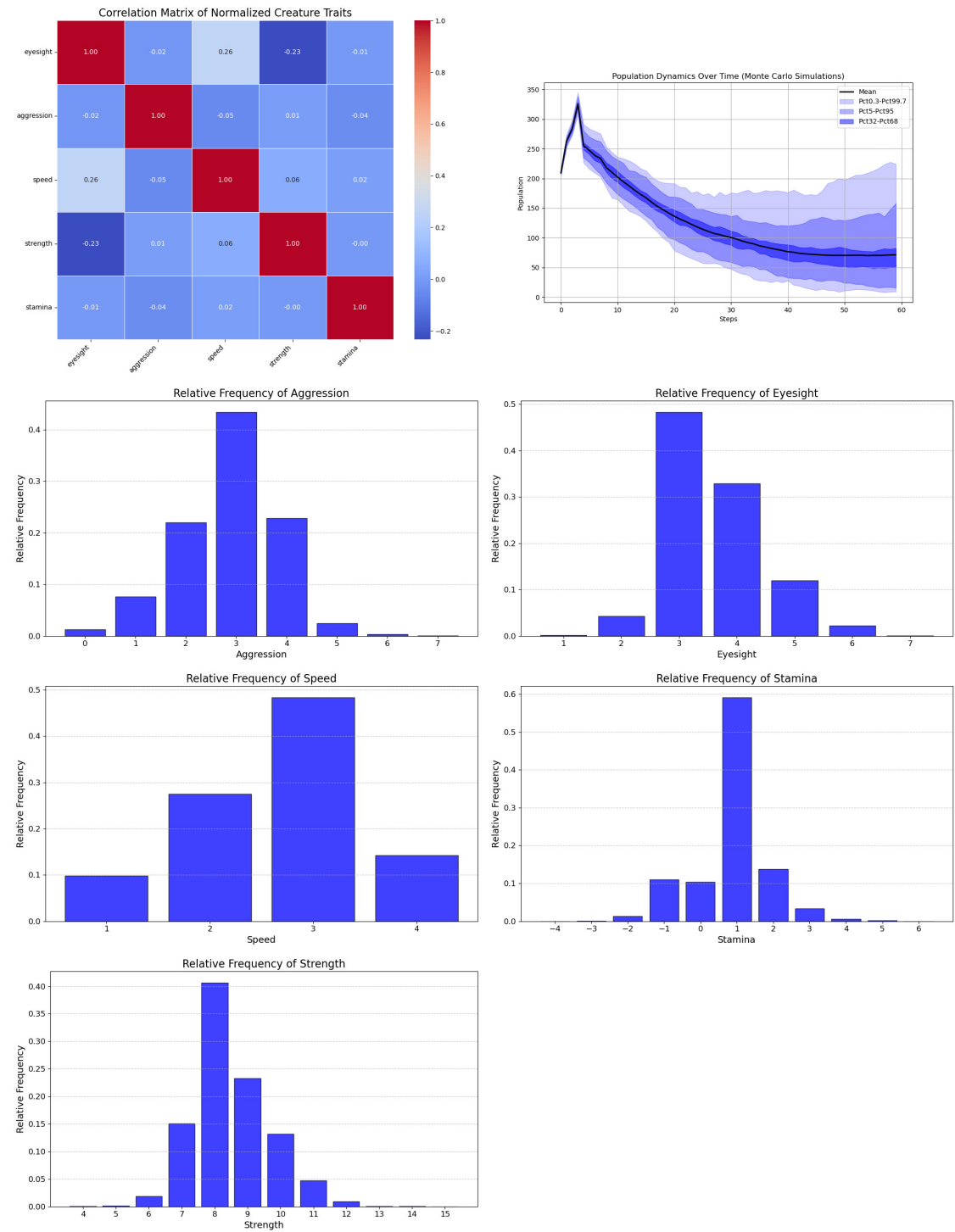


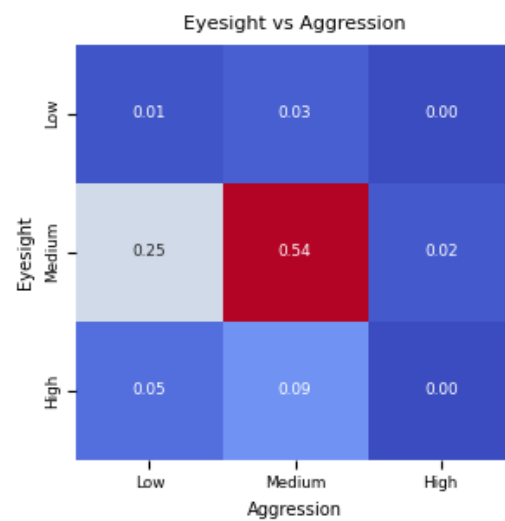
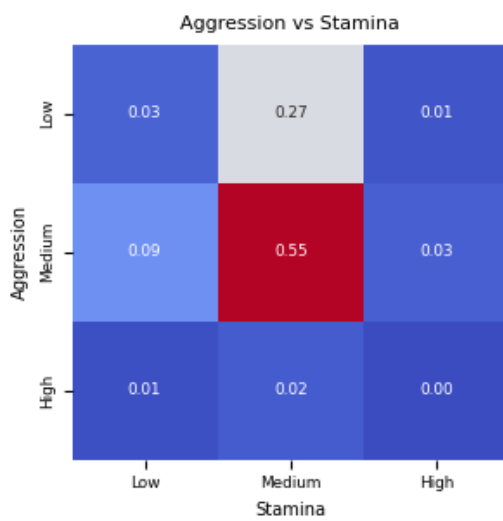
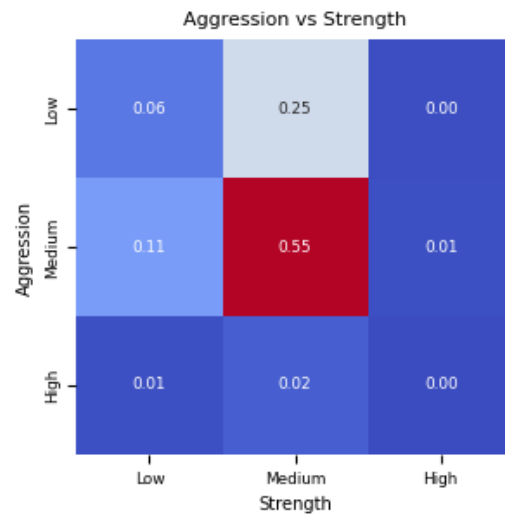
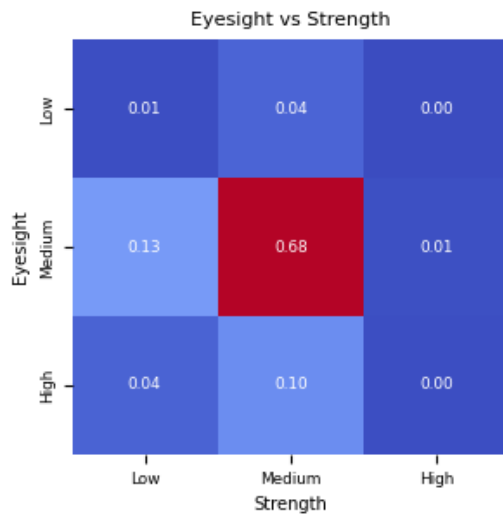
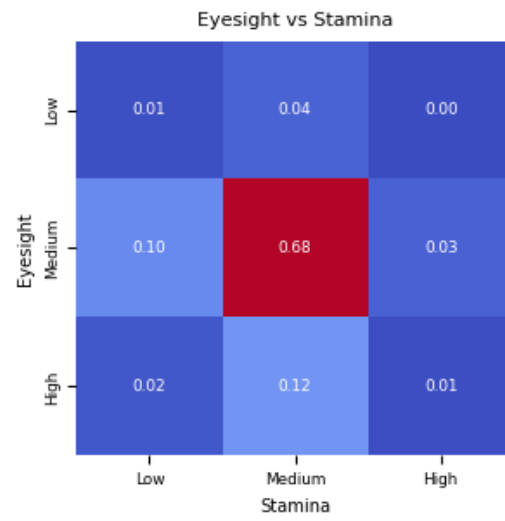
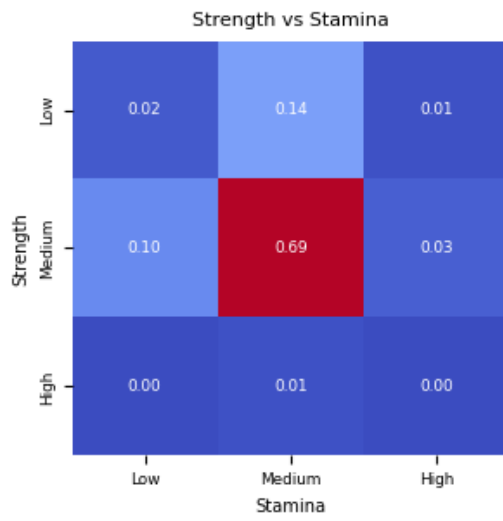
Simulation 5 - 3% Food, 3% Creatures



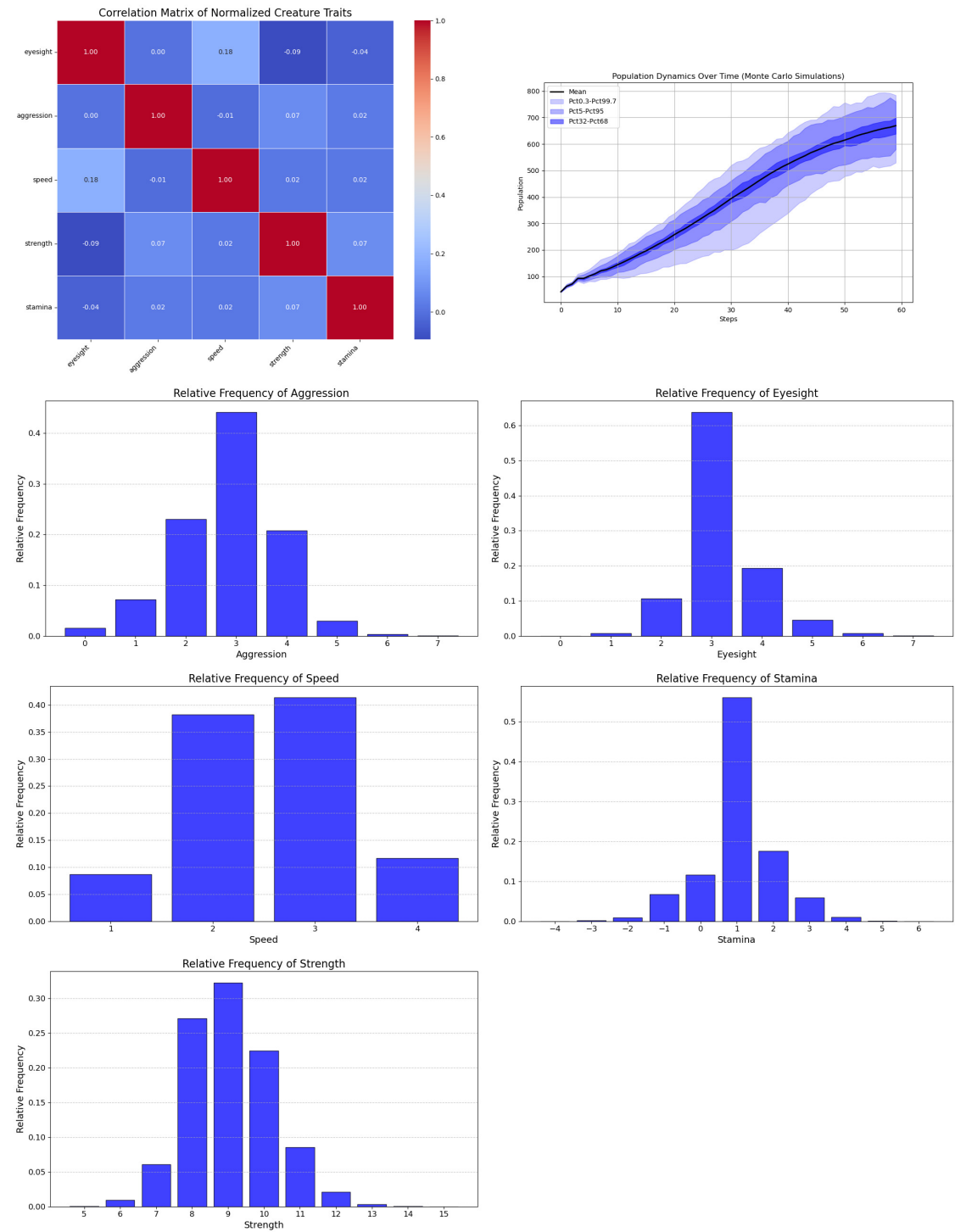


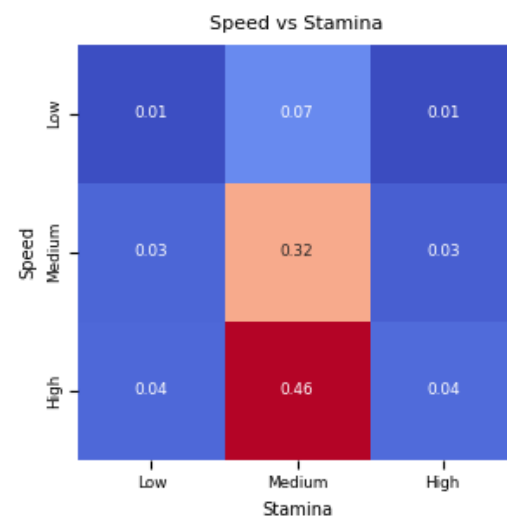
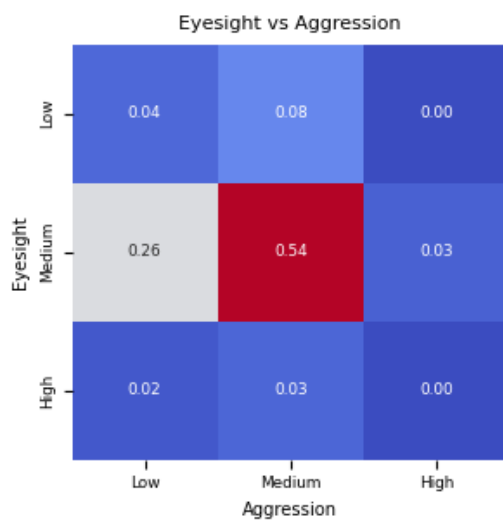
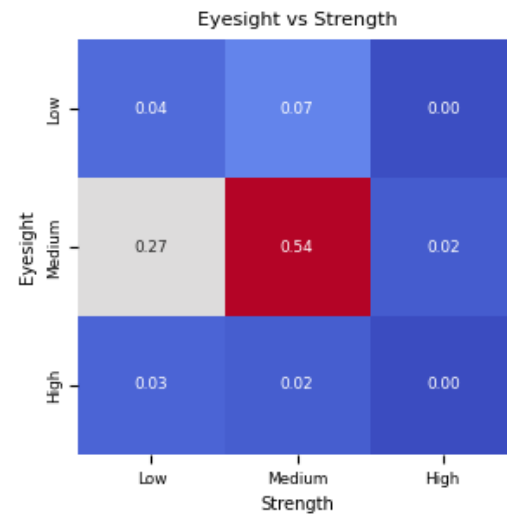
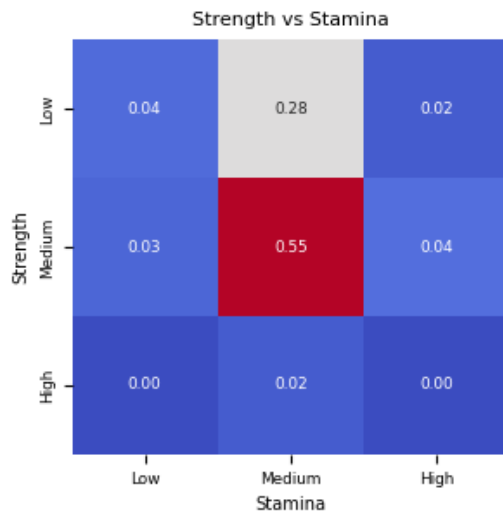
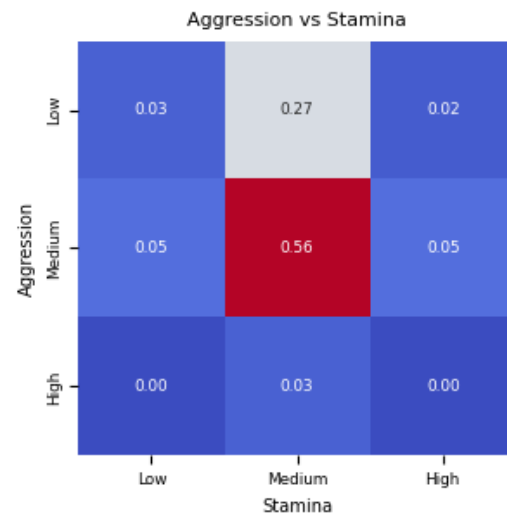
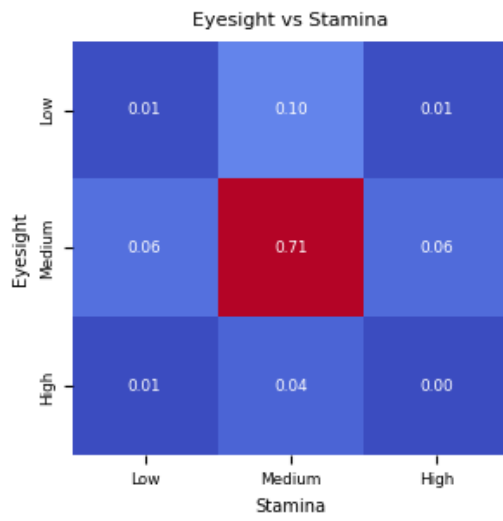
Simulation 6 - 3% Food, 5% Creatures



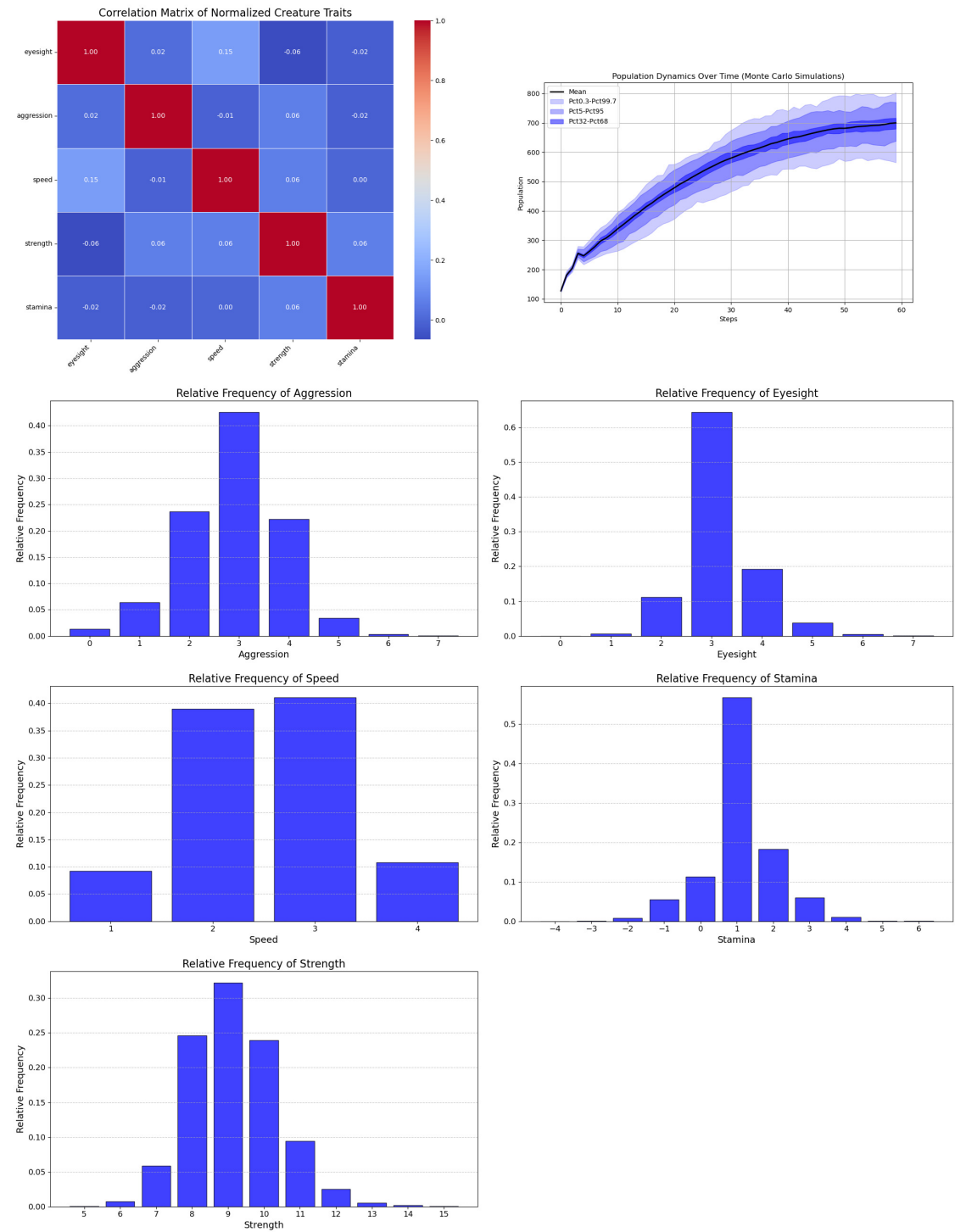


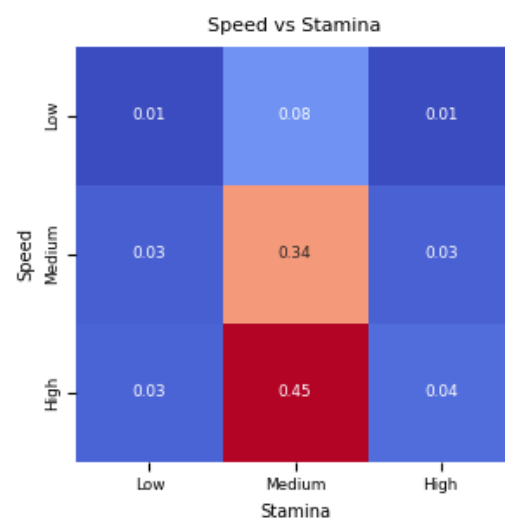
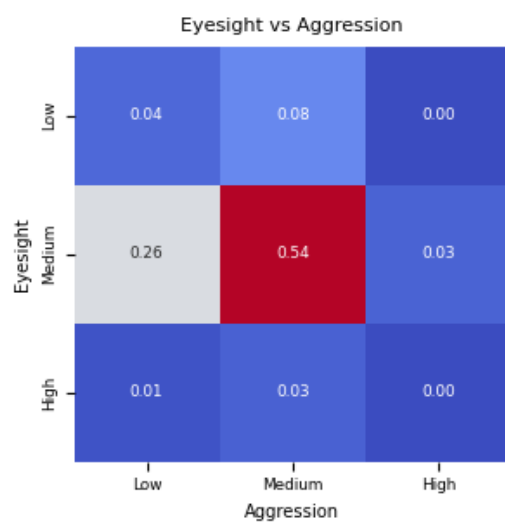
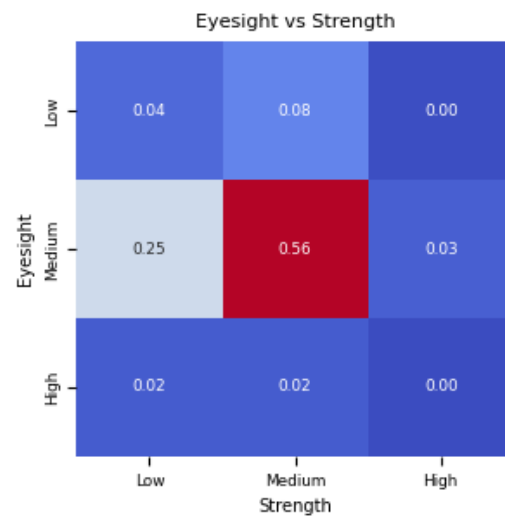
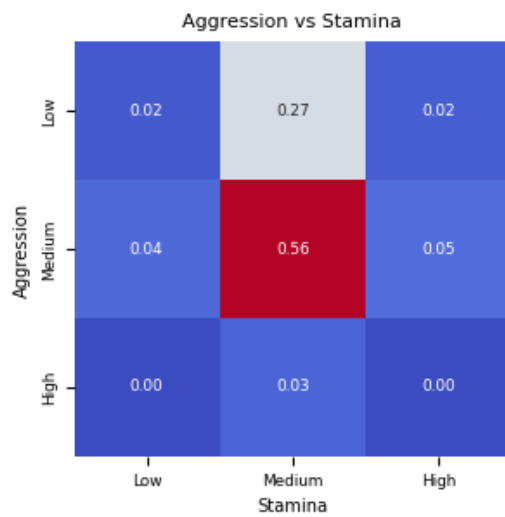
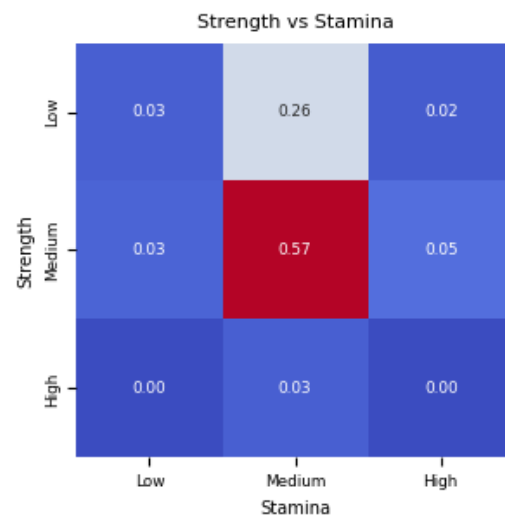
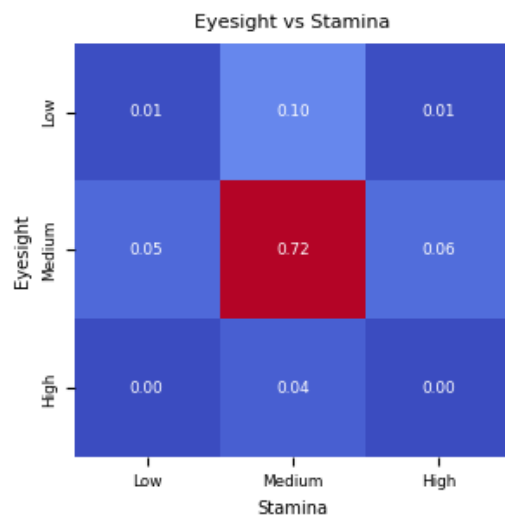
Simulation 7 - 5% Food, 1% Creatures



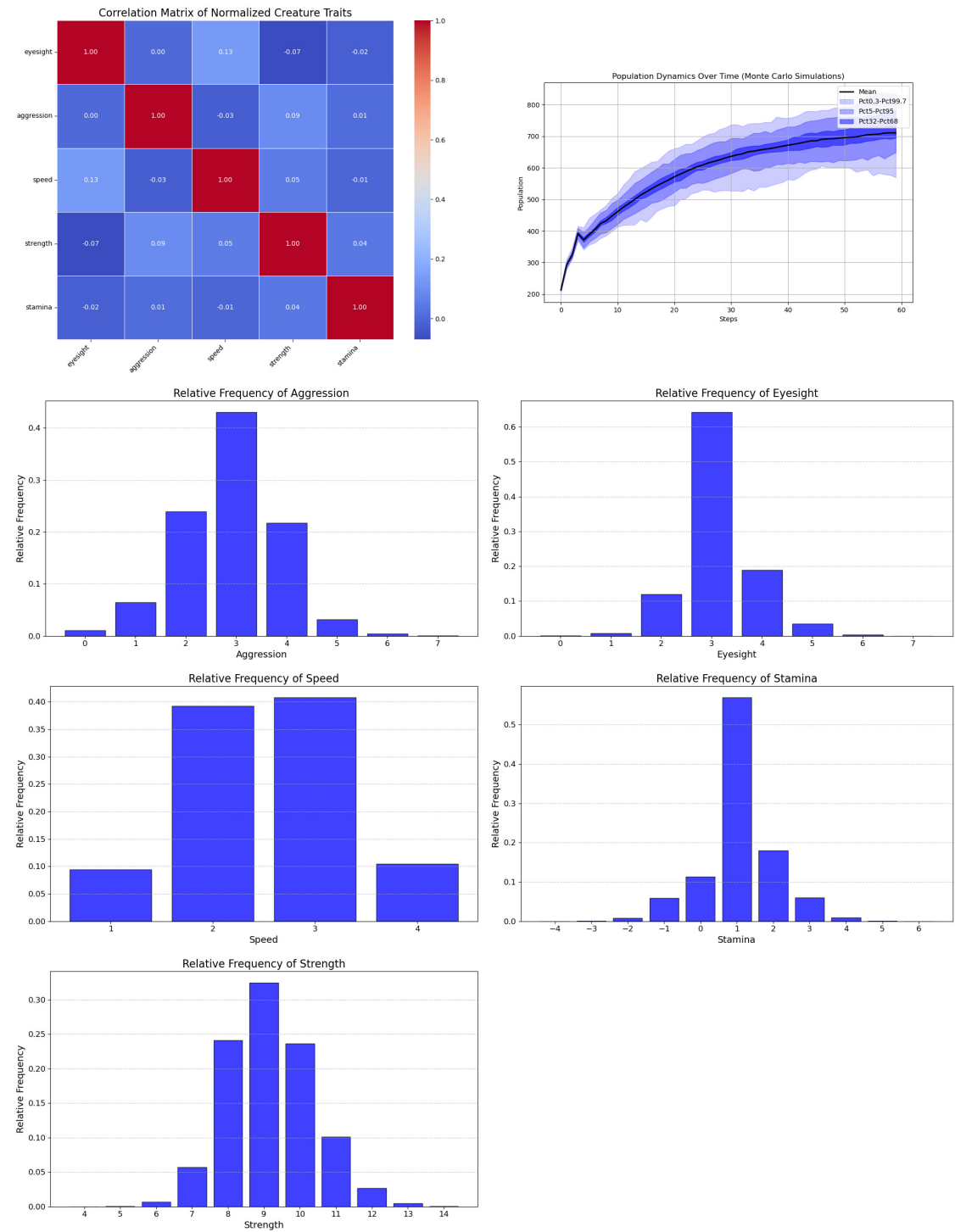


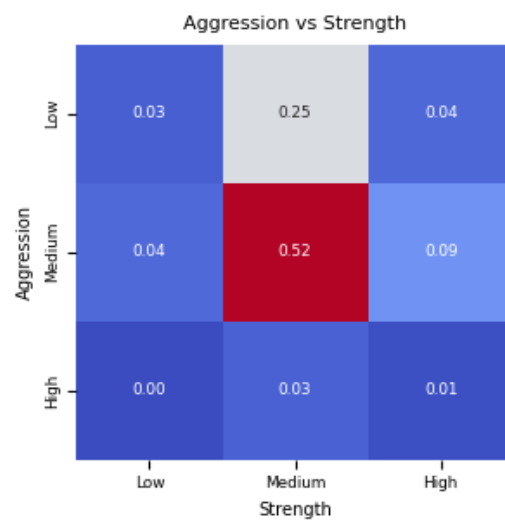
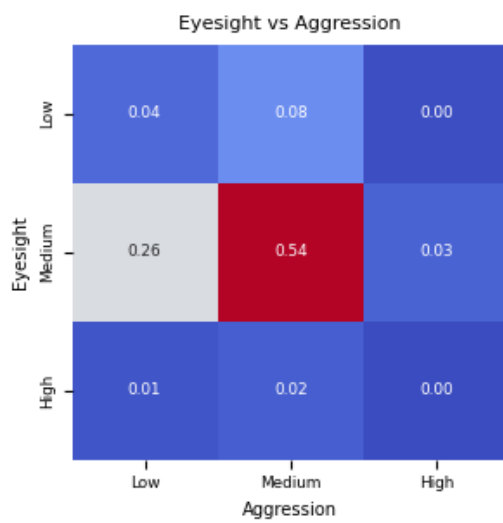
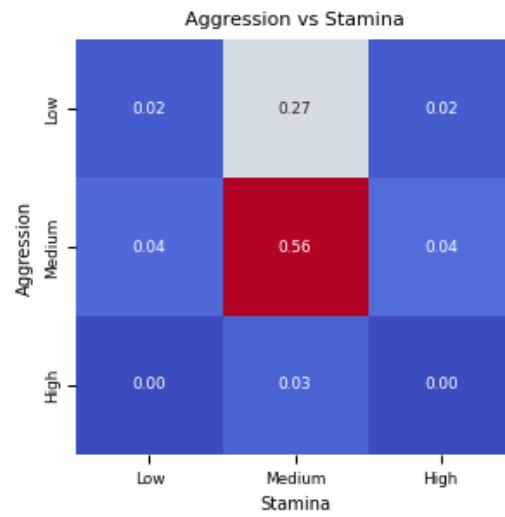
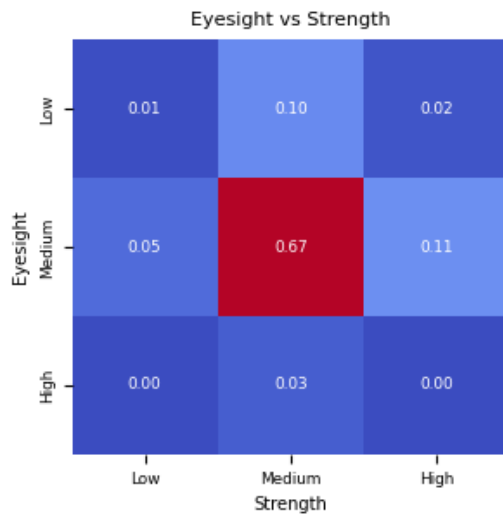
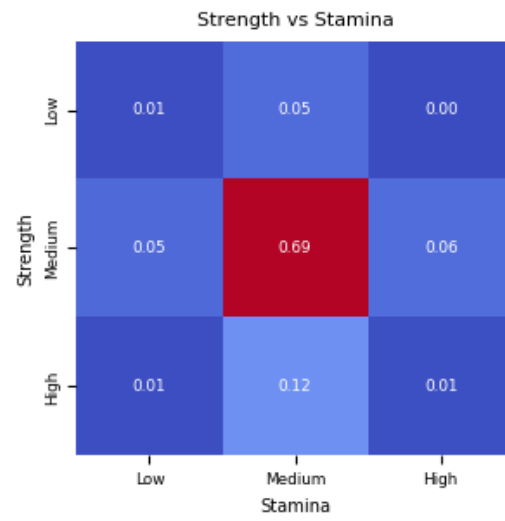
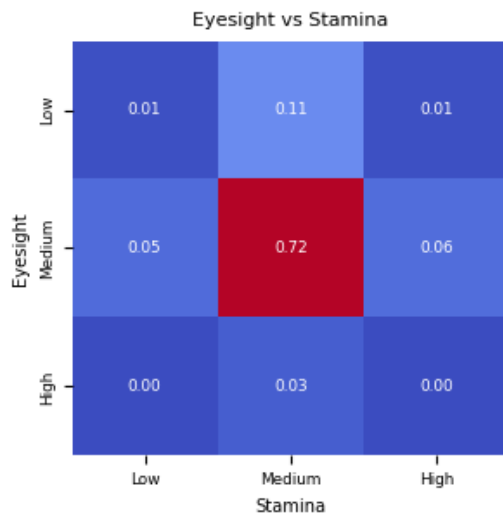
Simulation 8 - 5% Food, 3% Creatures





Simulation 9 - 5% Food, 5% Creatures





Observations

- **Low Amount of Food**

- The average genome fails to adapt to an environment with low food levels.

- **Medium Amount of Food**

- The average genome reaches a somewhat stable population size. The average ranges from 25 to 75 depending on the initial number of creatures.
- The speed is valued a lot, as approximately 60 to 70% of the final populace has a higher speed than at the start.
- There is a weak positive correlation between speed and eyesight, while at the same time there is weak negative correlation between strength and eyesight. The correlations are observed stronger when the population size is low.

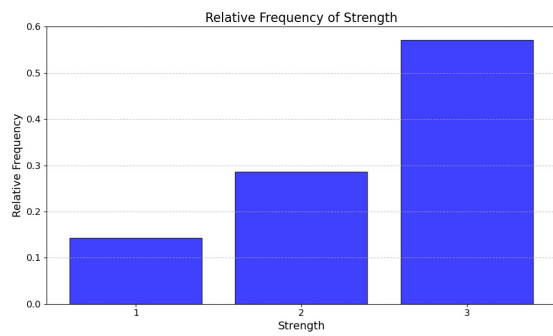
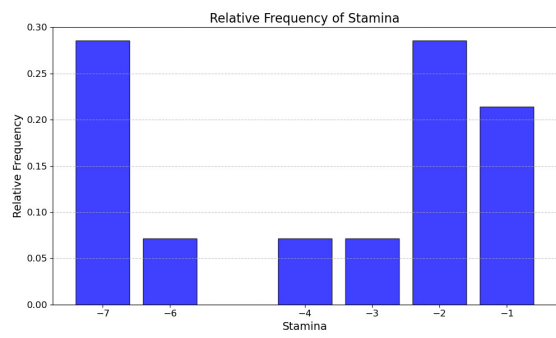
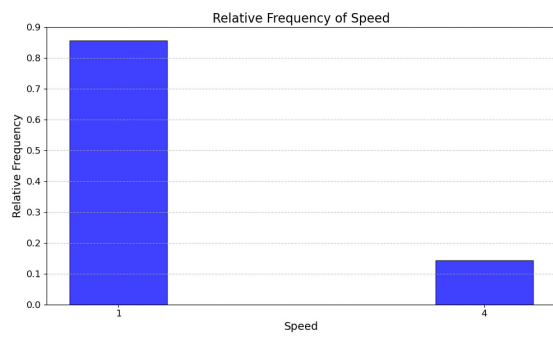
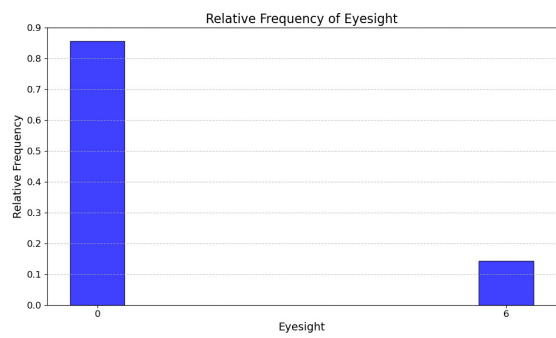
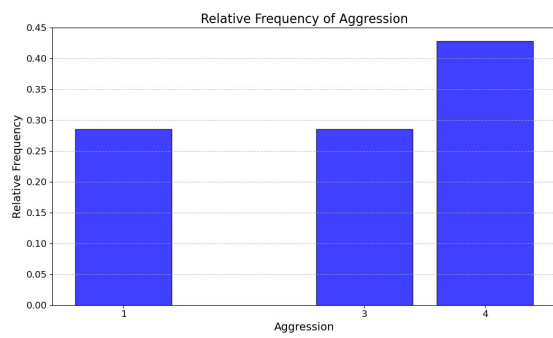
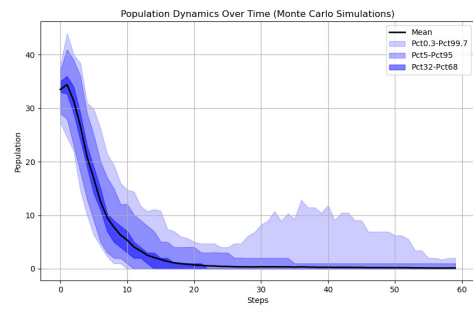
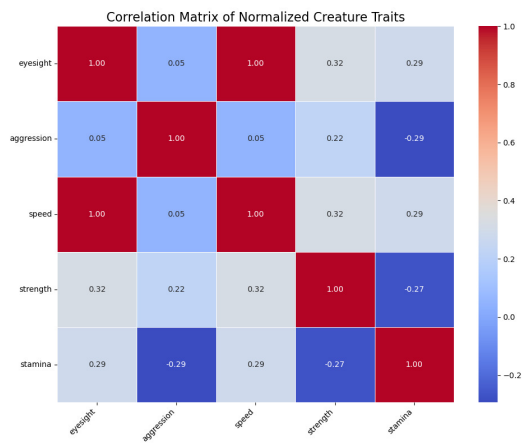
- **High Amount of Food**

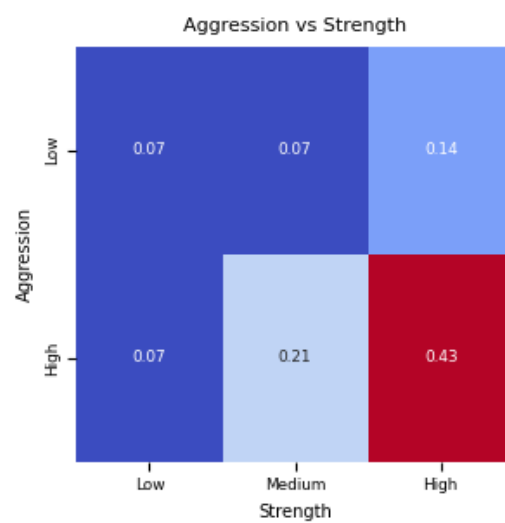
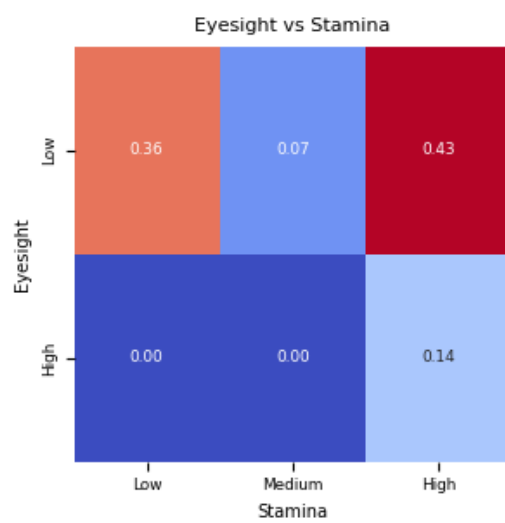
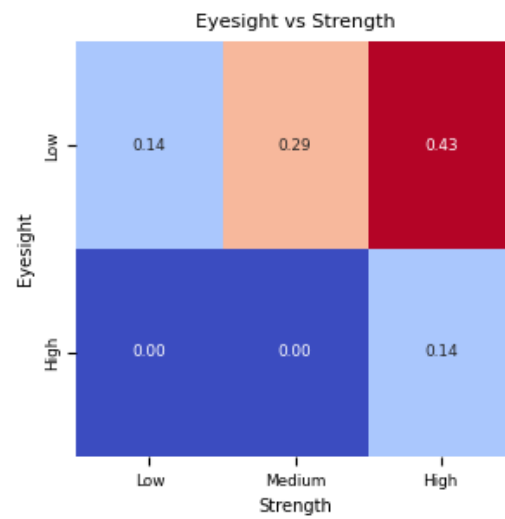
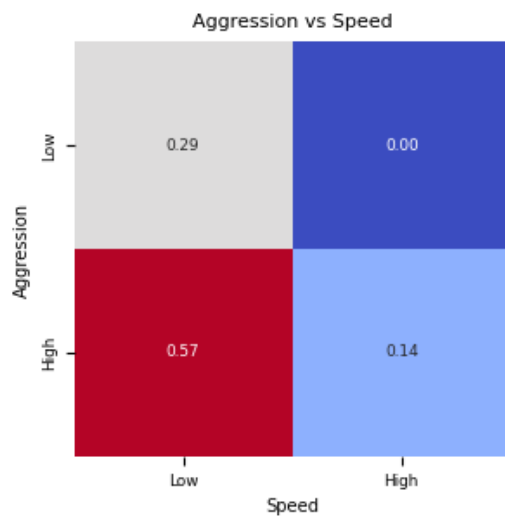
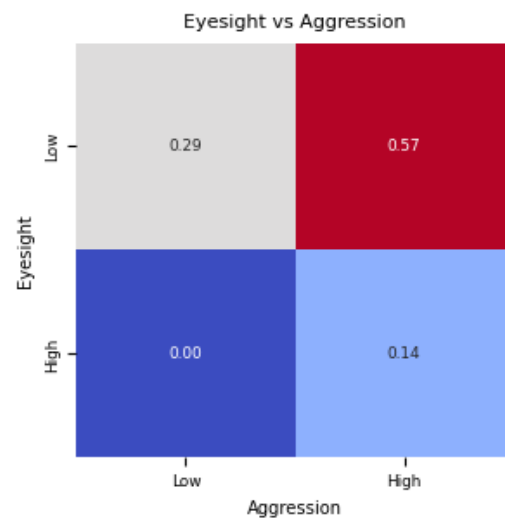
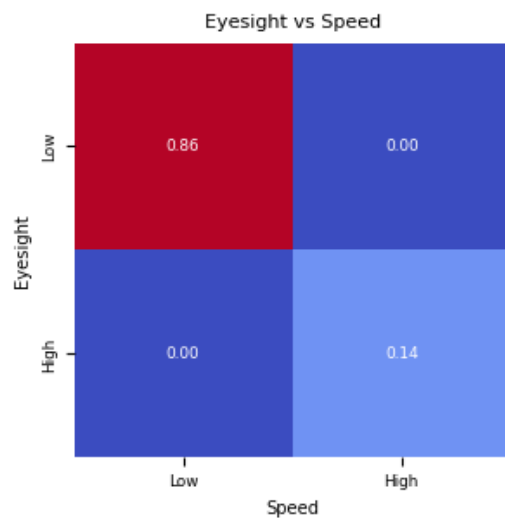
- The population grows rapidly when there is an abundance of food. The growth is eventually slowed down.
- There is no significant linear correlation between any of the traits.
- Majority of the populace with medium values for stamina have high values of speed while maintaining low values of aggression and strength. This means that a lot more creatures prefer spending energy in search for food rather than attacking other creatures and risking themselves in the process.
- The eyesight is not as valued for the creatures with medium aggression.

4.1.2 Scenario 2: Random

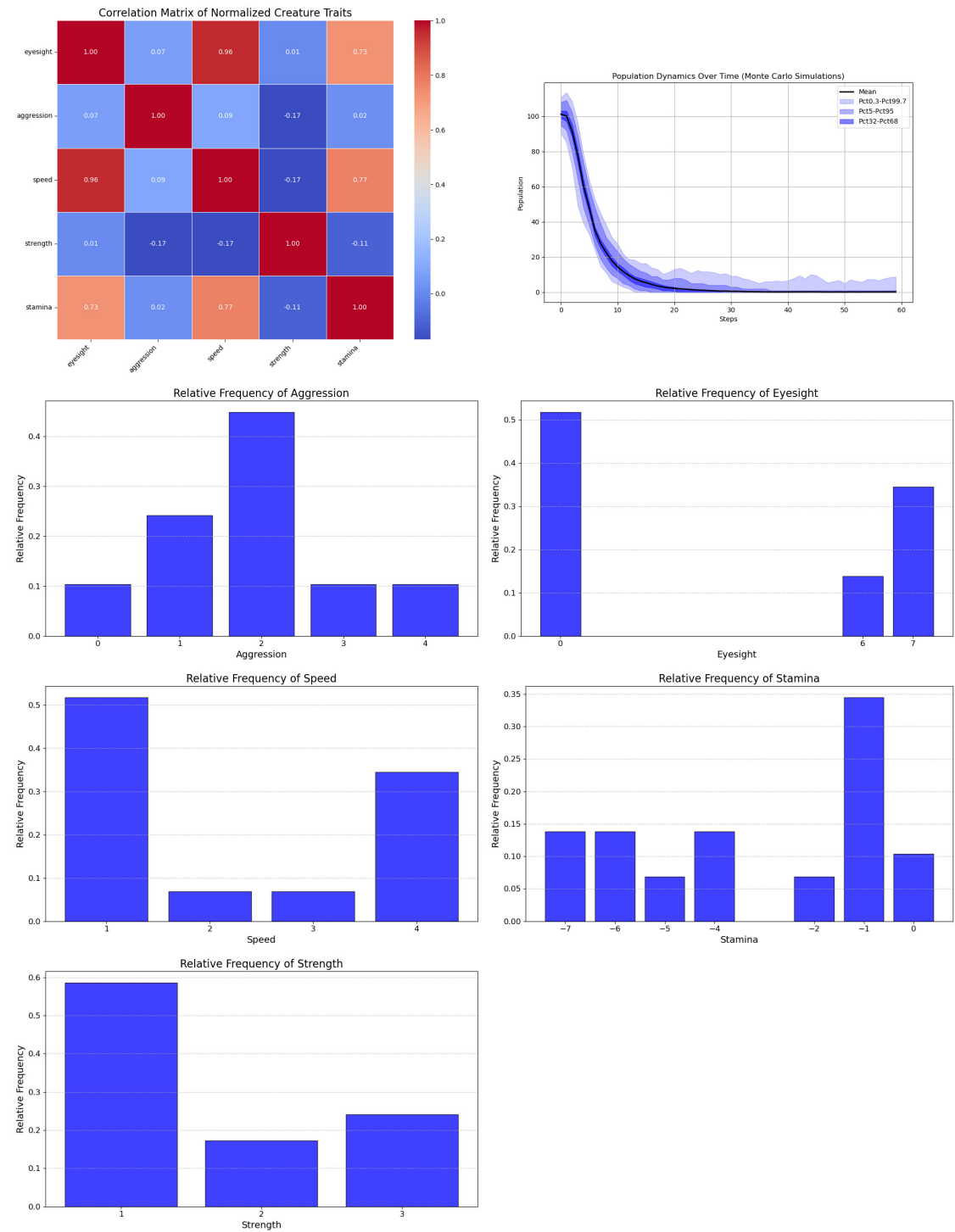
In this scenario, every creature starts up with a random gene.

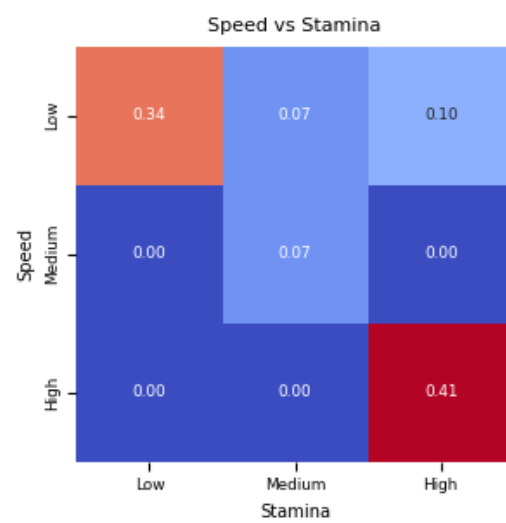
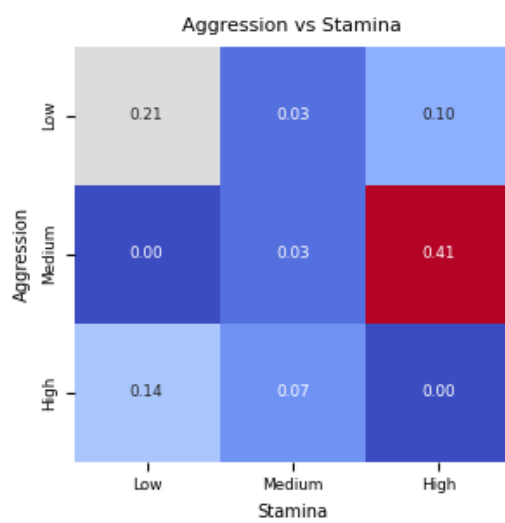
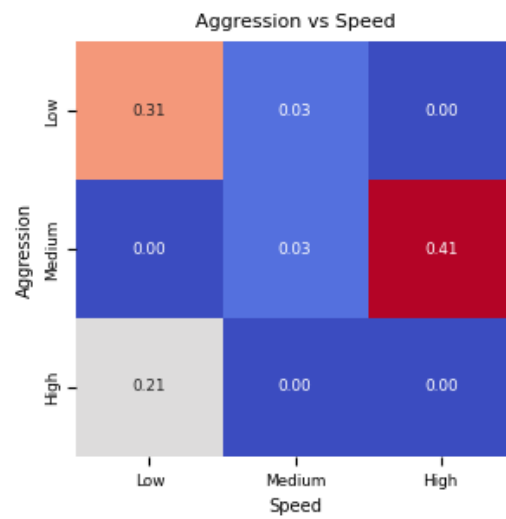
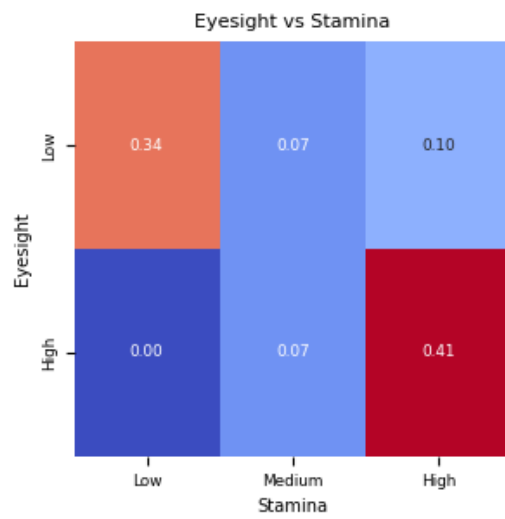
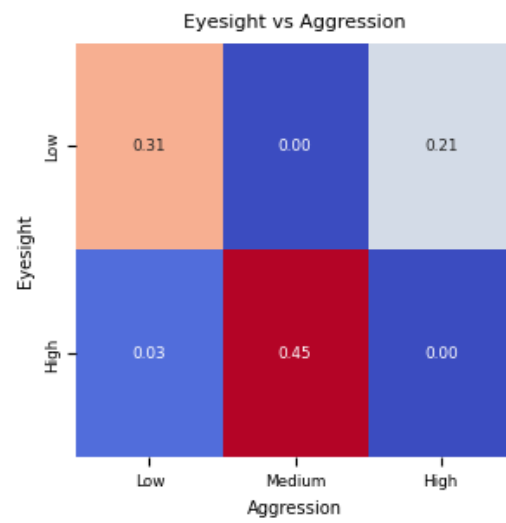
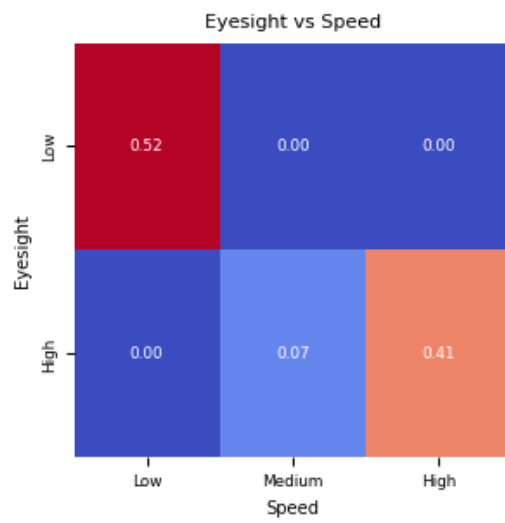
Simulation 1 - 1% Food, 1% Creatures



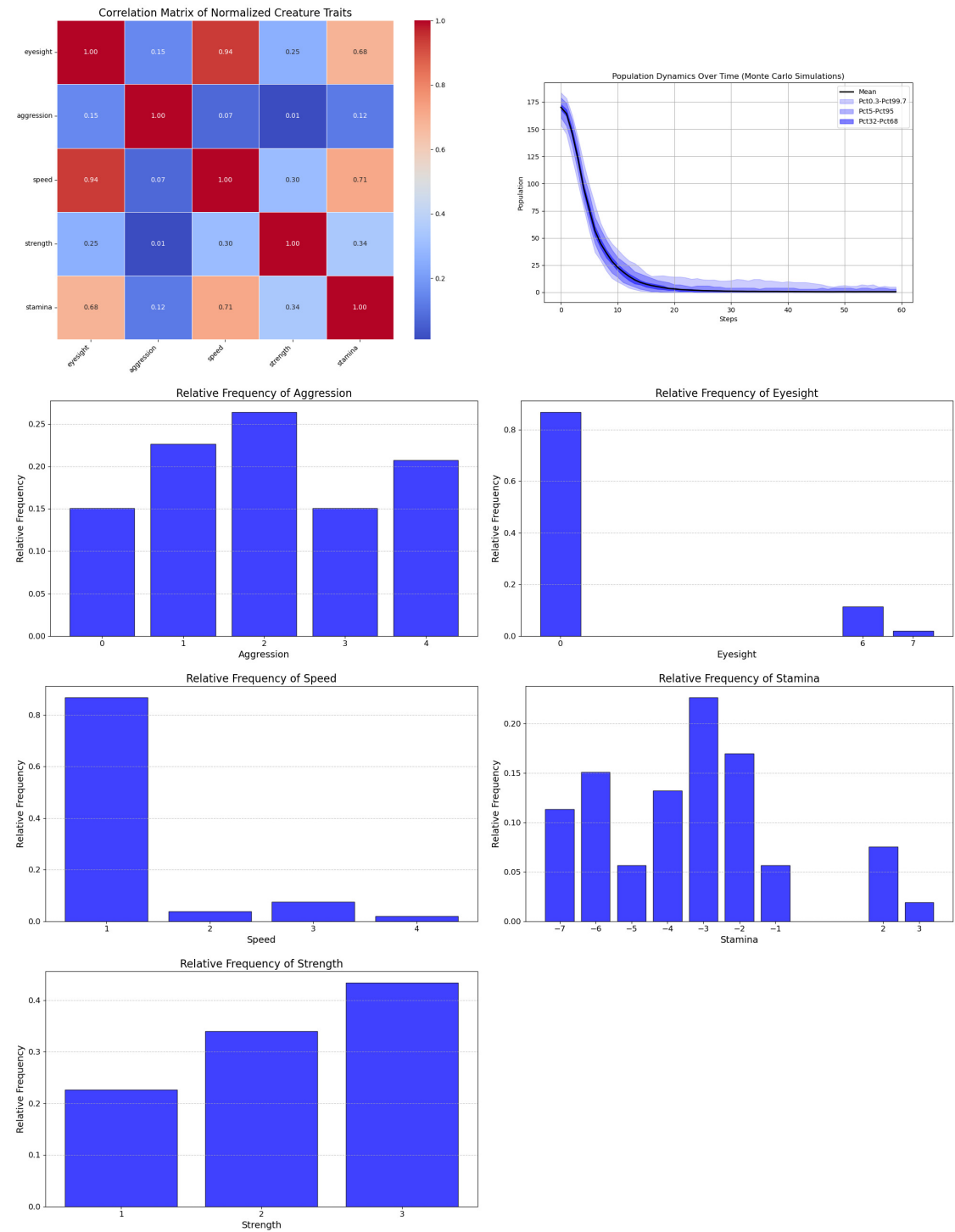


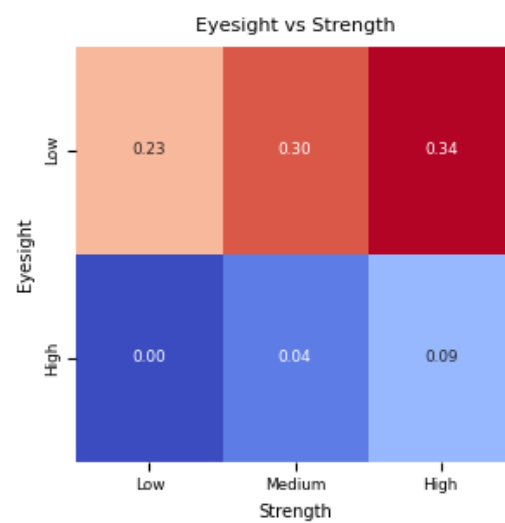
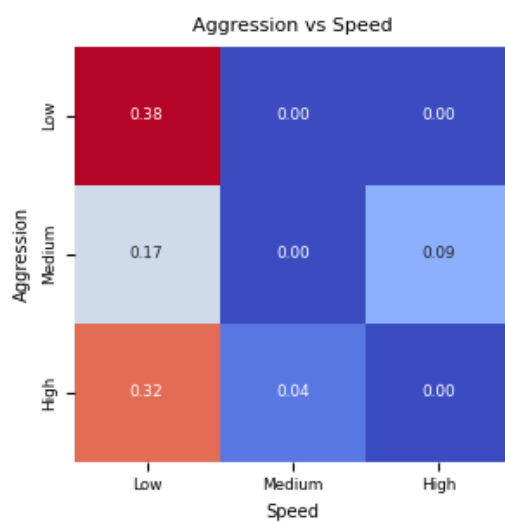
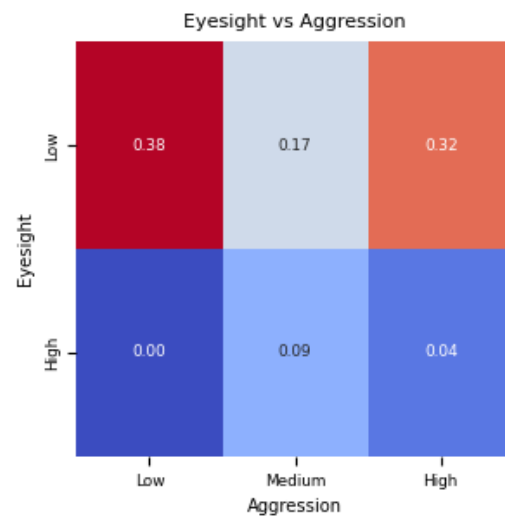
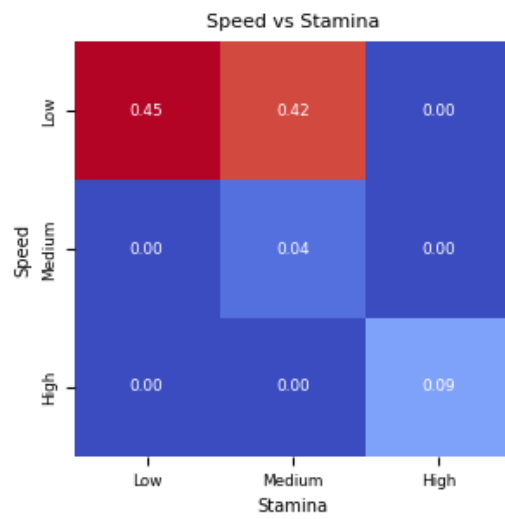
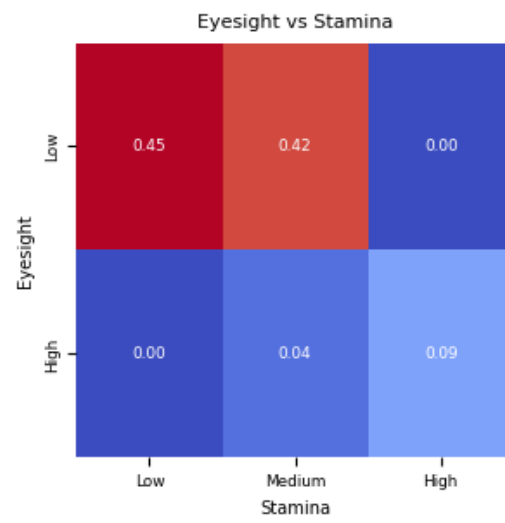
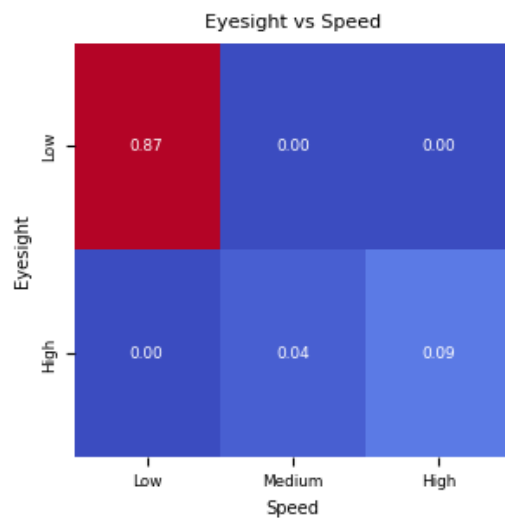
Simulation 2 - 1% Food, 3% Creatures



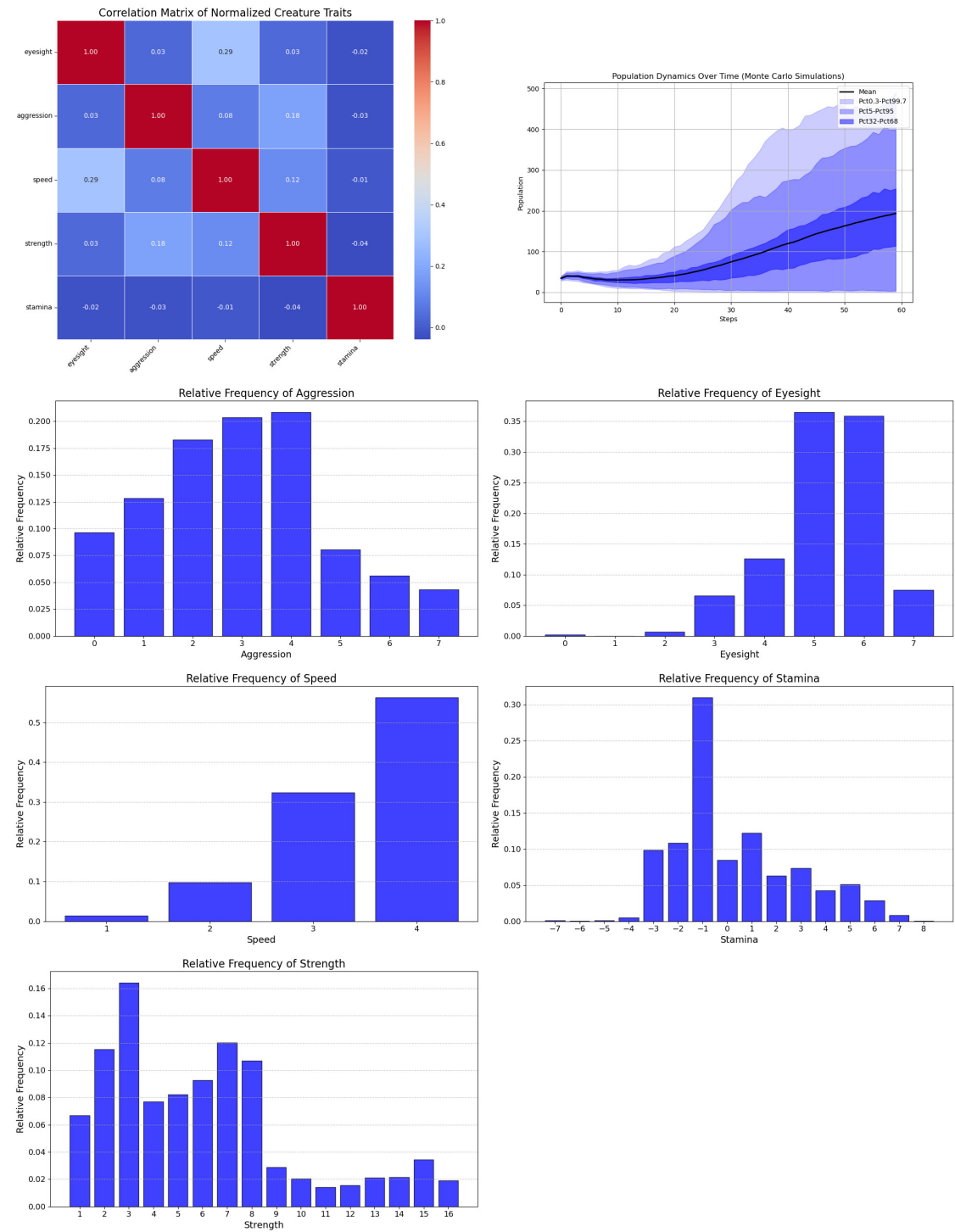


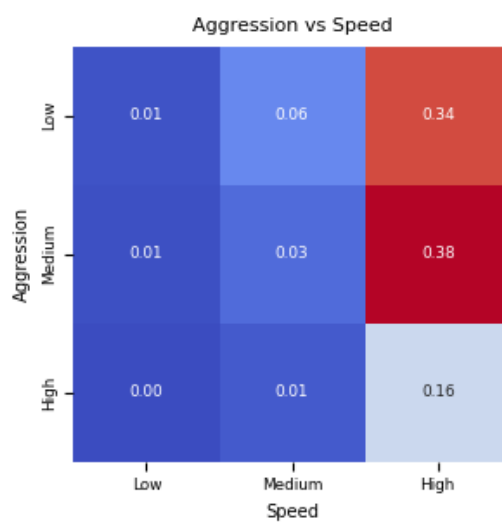
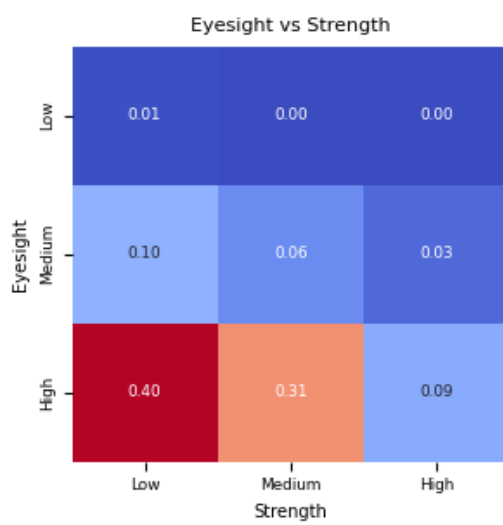
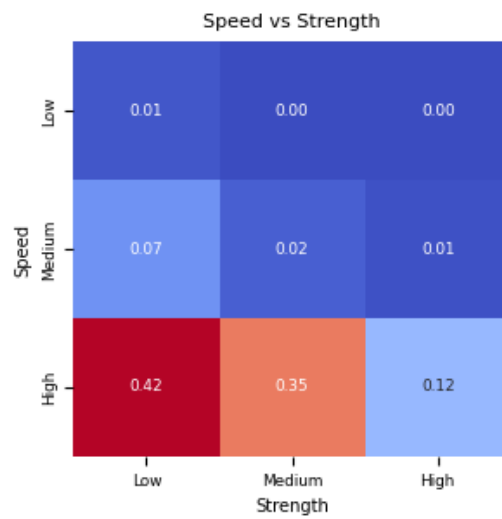
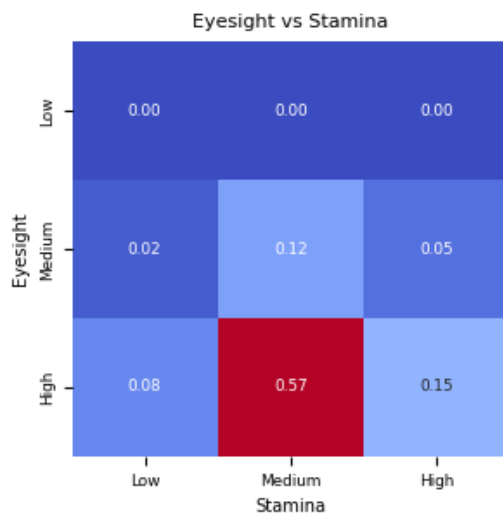
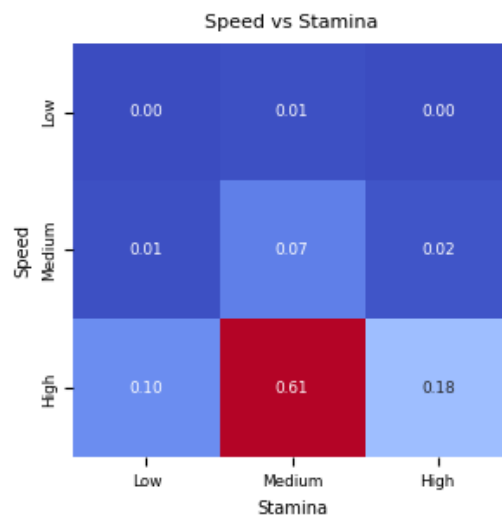
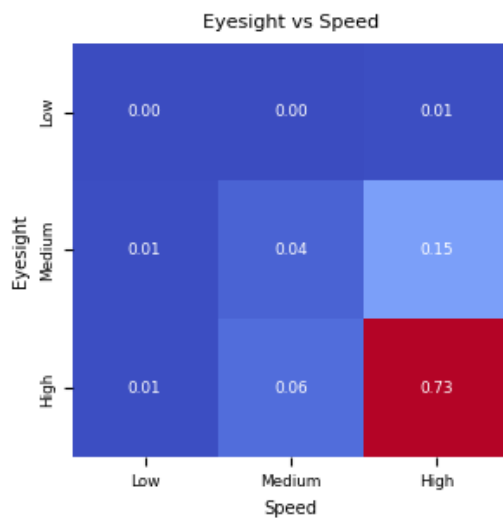
Simulation 3 - 1% Food, 5% Creatures



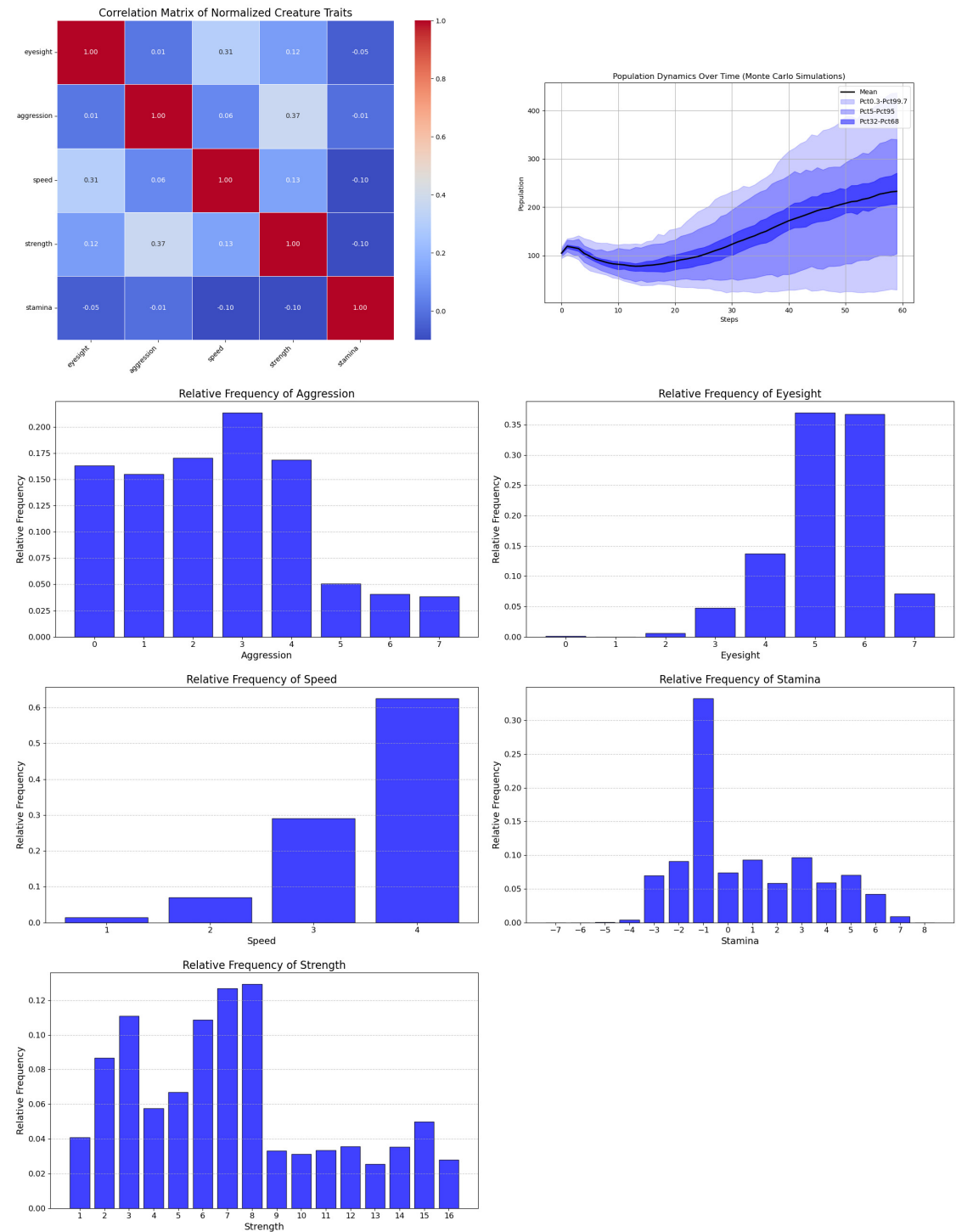


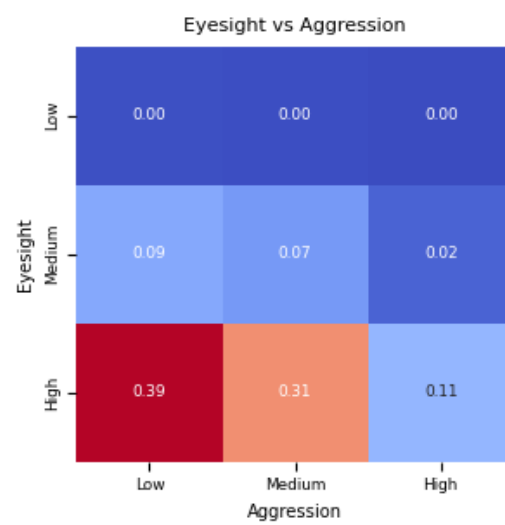
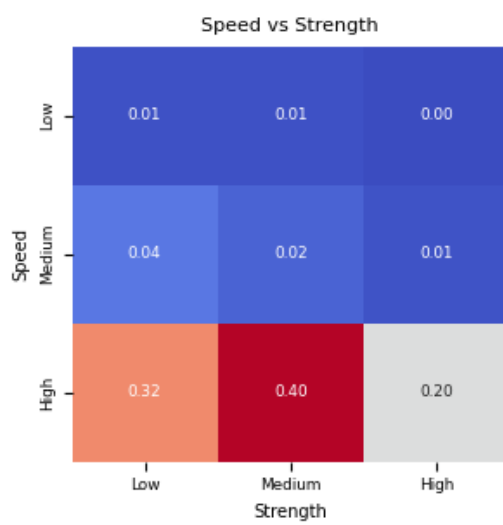
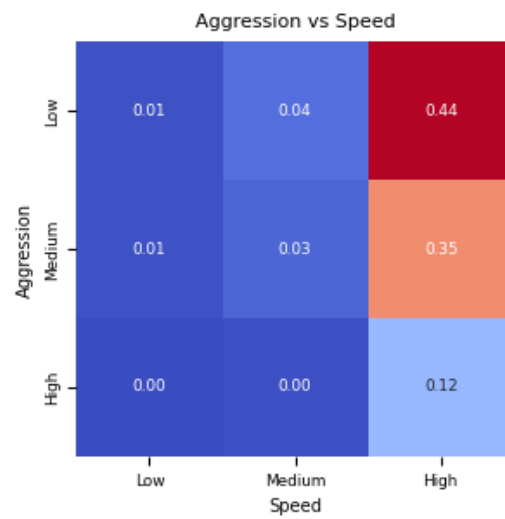
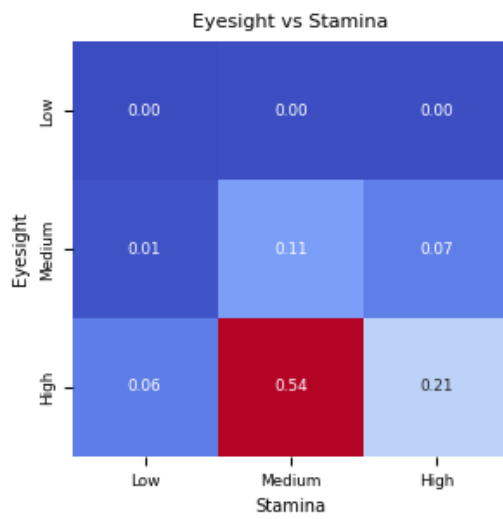
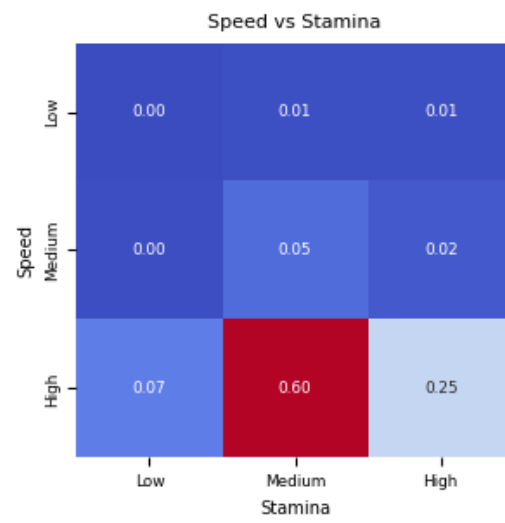
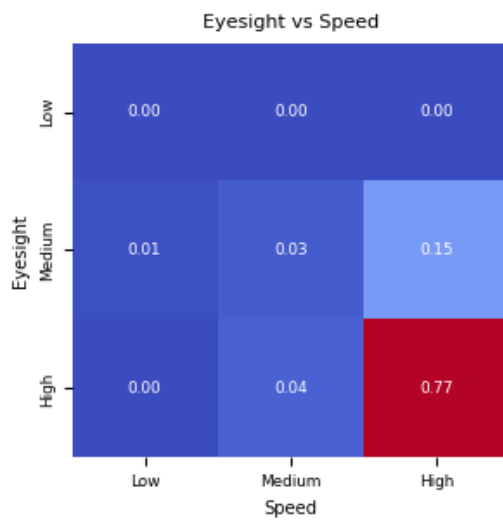
Simulation 4 - 3% Food, 1% Creatures



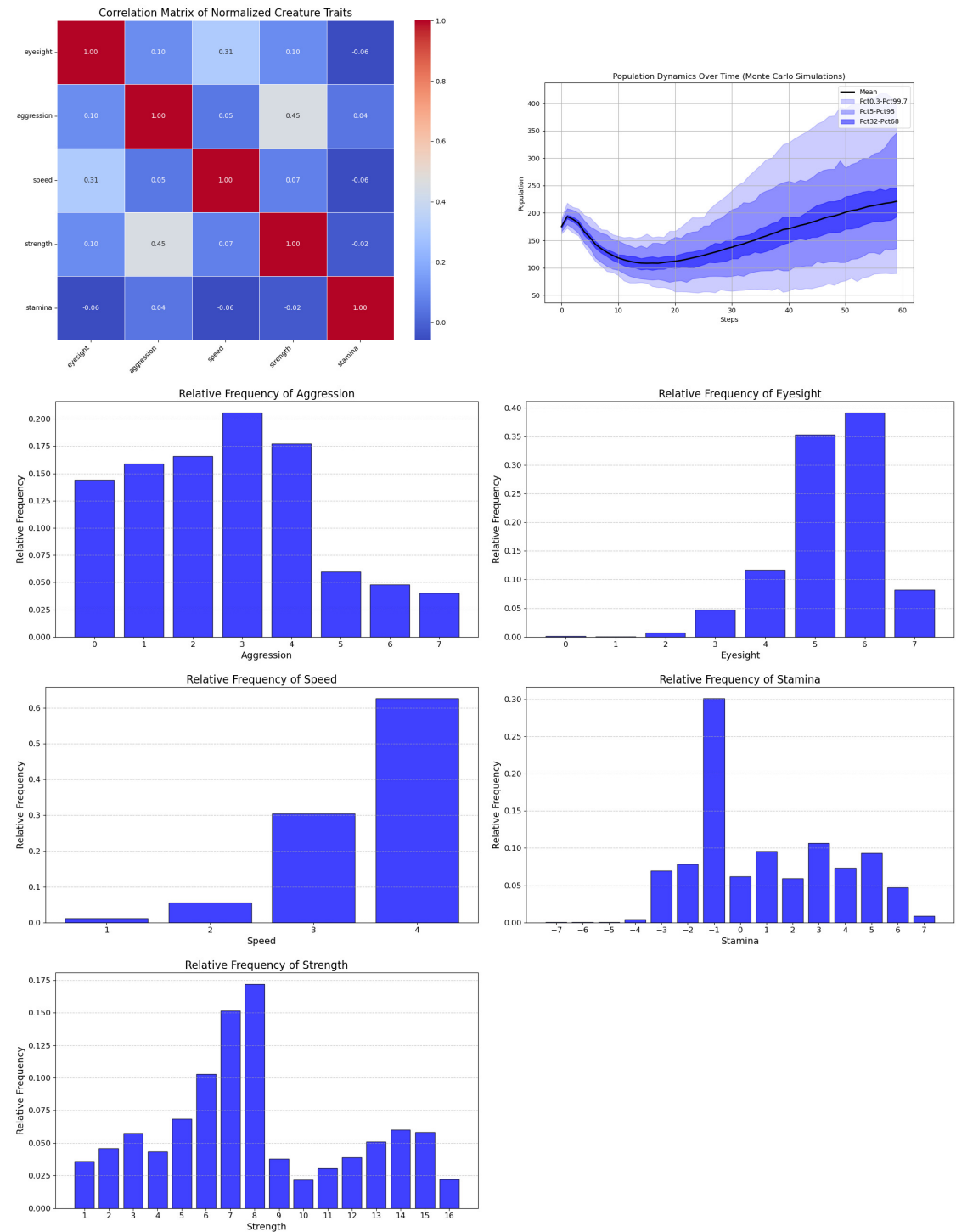


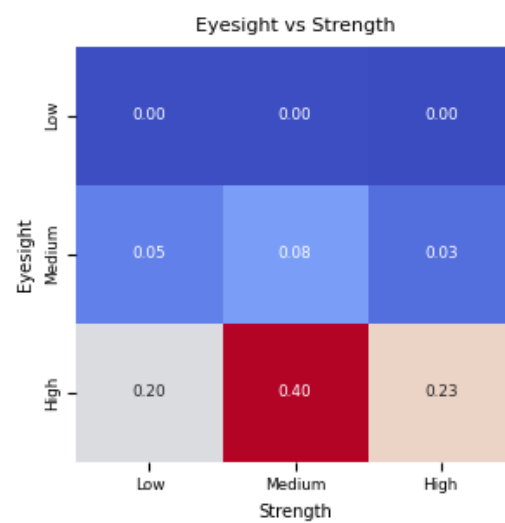
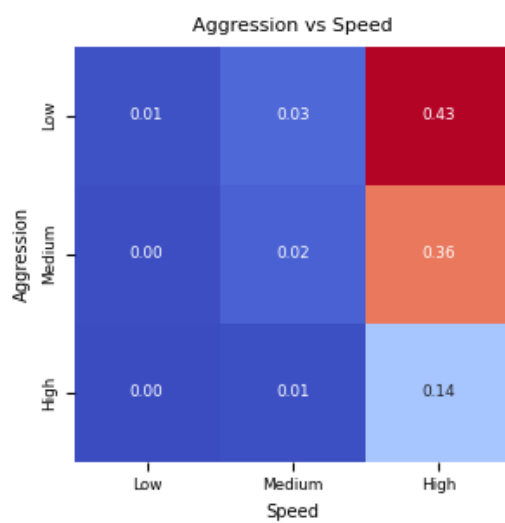
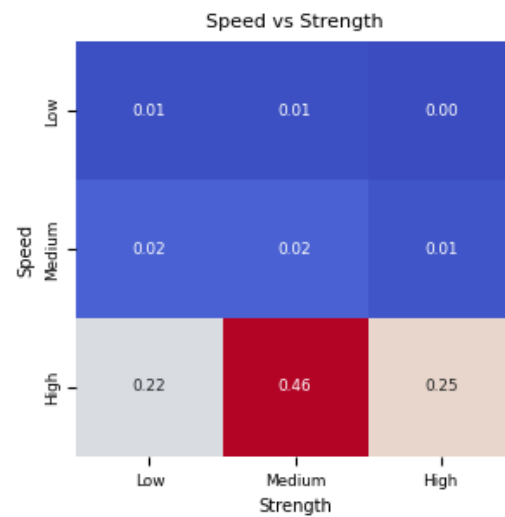
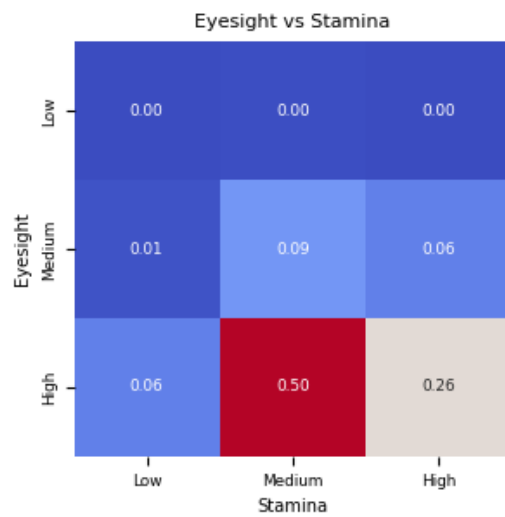
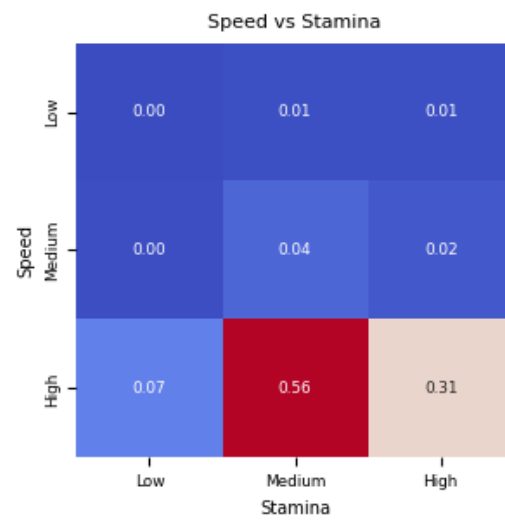
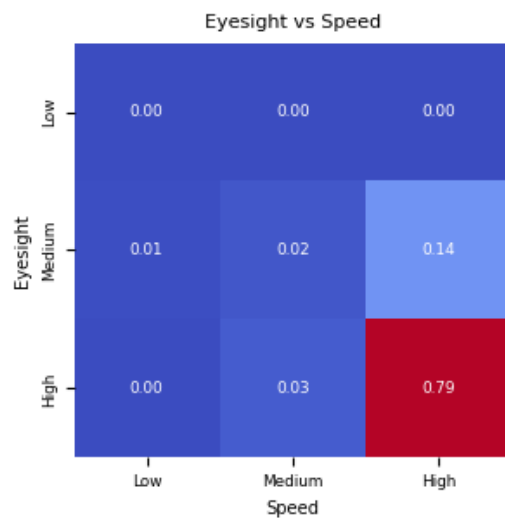
Simulation 5 - 3% Food, 3% Creatures



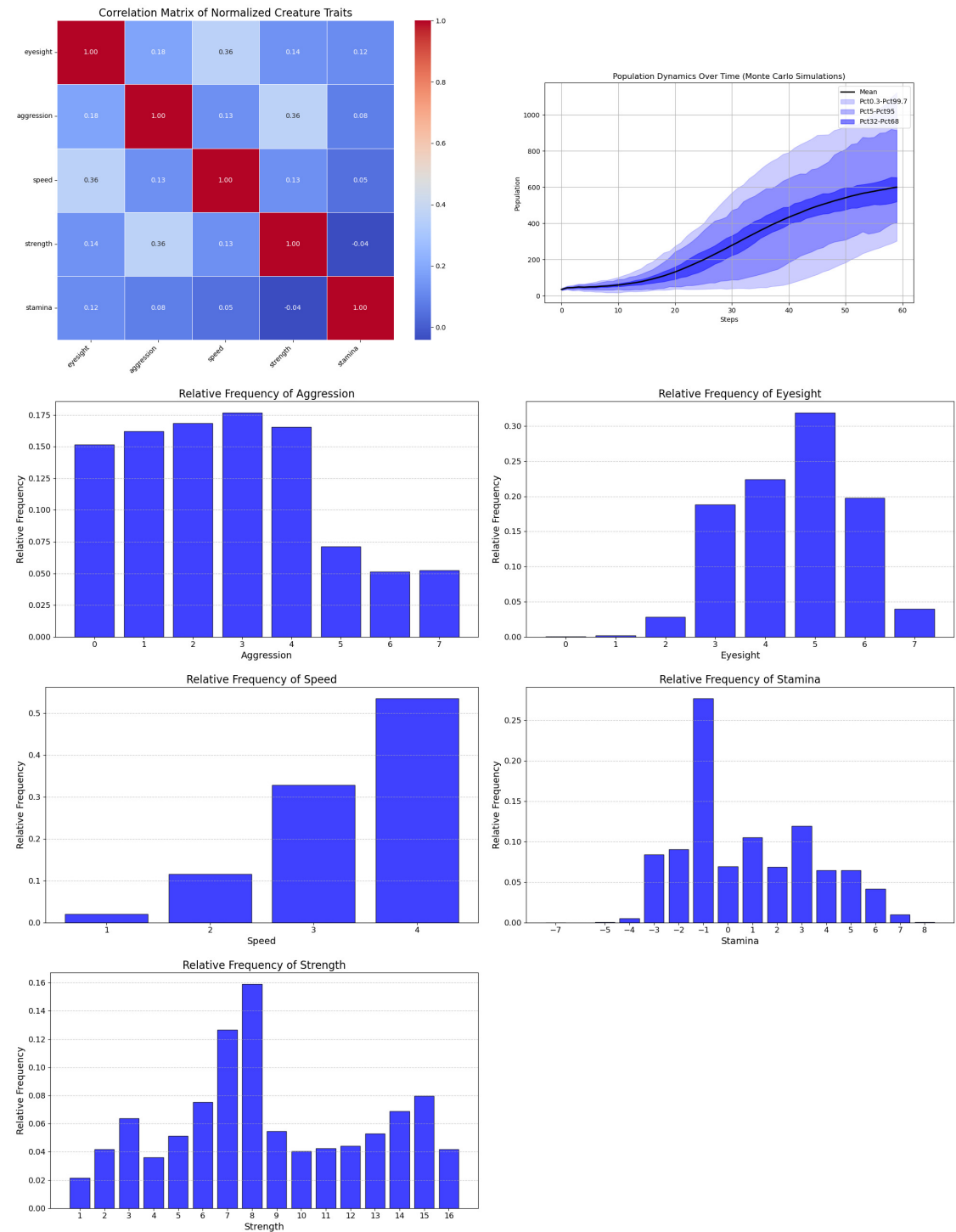


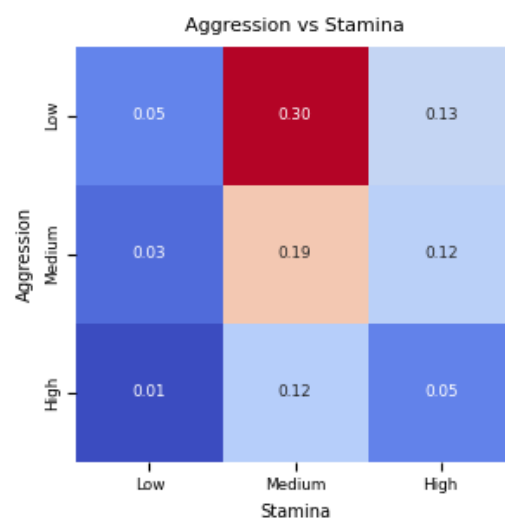
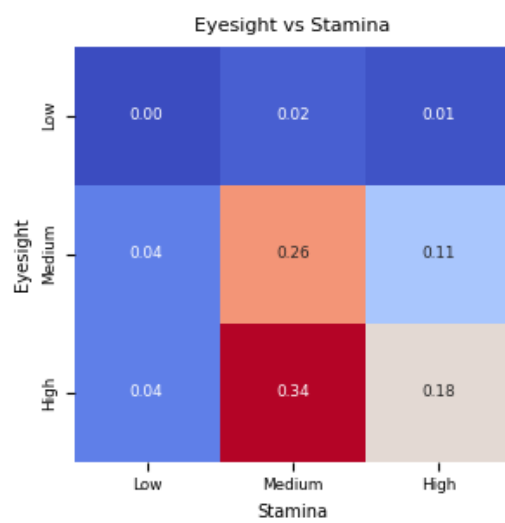
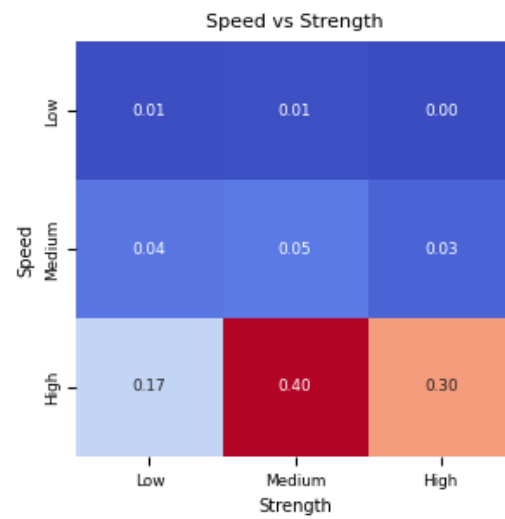
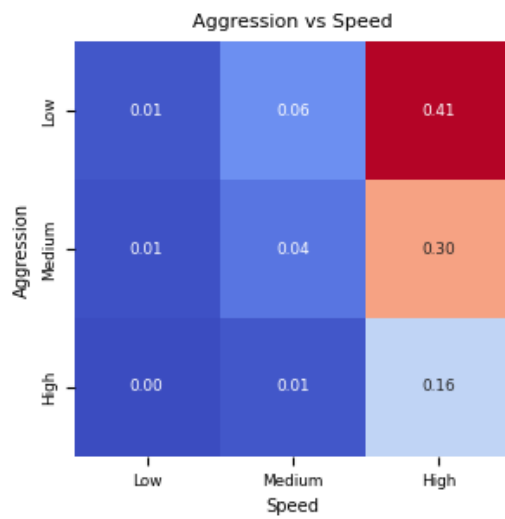
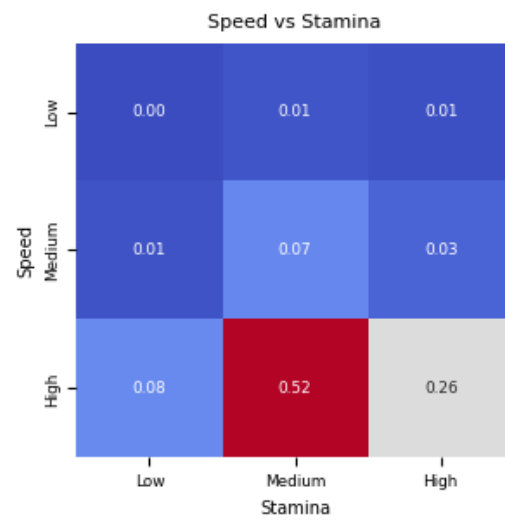
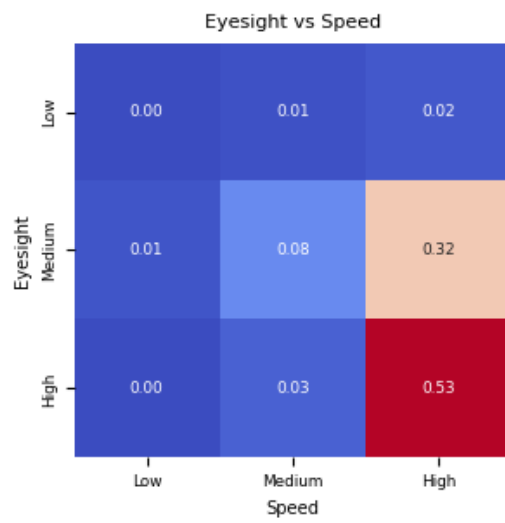
Simulation 6 - 3% Food, 5% Creatures



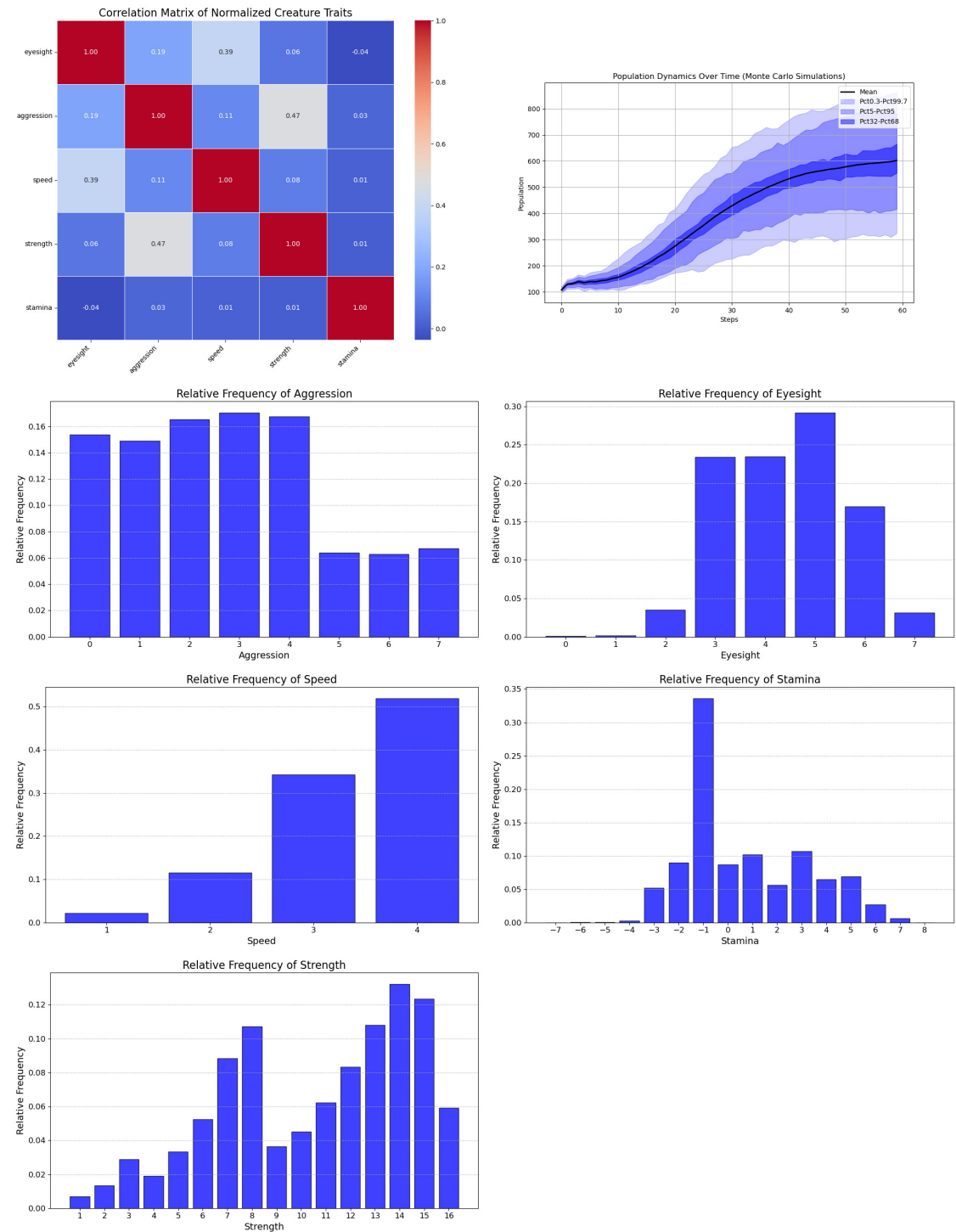


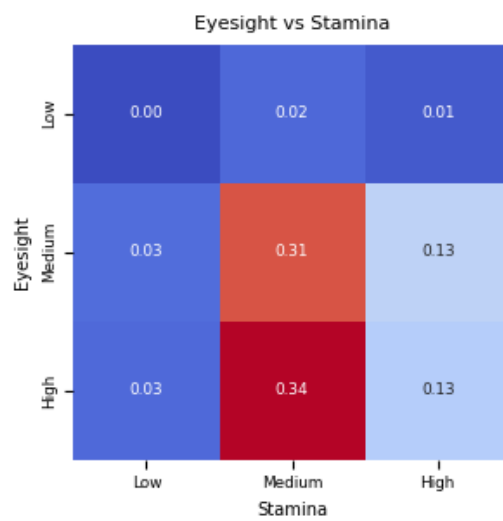
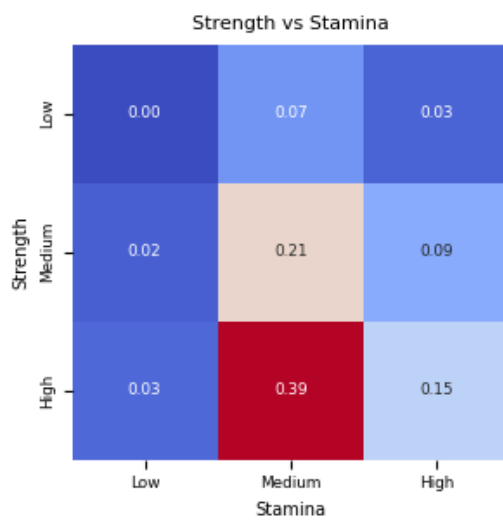
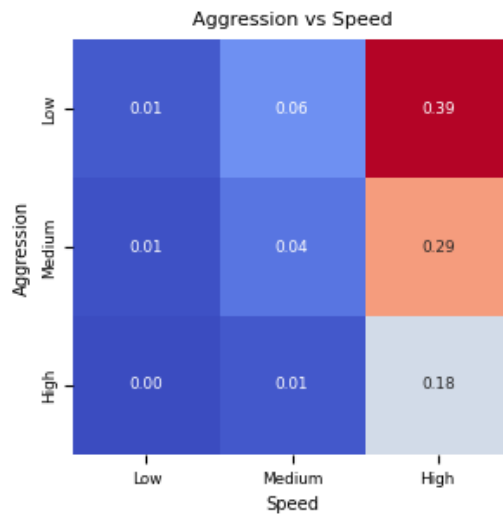
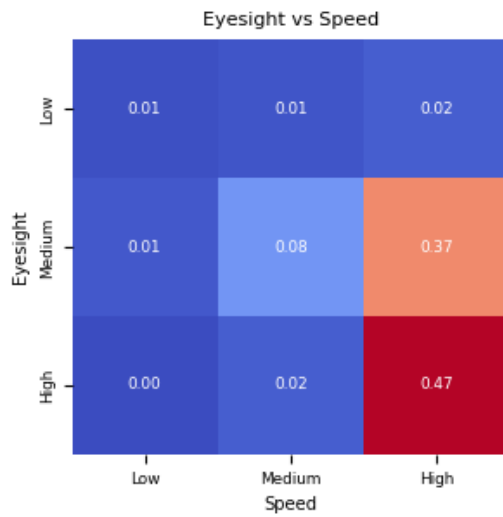
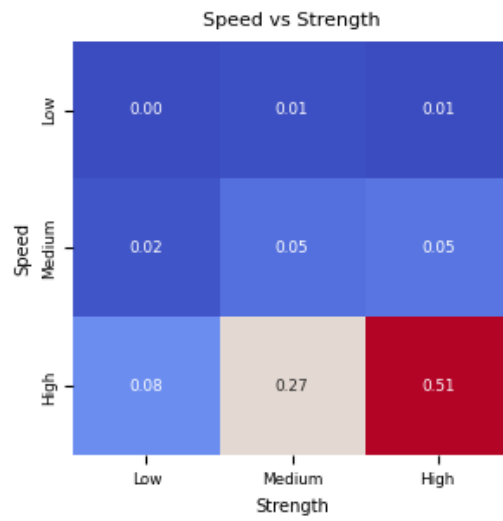
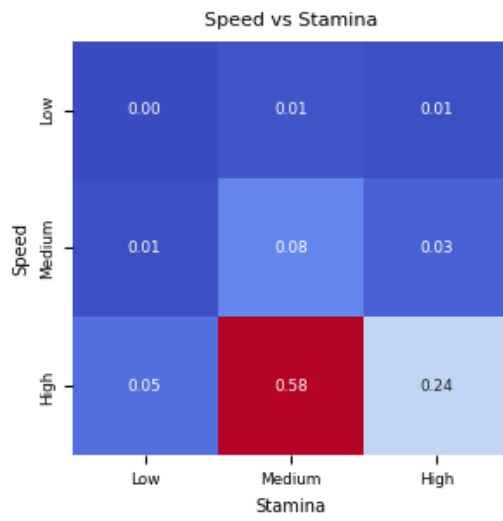
Simulation 7 - 5% Food, 1% Creatures



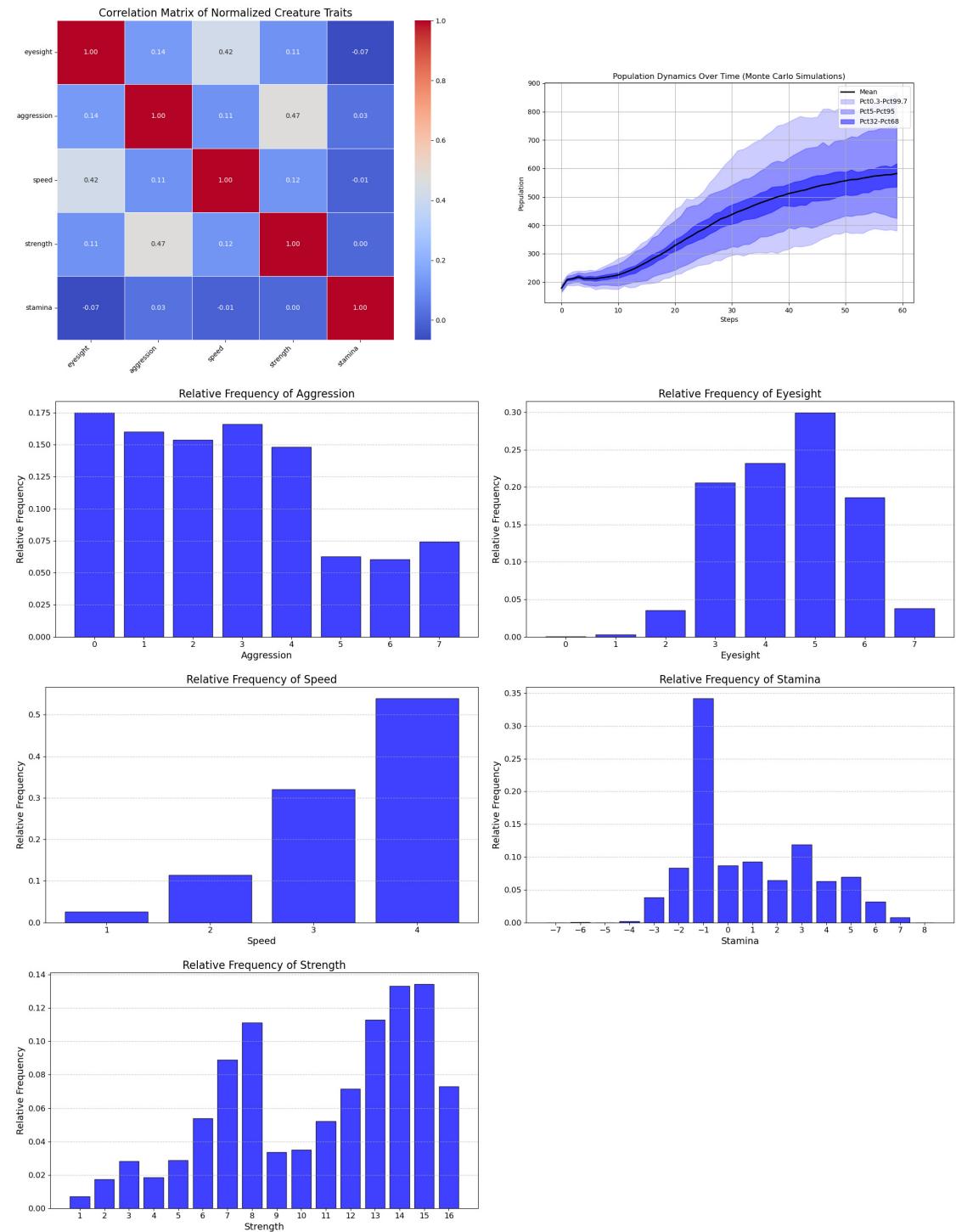


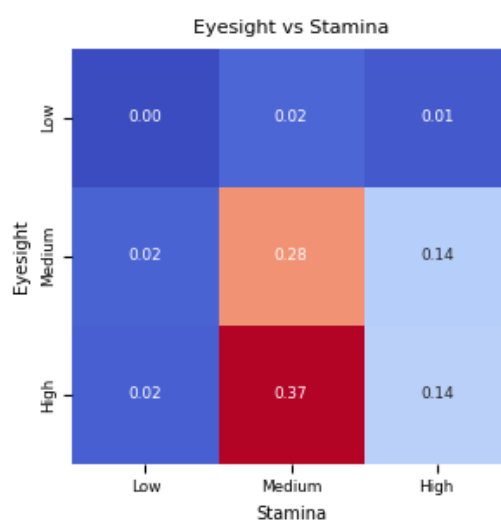
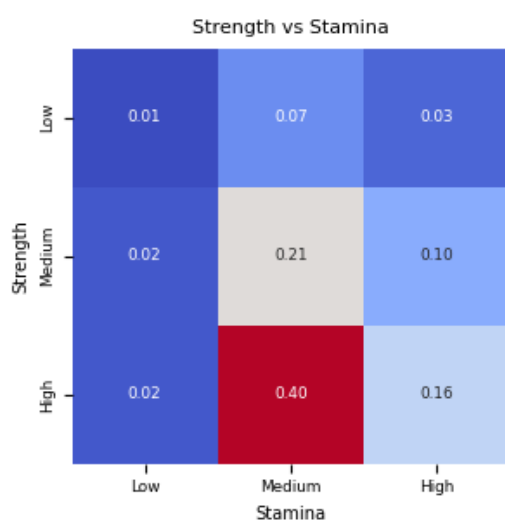
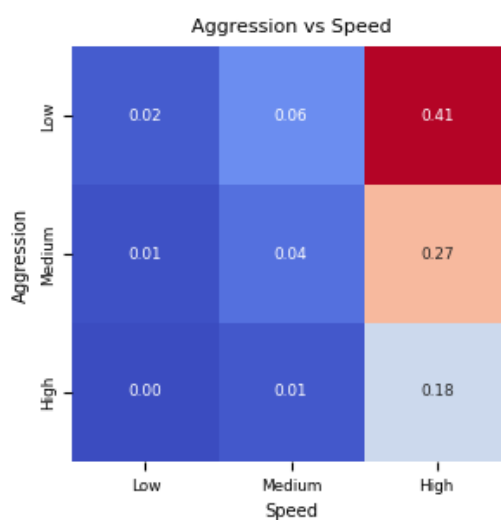
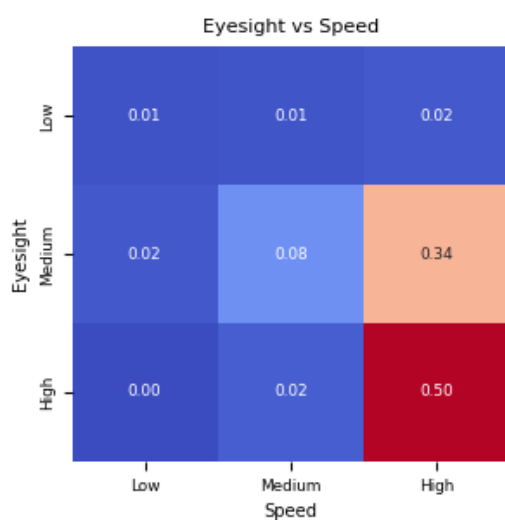
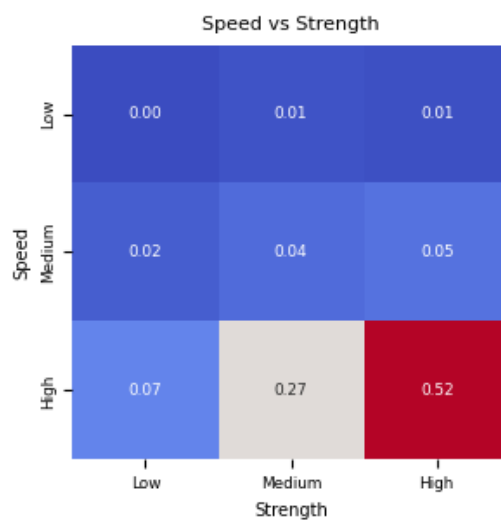
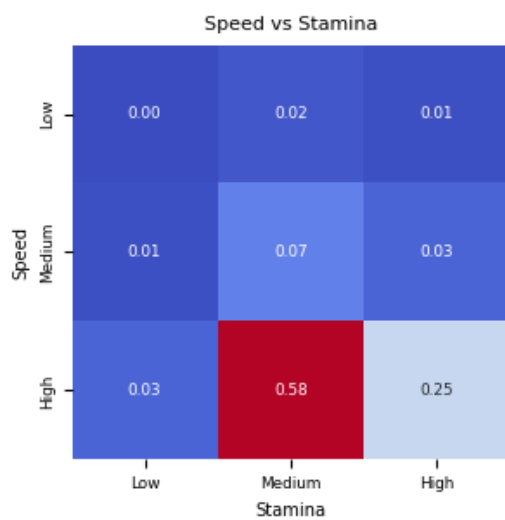
Simulation 8 - 5% Food, 3% Creatures



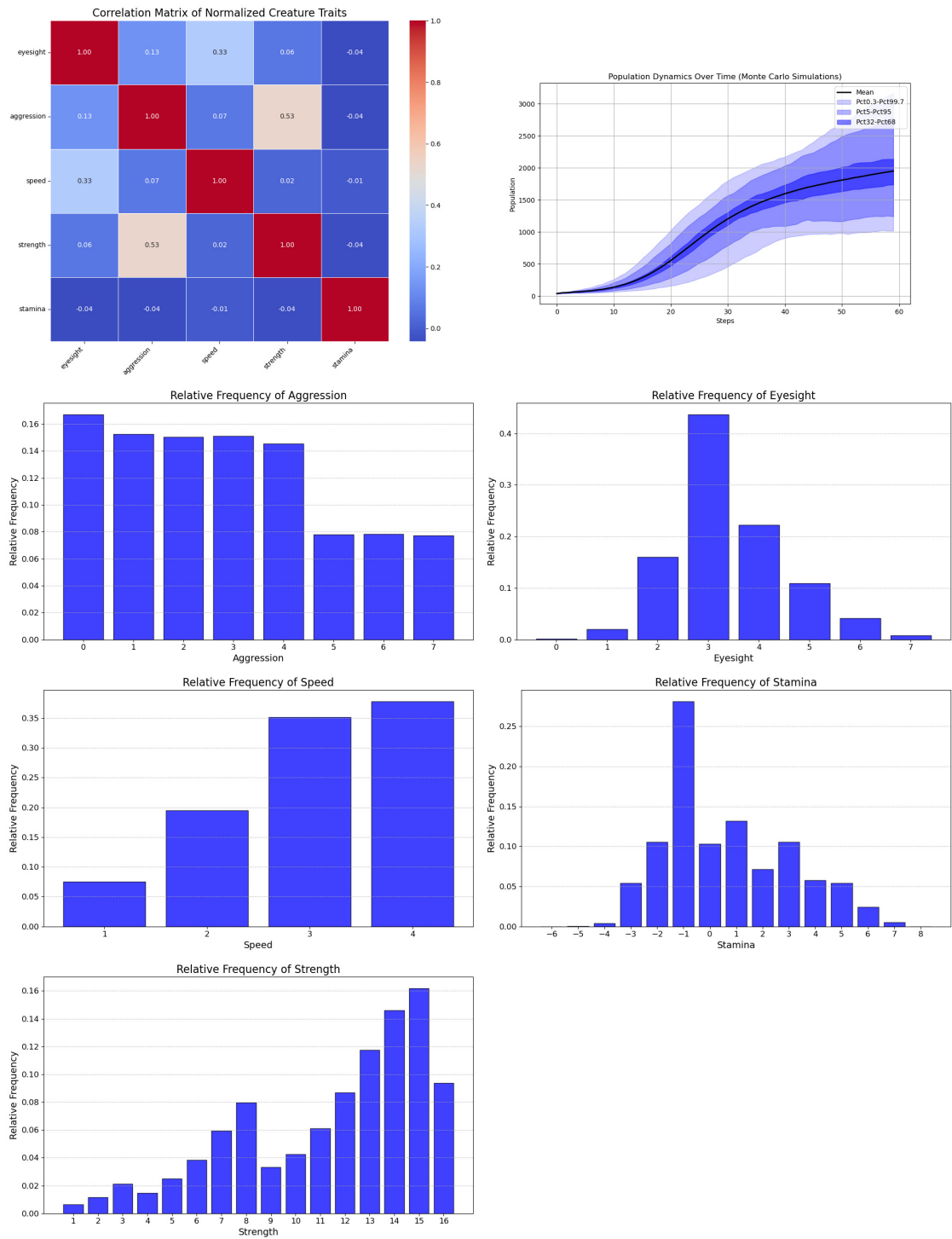


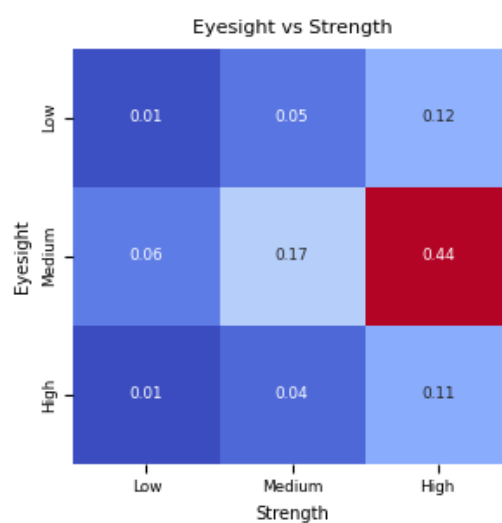
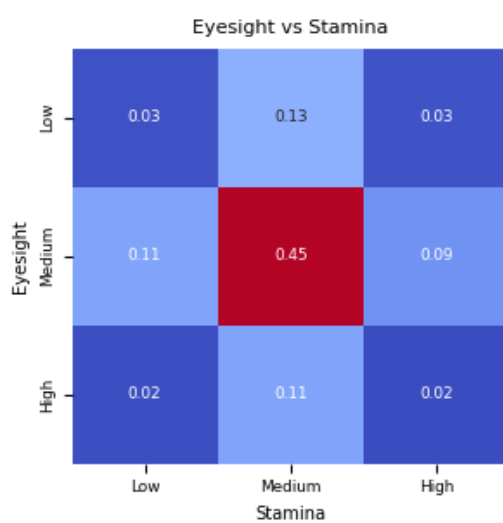
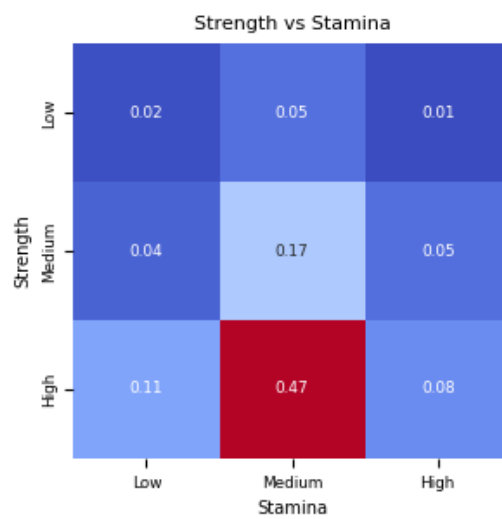
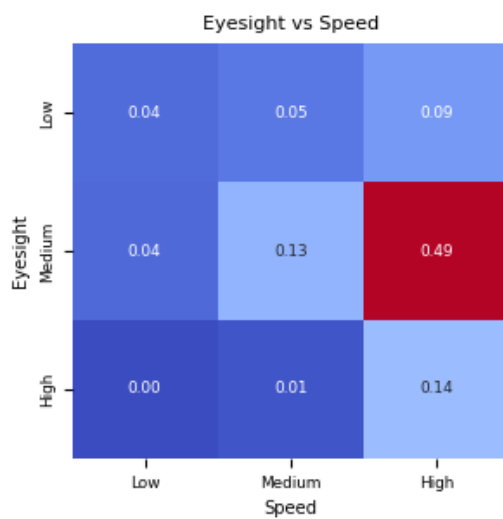
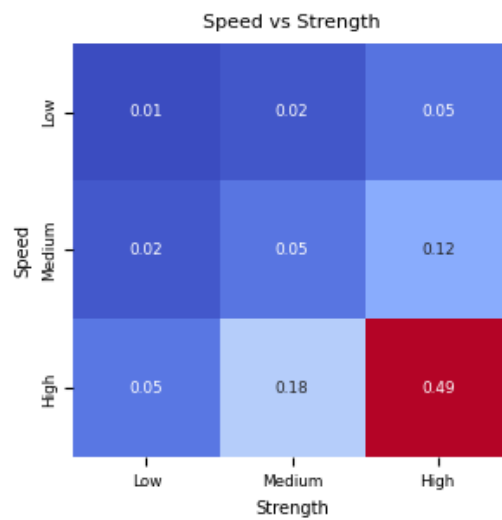
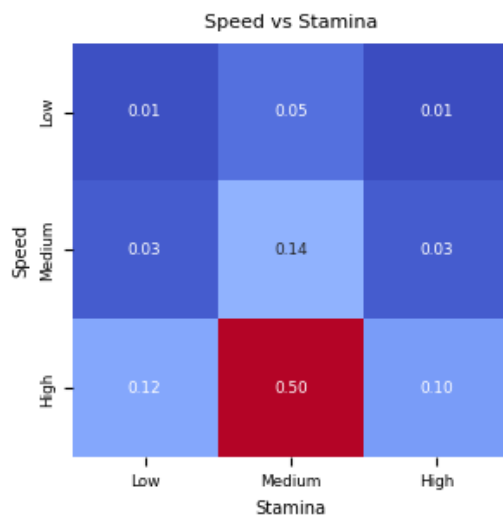
Simulation 9 - 5% Food, 5% Creatures





Simulation 10 - 10% Food, 1% Creatures





Observations

• Low Amount of Food

- The majority of simulations went extinct, while the surviving ones are on the verge of going extinct, with very low population sizes.
- There is a very strong (almost perfect) positive correlation between speed and eyesight. There is a strong positive correlation between stamina, eyesight and speed.
- Overall, the stamina of the populations is very low, where the lowest possible value for stamina is usually dominating. This results in creatures having practically no capacity of storing energy, which leaves only the most energy-saving creatures alive. That explains why the vast majority of the remaining population is blind, slow and very weak.
- There are outliers though, the ones which have a higher stamina and maintain a very high eyesight. The importance of eyesight for those who have the luxury to spend energy is very high, since the population is very low and only reliable source of energy becomes the food, which is also scarce, so eyesight becomes an essential skill to have in search for food. Same can be said about the speed. This is why the correlation between speed and eyesight is so strong.

• Medium Amount of Food

- The population size over time was stabilized at around an average of 200-250 creatures with high variance.
- The stamina values are much higher, which lets the creatures to spend energy, hence develop different traits.
- There is a weak positive correlation between speed and eyesight. Both of the traits are valued, since more than 70% of the population have both high speed and high eyesight.
- There is a moderate positive correlation between strength and aggression.
- Creatures with high speed and eyesight tend to have lower aggression and strength and vice versa. So, some creatures prefer to not fight and search food while others prefer fighting and getting their nutrition through strength. Additionally, there are more creatures which prefer the "runner" strategy than there are creatures which prefer the "fighter" strategy.

• High Amount of Food

- The average population size grows and eventually reaches 600 creatures.
- There is a moderate positive correlation between speed and eyesight. Likewise, there is a moderate positive correlation between strength and aggression.
- The same points made for the medium amount of food can be said here. The system is similar with the population size being bigger as there is more food generating, which is able to support a higher population. However there is a key difference, there are more creatures which prefer the "fighter" strategy. This can be seen by analyzing the average percentages for traits and correlations between the traits.

• Very High Amount of Food

- The population grows and averages out to 2000.
- The positive correlation between speed and eyesight is weakened, while the positive correlation between strength and aggression is rising. This shows that when the amount of food is not as high, it is more beneficial in general to be fast and search for food. However, as the food count rises, it is easier to find food nearby, and hence speed and eyesight become less important, while strength and aggression become essential. The population size is very large, and there is a lot of food nearby while also a lot of creatures which try to get the food, so it becomes optimal to be strong and fight one's way through.
- The stamina is mostly average for all creatures with small fluctuations. It appears that developing other traits was more important to creatures than improving the energy capacitance.

4.2 Other Environments

The study is to be continued on other environments as well, since the environments can affect how the population evolves. Some of those environments are, but are not limited to the following.

1. **Line** - all creatures live on a single axis and their location is described by a single number.
2. **Islands** - there are many islands which are interconnected with each other in some random fashion. Islands are of different size and have different food generation chances.
3. **Space** - a three dimensional environment where the position is described by three coordinates.

4.3 Future Development

The simulations above show how a species evolve in different starting conditions. However, there are many more conditions one can discuss.

1. Other starting genomes can be considered, for example a start where one trait dominates over the other four, or all the traits are as high as they can be.
2. The simulation code can be improved to reduce time complexity and allow for bigger simulations. The simulations above took hours if not days to execute and also limited the initial percentages one could take. For percentages such as 10 or above, the simulations took far too long.
3. Analysis and comparison of different results should be made when enough simulations are executed, trying to align the results to the real world.

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