The Effects of Temperature Fluctuation and Resource Generation Rates on the Population of Endothermic and Ectothermic Organisms (using MESA)

Matthew A. Ford

Department of Informatics, University of Sussex, BN1 9QH, UK

mf472@sussex.ac.uk

Abstract – This paper explores the link between resource generation, temperature fluctuation rates and the population of endothermic and ectothermic organisms. To gather the data, this study uses *MESA* to create an abstract agent-based "toy" model - loosely based on biological formulas - to simulate the two types of organism interacting within a single environment under the same outlined, changing environmental conditions.

The results given from this research give an indication to how resource generation is a limiting factor for total population, and how temperature fluctuation balances the reproduction of both organism types. The strengths and weaknesses for each will be outlined while the experiment lays the foundation for future development or biological models.

1. Introduction

The aim of this experiment is to explore the optimal resource generation and temperature fluctuation for both types of living organism. This is done as an abstract model, loosely based on true-to-life workings.

All organisms can be classified into two main types based on their methods of thermoregulation: ectothermic and endothermic. Ectotherms have low metabolic rates, and their body temperature shifts with the ambient temperature *(Geiser, F.)* meaning they heavily rely on the ambient temperature to function. This is different from endotherms as they have higher metabolic rates and can keep a constant temperature with their own internal heat production *(Geiser, F.).* Although this comes at a cost of requiring a higher energy intake.

The type of endotherms used in this experiment are hibernators, and during this period are efficient in reducing their energy consumption and this can reduce to around 5% of their normal rate. They also reproduce when the resources are abundant *(Geiser, F).* This is something that will also be assumed for ectotherms.

Ectotherms are sensitive to the effects of ambient temperature; it is often that they have an optimum temperature and a critical thermal minimum which is the point where the ectotherm becomes begin to lose function and eventually become dormant *(E. Taylor, et al)*. This helps them preserve energy.

To experiment with these organisms in a shared environment, agent-based modelling (ABM) in MESA is used. This is due to it providing a versatile framework for building, analysing and visualising agent-based models *(D. Masad, J. Kazil).*

ABM is a method that is increasingly becoming more commonly used in ecology to study species relationships and population dynamics *(A. McLane, et al).* Agent objects have defined states and rules of behaviour *(Axtell, R)* meaning that each organism could have its own methods of energy consumption, and movement as well as its response to colder climates. Having multiple types of agents makes this model a multi-agent system (MAS). These systems are reliant on a bottom-up approach where modelling agents’ behaviours allow properties to emerge that are observed at a system level *(F. Bousquet, C. Le Page).*

The model created in this experiment can be described as a ‘toy’ artificial life model. It starts to implement some of the features defined for a definition of life *(P. Macklem, A. Seely).* These being:

- Self-regulation: As the endothermic organisms have a state of thermoregulation, this means that they maintain a constant internal environment.
- Self-contained: each agent is well defined.

To add, each agent has a metabolism and reproductive capabilities.

For energy consumption and body temperature, some biological formulas are used. Although, other parts of the model are abstractions and only roughly based upon biological workings. Klieber’s Law is one of the formulas used to determine the basal metabolic rate (BMR) of varied sizes of organism. This formula indicates that the BMR increases as the mass to the power of ¾ *(K. Niklas).* This formula can be shown in *figure 1.1.*

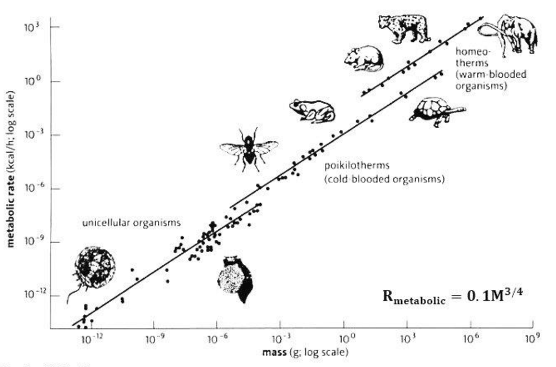

Figure 1.1: A graph showing Klieber's Law applying to mammals of increasing mass. https://universe-review.ca/R10-35-metabolic.htm

Another formula used is Newtons law of cooling. This describes heat loss as a function of temperature and the difference between the body and ambient temperatures *(R. Henshaw).* Although, as mentioned, this model is abstract and therefore a simplified version was used, multiplying the temperature difference with a cooling constant which is derived from the body mass and fat percentage (insulation).

But as an abstract model, there are assumptions made such as that the organisms do not adapt over time, and that temperature follows a sinusoidal function.

Most features in this model have an element of randomness, most notably in the temperature changes, resource generation, reproduction, and lifespans of agents. Therefore, adding this level of randomness makes the system to become stochastic which loosely mimics real life.

Limiting both types of organism is the resource availability. Due to there being a shared set of regenerating resources, it means that there is competition between the organisms and adds to the stochastic nature of the system. Making this the limiting factor is the energy reserves. If organisms need resources to survive, this allows for deaths by starvation, and reproduction opportunities to be related to the resources themselves *(R. Sibly, et al).*

Organisms traversing the grid is built off a directed random walk that is driven by a stochastic process constrained by probabilities for moving in certain directions *(W. Tang, D. Bennett).* Depending on the ambient temperature and resource amount the organisms will have different tasks, and their movement will be in response to these short-term goals *(A. McLane, et al).* For this experiment, an organism is considered dead when all energy reserves have been depleted.

Logical rules are used to control the agent's behaviour. This is because having rules can be a natural way to model individual agent's behaviour and any other processes. *(V. Grimm, S. Railsback).* As this specific system is simpler to that of one that can adapt to account for the scope of this report, logical modelling is the most appropriate solution. Although this comes at a slight disadvantage as variation in process outcomes is not captured by this approach *(V. Grimm, et al).*

Throughout this experiment, the focus is on the temperature fluctuation and resource generation rate and how this affects the system. The hypothesis for this is, that if the temperature fluctuates quickly, this will have a strong effect on the population of endotherms and possibly make them go extinct quicker. For the resource generation, the higher it is, the more likely that the overall population will inflate, and both populations will be sustained for a longer period but ultimately one organism type will prevail in the competition for resource.

Through this experiment, the dynamics of endothermic and ectothermic organisms can be understood. With current shifts in global temperatures and resources suffering as a result, this experiment hopes to put a light on the matter of how these changes may impact these groups and uncover if this impact is disproportionate. Another main goal for this experiment is to identify a stable point where both types of organism co-exist, and their populations are sustained.

The way these will be addressed is through a parameter sweep on an ABM over varied values of temperature fluctuation to show the effect on the different types of organism, and resource generation rate to evaluate how the competition changes the population dynamics.

By comparing these results and creating different visualisations, any patterns that emerge can be identified for the organisms when looked at singularly and when comparing them against each other.

2. Methods

MESA has two main components: agents, and models. The agents are the entities that can interact with each other and the environment. The model is the environment in which the agents can move around and interact within. The model has a grid which stores the position of agents, and in this case, this is a multi-grid, allowing agents to be contained in the same grid space. Also, the model has a schedule which stores all the active agents and calls their step functions when the model step is called.

To create both types of agents, it was decided that the best approach was to have a parent class to contain all the attributes and methods that are shared by both the endothermic and ectothermic organisms.

The environment itself is a single class. This class has a random activation function which causes the update of agents to be done in a random order every step. This eliminates any advantages to any agents by always stepping first and for this example, gathering resources first.

2.1 Organism

This class contains the main attributes stored by each type of organism, including remaining life, mass, fat percentage, energy reserve, body temperature and a list of resources.

One of the first methods shared by both organisms is their movement. Both have a state of 'resource gathering' in which they take a random directed walk until they are in the 'smelling' or 'sight' distance.

The directed walk gives agents a heading in which they will continue to move in until they come near a resource or turn by a random chance. As they enter the range of a resource, the probability that they will keep moving towards it grows the closer they get until they are placed next to it and the resource is ‘collected’. All distances and movement probabilities are done so with a Moore neighbourhood as shown in *figure 2.1.*

0.0	0.05	0.05
0.05	o	0.75
0.0	0.05	0.05

Figure 2.1: An example of the probabilities an agent will move in each direction using a Moore neighbourhood.

As both types of organism’s body temperatures are cooled when the ambient temperature decreases, the second method shared handles this using a simplified version of “Newton’s Law of Cooling” which was mentioned earlier *(R. Henshaw):*

$$\frac{dT}{dt} = -k(T_B - T_A) \qquad [1]$$

The amount that the organisms body temperature will decrease at any given step is decided using the difference of the current body temperature, T_B, to the ambient temperature, T_A, and then multiplied by a cooling constant, k.

To determine the value of k, it was decided to consider the mass of the organism as well as the fat percentage as this would naturally act as insulation to slow cooling. Therefore:

$$k = 1 - \frac{fatPercentage}{mass} \qquad [2]$$

The other way that both organisms consume energy is through their BMR. As according to Kleiber’s law *(K. Niklas)*:

$$BMR = m^{0.75} \qquad [3]$$

Meaning that the BMR is a function of the organism’s mass, m. As all organisms are similar in this experiment, a constant multiplier was deemed unnecessary.

BMR is for organisms that are stationary. When moving, there is a small multiplier for active basal metabolic rate (ABMR), which in this experiment is:

$$ABMR = m^{0.75} * (1 + \frac{mass}{100}) \qquad [4]$$

In the system design, this is handled through a single method which allows for it to be specified if the agent is moving as well as taking a multiplier for the change in BMR as the different organisms react to the colder ambient temperatures. These multipliers will be discussed in each of their respective sections.

As organisms need to have a lifespan and cannot be immortal, every step one day is taken from the agent’s remaining life. To make it fair between the agents, and to add some randomness, the lifespan of an agent (decided at birth) is:

$$lifespan = (365 * 6) + random(1{,}100) \qquad [5]$$

This therefore means that the agent will live for 6 ‘years’ - where a step is equal to a day - plus a random amount between 1 and 100.

Finally, the methods shared to manage resources are to collect any nearby resources, maintain the list (removing any ‘rotted’ ones), and to consume a resource, increasing the organism’s energy reserve by 4,000.

2.1.1 Endothermic Organism

The main addition to an endothermic organism is its need for thermoregulation. For this experiment, it is ensured that the endotherms body temperature remains in the range of 36°C - 40°C. To calculate the energy required to cool the body temperature, C_E, into the correct range, the following formulas are used:

$$C_E = \begin{cases} T_B - 38.0, & if\ T_B > 38.0 \\ 36.0 - T_B, & if\ T_B < 36.0 \\ 0, & otherwise. \end{cases} \quad [6]$$

As seen in *figure 2.2*, the flow diagram for the different motions of the endothermic organism has a simple structure. This alternates between resource gathering (as a primary state), random directed walking when the organism cannot carry any more resources, and finding a habitat when the ambient temperature drops below 2°C.

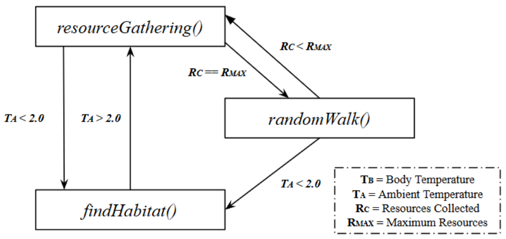

Figure 2.2: A flow diagram showing the different movement methods of the endothermic organism, along with the conditions that must apply for each.

The method for finding a habitat method works mostly the same as the resource gathering, but instead an agent can sense the general direction of a habitat, and from further away. This was a choice that was made to prevent too many habitats being in a single area as the other method is for the organism is to create its own habitat in its current position, using up 5 resources. This method is also subject to randomness as there is a 50% chance that the habitat will be created or that the agent will carry on walking to find one that has space available.

Once the agent does find a habitat with available space, and it is in the direct radius, the endotherm can enter the habitat. Doing so adds the agent to the list of occupants in the habitat, removes the organism from the grid, and adds all the resources into one shared 'pool'. Here, they will hibernate until the ambient temperature warms up again.

As referenced earlier, during hibernation, the organism's BMR is reduced to 5% of its standard BMR *(Geiser F)*.

2.1.2 Ectothermic Organism

Unlike the endotherms, the ectothermic organisms do not require a habitat as they a do not hibernate for but instead go into a state of brumation.

To determine how many steps must pass before the organism moves once, S_M, the body temperature, T_B, must be considered.

$$S_M = \begin{cases} \infty, & if\ T_B < 2.0 \\ 5, & if\ T_B < 5.0 \\ 3, & if\ T_B < 9.0 \\ 1, & otherwise. \end{cases} \quad [7]$$

As the body temperature of ectotherms affect their function, when the temperature drops below the critical thermal minimum *(E. Taylor et al)* of 2°C, the agent will not move but instead enter a state of dormancy, consuming $\frac{1}{4}BMR$.

This multiplier increases by a quarter for each subsequent value of S_M until the value is back to 1.

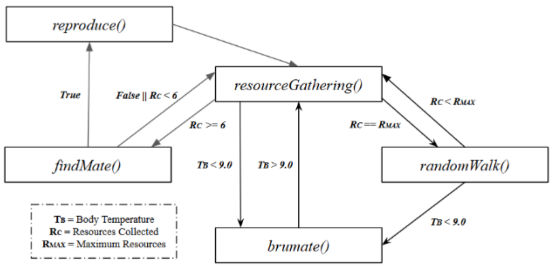

Figure 2.3: A flow diagram showing the different movement methods of the ectothermic organism, along with the conditions that must apply for each.

Figure 2.3 shows the flow diagram of an ectotherm in this experiment. As seen, this is more complex than the endotherm as reproduction is handled in its own class instead of being controlled in a habitat.

For ectotherms to reproduce in this model, they must find a mate and have more than 6 resources between them. If there are any potential mates within the given radius, the agent will move towards the closest one in a similar manner to the directed walk.

To limit agents constantly reproducing, each one stores the last step that they reproduced. For ectotherms, if:

$$Step_{current} \geq Step_{lastRepoduction} + 200$$
$$AND$$
$$T_A > 15.0$$

Then the agent is allowed to reproduce again. Once the agent is close enough the reproduction method is used. This involves creating a child in the same square, with a random mass in the range of the two parent's mass, following a form of blended inheritance. Then, the two resources required to reproduce are consumed.

2.2 Other Agents

The other agents in the system include resources and habitats. These are static agents and are for the organisms to interact with and use. Therefore, they have a simple set of variables and limited methods.

2.2.1 Habitats

Habitats are created with a lifespan in the range of 1200 to 2500 steps. They also have a capacity between 3 and 15, a list of occupants, and a list of the shared resources that all the occupants can consume. For the endotherms in hibernation, the habitat controls the reproduction by selecting all possible parents from the occupant list that can reproduce. This is determined by:

$$Step_{current} \geq Step_{lastRepoduction} + 500$$

Then, given the random number is lower than the birthrate, a child can be created, from two random parents in the list, and resources consumed. Like the ectothermic children, the endothermic child's mass is set randomly in a range between that of the parents.

Each step, the habitat lifespan is decreased by 1, and the resources are maintained to allow occupants to consume them if their energy store is running low and if there are any available.

2.2.2 Resources

Each resource has a random lifespan between 200 and 800 steps. This is to simulate the resources rotting and by having a large range for the randomness allows for more unpredictability. To add, the resources also have a Boolean variable to mark them as collected once done so by an agent. This removes them from the grid and adds them to the agent's list of resources.

Again, each step the resource lifespan is decreased, and upon reaching 0, is removed from the schedule.

2.3 Environment

The environment class is the grid where the agents are placed and interact. This class is also responsible for storing any data produced during experimentation. On creation, an environment takes the inputs for the starting number of ectotherms, endotherms, habitats and resources as well as the resource generation rate, minimum and maximum temperature, fluctuation speed, and birthrate.

The resource generation rate determines how fast the resources replenish, and the temperature fluctuation determines how quickly the temperature moves between its minimum and maximum (the higher the number the slower the change). Birthrate is a float between 0 and 1 and is used in reproduction to determine a successful birth.

The variables of the environment include the current and average ambient temperature, the base and current resource generation rate, a counter enum, a resource pool counter, a step counter, and a data dictionary.

The counter enum includes a state for each agent. As an agent is added to the grid, the number corresponding to the agent's type is incremented by 1, and de-incremented when an agent is removed.

The agent type is also determined by an enum with a state for each class. This is used in the method for creating agents to specify the desired agent to be created along with the amount. From here, the agent is created, the respective counter incremented, and the agent added to the schedule and grid. Organisms (not including children) are all created at the same position in the grid when the experiment starts. For resources and initial habitats, a random, empty grid position is chosen, and the agent is created in that given space.

To fluctuate the ambient temperature, for simplicity it was decided to use a sinusoidal function where T_{fluc} is the temperature fluctuation, and F_{speed} is the fluctuation speed.

$$T_{fluc} = \sin\left(\frac{2\pi}{365 * F_{speed}} * (Step_{current} - (365 * F_{speed} * (Step_{current} \bmod (365 * F_{speed})))) \right) \quad [8]$$

This allows the formula to be based on a sine wave that is scaled by the fluctuation rate over the course of 365 steps (1 year). From here the temperature range, T_{range}, is calculated from the difference between the minimum and maximum temperature, and the fluctuation normal is calculated as:

$$F_{norm} = \frac{T_{fluc}+1}{2} \quad [9]$$

Using these values, the new temperature can then be calculated to be:

$$T_{new} = F_{norm} * T_{range} - 5 \quad [10]$$

To add some noise to the fluctuation, a random value between -0.5 and 0.5 is added.

The resource generation rate changes due to the ambient temperature, making resource generation less effective in the winter and summer climates. The new resource generation rate, R_G, is calculated as:

$$R_G = R_{base} * e^{-\frac{(T_A-20)^2}{800}} \quad [11]$$

Where R_{base} is the initial resource generation rate and T_A is the current ambient temperature. The peak temperature for resource generation is 20°C, and using this formula makes the resource generation rate decrease exponentially from that point. Having a denominator of 800 ensures that the decay is not too fast, widening the optimal resource generation window.

Every step, both the temperature and resource generation are updates, and the current resource generation rate is added to the resource pool along with a random value between 0 and 1. When this value goes above 1, the respective number of resources are created until the value in the pool is back below 1.

3. Results and Analysis

This section discusses the results of the parameter sweep. First giving a general overview of the effects on each organism's population and then analysing the best and worst points, discussing the possible reasons behind them and seeing if at any point there any signs of stability between the two populations.

Figure 3.1 shows how the temperature fluctuation and resource generation affect the average of both populations.

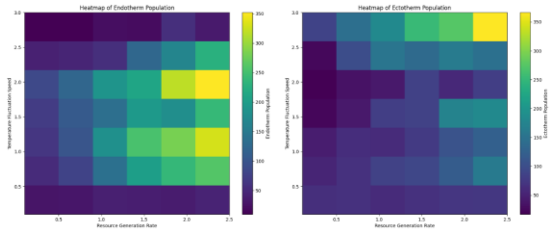

*Figure 3.1: Heatmaps of Average Endothermic **(Left)** and Ectothermic **(Right)** Populations as Temperature Fluctuation and Resource Generation Rates Change.*

From the results given, it can be seen that the resource generation rate is important for the average population of both organisms to grow. This is due to there being a clear gradient along the x-axis. As the resource generation increases, the average population grows and therefore both classes reach the highest average population when resources are abundant. This dependence on resource generation shows the importance of resource availability for a population to grow and either co-exist or thrive over the other.

For the temperature fluctuation, the two organism have slightly different preferences. As seen, the endotherms have a higher population when the fluctuation is slower by a factor of 2 whereas the ectotherms have a higher population at a factor of 3.

3.1 Endothermic Population

As stated before, the heatmap shows that the highest average population for endothermic organisms is where the resource generation is at 2.5, and the fluctuation speed is slowed by a factor of 2.0.

Figure 3.2 graphs the results for this specific run.

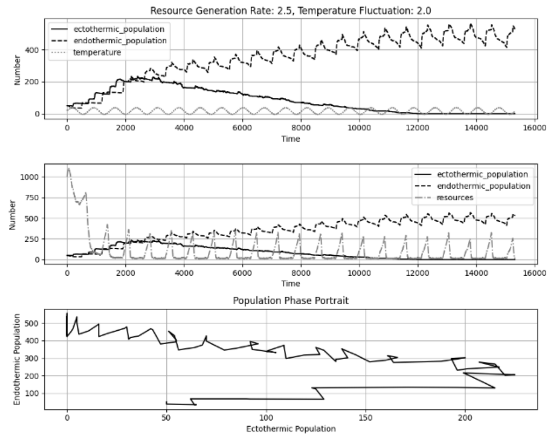

*Figure 3.2: Results of running the model with a 2.5 resource generation rate and a 2.0 temperature fluctuation. From top to bottom: **1)** Both populations compared to temperature. **2)** Both populations compared to the available resources. **3)** A phase portrait comparing both populations.*

As seen from the top-most and centre graphs, both populations rise in a stable manner while the resources are in abundance. This is due to there being little to no competition for resources between the classes initially, but as the model progresses the population shows that the endothermic organisms become more dominant and therefore starts to neglect the ectotherms of resources making them unable to reproduce.

The last graph shows the phase portrait between the two classes over time, and as seen in *figure 3.3*, most of the phase portraits follow the same structure of 'stepping' up as both populations grow before one population collapses and the portrait has a noisy decent in one direction.

This decent mostly takes a form of a chaotic spiral, where there are births, and deaths happening for both types, but one type is having a population decline.

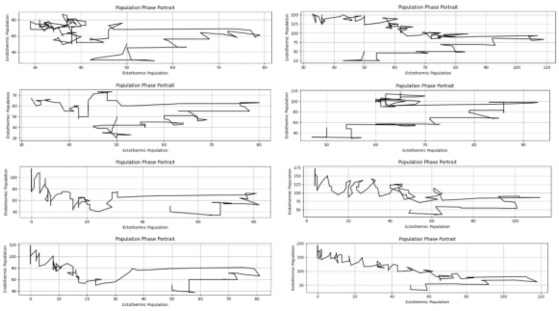

Figure 3.3: Different phase portraits generated showing a general pattern.

Going back to *figure 3.1*, the lowest average population occurs when the temperature fluctuation is slow (a factor of 3), and the resource generation is low (0.1). The results are shown *in figure 3.4*.

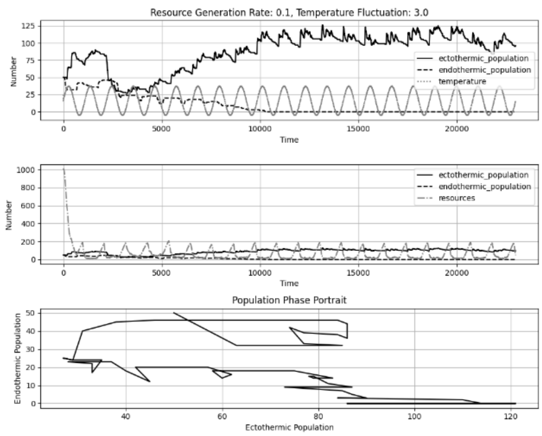

Figure 3.4: Results of running the model with a 0.1 resource generation rate and a 3.0 temperature fluctuation. From top to bottom: 1) Both populations compared to temperature. 2) Both populations compared to the available resources. 3) A phase portrait comparing both populations.

As seen here, the population for endotherms is massively supressed by the large surge in the ectothermic population at the beginning. This therefore causes the resource competition to lean towards the ectotherms and then as a result, the endotherms die out sooner, therefore reducing the average for the run. As this is a resource-based issue, it again supports the fact that resource generation is important for the survival of both populations as in the centre graph, there were only a small number of resources to just about match the total population, but not enough for each type or organism to have them in abundance and therefore a big jump in one organism type supresses the other's ability to reproduce.

3.2 Ectothermic Population

As discussed, in the right side heatmap of *figure 3.1*, the highest average population of ectothermic organisms is when the resource generation is at its highest (2.5), and the temperature fluctuation is at its slowest (3.0).

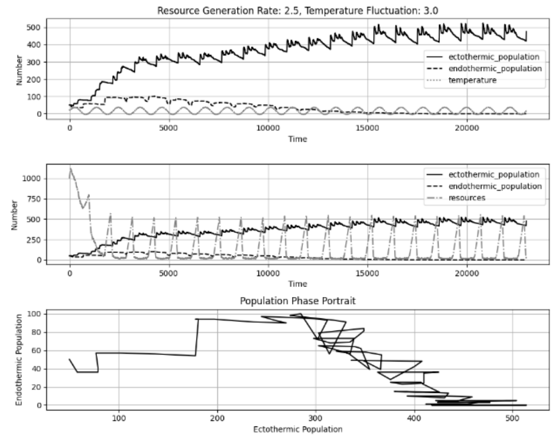

Figure 2.5: Results of running the model with a 2.5 resource generation rate and a 3.0 temperature fluctuation. From top to bottom: 1) Both populations compared to temperature. 2) Both populations compared to the available resources. 3) A phase portrait comparing both populations.

In the results shown in *figure 3.5*, the first graph shows the population of ectothermic organism growing consistently and mimicking the peaks and troughs of the temperature fluctuation. This is due to ectotherms only reproducing when the temperature is above 15ºC, and therefore the height of their reproduction would lie in the warmer climates. In the second graph, it shows there being a consistent abundance of resources and the population works towards the peak of these resources therefore making this the limiting factor. Due to the rapid increase in the early steps for the ectotherms, this meant that there became a class imbalance and therefore they started to suppress the endotherm population.

The phase portrait again shows a similar shape, with a 'step' like structure as both populations reproduce in different temperature ranges. This is then followed by a chaotic spiral downwards as deaths start to occur for both types and the suppression starts to show.

The lowest average population for the ectothermic organisms seems to be when the temperature fluctuation is 2.0, and the resource generation is 0.1.

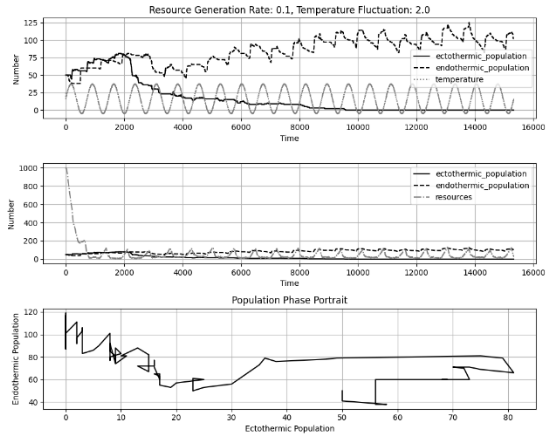

Figure 3.6: Results of running the model with a 0.1 resource generation rate and a 2.0 temperature fluctuation. From top to bottom: 1) Both populations compared to temperature. 2) Both populations compared to the available resources. 3) A phase portrait comparing both populations.

As seen in *figure 3.6*, both populations seem to be growing at a similar rate to begin. This is then followed by a dramatic decrease in the ectothermic population. One reason that this may have happened is that from the initial starting positions, the endotherms collected more resources than the ectotherms and therefore when it came to reproducing, they could both do so to an extent, but the endotherms had more resources to survive after using some for reproduction. Therefore, it would also be reasonable to assume that the population is somewhat based on luck, as its down to what agents choose the best starting directions to head, and whether that agent gets to resources before another. This is something that could be fixed about the model by adding adaptive behaviour and will be explored further in the discussion.

3.3 The Search for Stability

Through analysing the results, it was a main goal to find any that may show signs of stability. This led to two possible candidates.

These can be seen in *figure 3.7* which outlines them on both heatmaps.

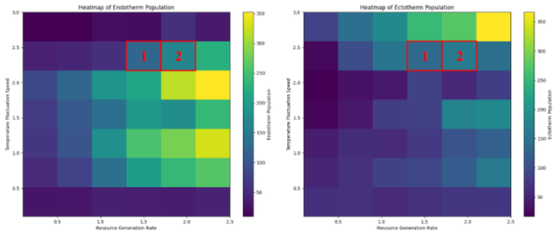

Figure 3.7: The heatmaps of both populations with the two candidates for stability outlined.

The candidates seen were identified due to them both having very similar (if not the same) average populations. The main trends that would support the observation of a system being stable would to be alternating waves between the populations, and a phase portrait that shows signs of an inwards spiral.

Finding the point where both populations are alive and co-existing together will show the optimum values for both temperature fluctuation and resource generation. As both candidates share the same fluctuation factor, this means that this is already the optimal for both classes. This is supported by the heat maps as it is the only fluctuation value between both type's optimums.
Figure 3.8 shows the first candidate. As see, the populations in the first graph do follow an alternating wave pattern. This is the first sign of stability in the system as it shows that neither type of organism is supressing the other disproportionately.

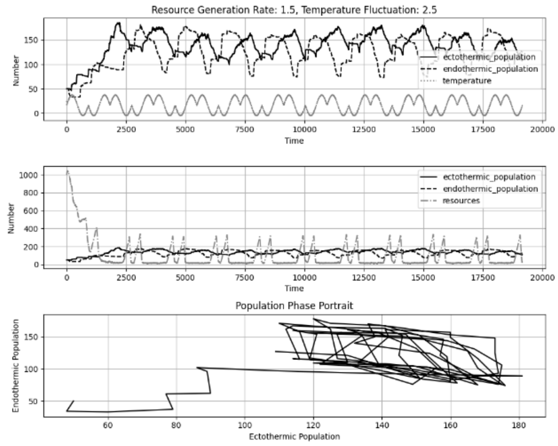

Figure 3.8: Results of running the model with a 1.5 resource generation rate and a 2.5 temperature fluctuation. From top to bottom: 1) Both populations compared to temperature. 2) Both populations compared to the available resources. 3) A phase portrait comparing both populations.

The phase portrait for the populations in this case shows the regular stepping pattern before entering a spiral. Although seemingly chaotic, it would appear that the spiral does not get larger per loop but instead just shifts in direction. This concentrated spiral pattern is a very common sign of stability between both the populations as they start to converge on a single value. Although this could still be improved.

Figure 3.9 shows the second candidate. Again, this follows a similar pattern as seen in *figure 3.8* with an alternating wave. This time however, the phase portrait seems to have a much tighter spiral and does not seem to shift as much. Therefore, it would be reasonable to suggest that this candidate is more stable than the last.

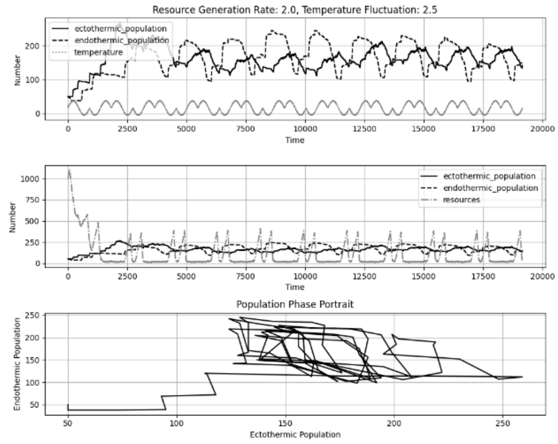

Figure 3.9: Results of running the model with a 2.0 resource generation rate and a 2.5 temperature fluctuation. From top to bottom: 1) Both populations compared to temperature. 2) Both populations compared to the available resources. 3) A phase portrait comparing both populations.

3.4 Analysis of Results

Given all the data provided in the experiment, the resource generation rate is the most vital part of population growth and survival for both types of organism.

As seen in the total population of both organisms always moves towards the highest point of the resources available.

This can be represented as:

$$P_{Endo} + P_{Ecto} \leq R_{peak}$$

As long as the peak value of the resources, R_{peak}, is found after the initial resources have been depleted.

Regarding the temperature fluctuation, the most optimal value for both classes is when the factor is higher (fluctuation is slower). This is likely because having too quick of a temperature fluctuation does not allow the organisms enough time to find mates or a habitat and try to reproduce. Adding in the factor of birthrate also makes it so it can take longer for some to reproduce.

With stability, this model's results have shown that there is a very strong competition for resources that may also be determined by an element of luck. But in the cases where the system seemed to start stabilising, it was when the resources were generating fast, and where the temperature fluctuation was between the boundary of not too slow and not too fast.

The reason for the temperature fluctuation is that if it was too slow, one type of organism may have more time to reproduce than the other, causing an imbalance. But at $T_{fluc} = 2.5$, it seems that the reproductive windows become even.

Again, the system has a luck element as resources spawn in random locations. This means that resources may spawn near more ectotherms than endotherms and therefore cause instability, and lead to suppression. This suppression can notably be seen in the heatmaps as where one class has a high average, the other will be low. This is why the stability comes when there is a population balance.

4. Discussion

To conclude this experiment, the results shown have shown that the resource generation is the most important factor for the survival of endothermic and ectothermic organisms and that the population is limited by this. It also shows that having an unpredictable and fast temperature change is in no way beneficial for either organism type. To have a system of a sustainable nature, the fluctuation should be relatively slow, and the resource generation should be high enough to provide excess for reproduction as this is dependent on resources *(R. Sibly)*. If either of these are too high, or too low, the system becomes imbalanced and leads to the suppression and extinction of one organism's population. The overall conclusion from these results shows that the optimal solution for both types of organism lies where the temperature fluctuation is 2.5, and the resource generation rate is somewhere between 1.5 and 2.0.

In terms of artificial life, this experiment starts to explore how a working ecosystem can be modelled, and specific types of organism studied within these differing environments.

The current implemented system performed well for the given data and task. But there could have been some improvements such as the optimisation of energy consumption between classes, and mass having more of an effect on the organism in terms of insulation and movement speed. The main limitations to the system were that it was logic-based where variation cannot be assessed *(V. Grimm, et al)*. Having this lack of adaptability stops the model from properly settling on a clearly defined attractor. If the model included more true-to-life features such as agent adaptation, environmental conditions, and direct organism-organism interaction (e.g. fighting, sharing and stealing) this may have helped with getting results that are perhaps more realistic, but then that also puts the model's integrity at risk as it gets closer to the boundary between artificial life and biological modelling. Also, the system had an element of luck. Although not inherently bad, this made it so it was a random chance that one type would gather more resources initially instead of being based on attribute strengths.

Compared to the original hypothesis, the results given do not necessarily support them as the fast temperature fluctuations ended up having an adversely negative effect on both populations. Although, the results do support the fact that resource generation inflates the overall population, the average populations were always highest when the resources generated quickly.

In terms of one organism always ultimately prevailing, this was not an entirely correct judgement as there are a select number of values that show some evidence of stability, but for this to be either proven or disproven, the values would have to be run for much longer.

From seeing the results and how this compares to the original hypothesis, this leads to a new one being formed where it is thought that with the ability to interact directly with other agents, share, and fight for resources, the system will offer a more stable point of population balance.

The research produced from this abstract model could form a basis for someone to make a fully biological model, basing temperature, masses, birthrates, and speeds on true-to-life data and therefore getting even closer to precise answers.

The most logical next steps that could be taken from here are to implement some of the features mentioned earlier, such as adaptive agents. This can be done by using neural networks for decision making, along with a NEAT algorithm to evolve the networks over generations. Doing so would be a good way to further solidify the artificial life concepts and generate even further in-depth results as this then adds a Darwinian style of evolution where the organisms that make the best decisions and are more optimal for the environment and are the ones that survive to reproduce.

This report gives contributions to the study of ecological systems of organisms with different methods of thermoregulation showing the effects of resources and temperature on these groups. In a real-world application, this can also be used to study the effects of climate change where the minimum and maximum temperatures rise, and hibernation / brumation becomes more infrequent as this seems to be becoming an increasingly relevant topic. Therefore, this experiment acts as a stepping stone for the deeper understanding of these effects.

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