Modelling and Simulation of Natural Systems

COM3001: Report
Group 12

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1 Abstract

The equilibrium of natural systems is suffering a lot as a result of human interactions due to hunting purposes for parts such as fur. This model investigates the effect of humans on such a natural predator prey system. The three agents in this model are humans, lynxes and hares. An agent-based modelling approach is used to model each of the agents as they vary slightly from each other whilst interacting in the environment. Throughout this report the birth rate of the hares is analysed to investigate the optimum parameter at which the natural system can cope with the interaction of humans with the system. Further in the report it becomes apparent that human interaction with the natural system can sometimes be beneficial for helping specific agents survive longer, however they make the system more unstable and unpredictable.

2 Introduction & Background (Literature Review)

The main aim of our investigation was to calculate the birth rate of hares at which they become an unsustainable food source for the lynx population, whilst also factoring in the effects of humans hunting the lynxes. Specifically, our model's environment was based loosely on an area of field land in Russia.

A well-documented example of using predator-prey agent-based modelling was discussed by researchers in Canada in 2009[1]. Although this study uses a much more complex model, namely involving the usage of a Fuzzy Cognitive Map (FCM), there are some similarities.
In this example, the agents evaluate their environment before deciding what action to take, such as the distance between a given predator and their potential prey. Our implementation of this specific mechanic was similar - should a lynx come across two hares at equal distances from itself, the targeted hare will be chosen uniformly at random. Should the hares differ in distance from the lynx, the closest one will be targeted. However, the paper here also considers other factors, such as how fast both predator and prey could run, and how far (in number of cells) a given agent could perceive things (food, foe, etc.).

Another example of using agent-based modelling may be found in "An Introduction to Repast Simphony Modeling Using a Simple Predator-Prey Example"[2]. This paper documents using a program called "Repast" to model a simple wolf-sheep scenario. They utilise 3 agents (wolves, sheep, and grass), compared to our 4 (humans, lynxes, hares, and grass). The model used here has many similarities to our own, except for the fourth agent/apex predator (humans), such as the requirements of wolves and sheep to eat food, and that grass is eaten and subsequently regrows over time.
The implementation of wolves hunting sheep in this example is rather facile - a wolf in any given grid square simply scans through the objects at its location and, if a sheep exists there, it will eat it. Our implementation is a little more in-depth, as discussed beforehand. The mechanics of sheep eating grass is implemented similarly; if alive grass is detected in the same location as a sheep, the sheep will eat it and regain energy. This is identical to our implementation of hares eating grass.

In "From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools"[3], the authors first reference a system dynamics predator-prey model first conceived by Lotka in 1925 and Volterra in 1926. The model referenced simplifies the simulation greatly, such as giving the prey access to unlimited food resources, and no natural death from starvation or old age. The predators modelled also only die from starvation, with the singular prey type being their only food source, and they can consume infinite quantities of prey.
In comparison to our model, we do incorporate a life expectancy for both the main predator (lynxes) and main prey (hares), where they could potentially die from both starvation (due to both having extinguishable food resources), and old age, as well as being hunted (hares hunted by lynxes, lynxes hunted by humans). Our agents also do not mindlessly aim to consume as much prey/other as possible, with a hunting rate being determined by a randomly generated likelihood of a successful hunt. One similarity, however, is in the environmental complexity - both model a 2D space (a homogeneous environment).

The model used by the authors of this paper, however, makes some changes to create a more complex representation. Firstly of note is that the authors also use hares and lynxes and prey and predator, respectively. In the model itself they, like us, introduce a life expectancy for both hares and lynxes. They ensure that their agents are space-aware, whilst also being modelled in a 2D space. This includes restrictions on breeding, such as hares only being able to breed if there is enough space around them, something we did not incorporate. Their inclusion of a starvation aspect is also similar, albeit more simplistic, in that "if lynx does not eat a hare within

a certain period of time, it dies", however their is no mention of hares having a similar behaviour modelled. Their results (Figure 13 in the paper) show that even a small increase in the lynx population results in a drastic decrease in the hare population. This is likely due to how the behaviour is modelled - it appears that as soon as a lynx has eaten a hare, it re-enters the hungry state and looks for more prey.
The authors also note a major difference between the system dynamics (SD) model and the agent-based model used here. They state that "subject to the model parameters, lynx (or hares and lynx together) may become totally extinct, which never happens in the SD model due to its continuous nature". They also note that an agent-based model allows one to trace a single agent, and their families/generations, if they so wish.

3 Methodology

3.1 Purpose

The purpose of this model is to investigate at which birth rate the hares will be a sustainable food source for the lynx in a simplified habitual environment.
The investigation will consist in varying the birth rate of the hares in order to explore a threshold at which the described food chain will reach an equilibrium point. We aim for a self-sustaining system where no agents become extinct due to the dependencies between them.

3.2 State variables and scales

The environment defined within our model consists of a predator prey interaction between three agents. The agents modelled are humans, lynx and hares. The food chain can be best conceptualised as shown below:

- Humans hunt the Lynx ⇒ Lynx eat the Hares ⇒ Hares eat grass

Our model simulates the three specified agents (Humans, Lynxes, Hares) co-existing in a predefined environment space. Due to the fact that the agents are only able to move in a Cartesian plane (x,y) it has been decided that the best representation of the environment space is a 2D representation. A 3D representation would not be adequate in this given scenario as it would only add unnecessary computation and therefore would only increase time taken to obtain required results.
The hares and the lynxes are represented by similar characteristics; location, speed, breeding frequency, minimum food frequency for breeding and maximum age allowed. On the other hand, the humans are characterised by the following; location and kill efficiency.
The basic ideology behind the model is that the agents co-exist in the specified environment and kill or hunt according to their position in the food chain defined above. Humans will consistently hunt the Lynxes unless they are hungry, in which case they will sit out for one iteration to replenish their food level. Lynxes will continuously eat Hares and will have no notion of being full. Hares will eat grass (which regrows over time) again with no concept of being full. The agents will constantly explore the environment space performing their actions.
A full table illustrating the parameters used in the model can be found in the appendix under Table 1.

3.3 Process overview and scheduling

As our model consists of simulating a natural system of three agents which must interact with each other regularly in order to eat and migrate around the environment. As a result, each time step in the model will be represented by one week. Our reasoning behind the proposed time step is to, firstly, ensure enough agent interactions are allowed to occur during each iteration and, secondly, to model an appropriate number of years for our investigation.

3.4 Design concepts

Similar to a real-world environment, as time progresses the agents will inevitably acquire some different emergent behaviours whilst navigating the environment and interacting with other agents. As a result, the hares will be located in collective groups scattered across the environment as their only source of food is grass which is found

in abundance in the model. On the contrary, the other two agents (humans and lynxes) will be scattered across the environment also, however each agent will tend to be alone in the surrounding neighbourhood due to the desire of reducing the factor of competing for food resources with other agents alike.
The humans, lynxes and hares are aware of their surroundings up to their respective search radius defined by their speed parameter included above. They can locate their nearest food source according to their needs. All agents also have the capability to navigate the map during each iteration in case their quest of gathering food has been unsuccessful. They will be able to move a maximum distance according to their speed parameter.
Each iteration the humans will attempt to hunt a lynx, a lynx will attempt to kill a hare and a hare will attempt to feed on grass. If any of these agents are unsuccessful to feed themselves they will start starving (with the exception of the human) meaning their food parameter will decrease. Our model includes a life expectancy for hares and lynxes, with their age increasing with each iteration. If the food parameter of the lynx or hare decreases below the threshold specified in the parameters above, then that agent will die.

3.5 Initialisation

The simulation has been initialised in an environment space of 60 km^2. The initial population of Lynxes, Hares and Humans were 40, 400 and 10 respectively. The time of the simulation has been capped at 208 iterations which will represent 4 years. 100 units of grass have been placed in every square km of space as source of food for the hares. Through careful calibration adjustments it has become apparent that these parameters produce the best results for the system to be self-sustaining for the whole period of the simulation with no agent becoming extinct prematurely.

3.6 Input

The agents will explore the map executing out their actions (hunting and/or breeding). These agents will interact with each other and will remain within the environment space provided at all times without crossing the boundary.

3.7 Submodels

In order to accurately allow the model to simulate the real world, stochasticity has been introduced into the model. This will represent the likelihood that a predator's attack upon a prey can be unsuccessful, hence the prey can escape. This is modelled by composing a likelihood function for the hunting attribute of humans and lynx. These functions will be calibrated to produce an outcome in the range 0-1 and will be compared with a random number generated in the range 0-1 also. If the result of the function is above the generated number the predator's attack will be classified as successful and as a result of that the predator will write a message to inform the prey that they have been killed.

The functions which will determine the success of a hunt are given below:

$$humanKillProbability = 1 - (distance/speed) - (killEfficiency^{-1}) \tag{1}$$

$$lynxKillProbability = 1 - (d/(speed/2)) \tag{2}$$

The speed and distance will contribute to the success of a lynx agent to kill. To maximise their kill potential they need to be as close to the prey as possible and have a large enough speed of movement, with these values the equation will be closer to the value of one signifying a higher likelihood of a hare being hunted and killed. For the human agent we consider an additional factor. We model a kill efficiency term. To maximise the kill potential, humans must be as close as possible to the lynx and have a high movement speed parameter with a high kill efficiency score. Due to the kill efficiency being modelled as inverse, the higher the value the less it contributes to the overall equation. Humans with a high kill efficiency will have an overall value closer to one signifying a higher likelihood of a lynx being hunted and killed.

A flow chart showing the model in full has been provided in the appendix under Figure 6.

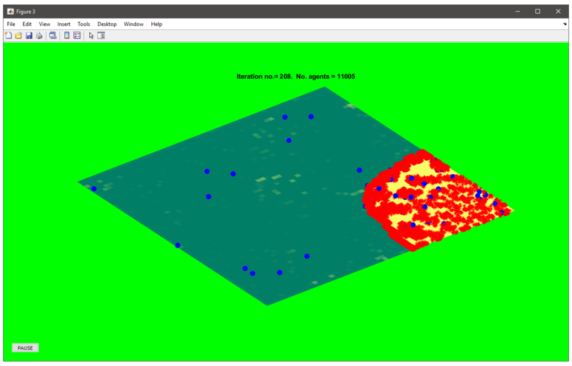
Assumptions

- The size of the environment will remain constant. Urbanisation and deforestation will not be taken into account.
- The grass regrowth factor will be high enough such that the food available for the hares will always suffice under normal conditions.
- All agent reproduce asexually so there is no concept of male or female agents.
- Humans will not die.
- Humans will not reproduce.

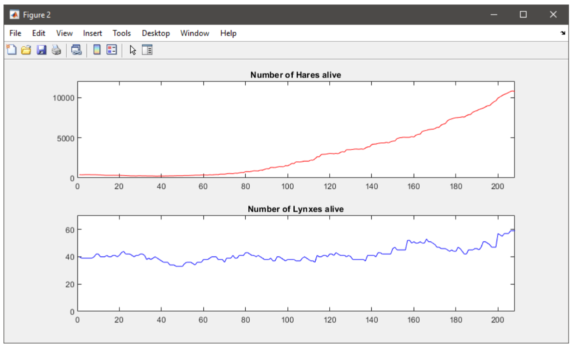
4 Results

4.1 Case 1: System in balance using optimum parameters

Through careful adjustment of the specified parameters, we were able to find a point at which the set breeding frequency of the hares produces a balanced system, as neither agent dies out in our 4-year long simulation period. The case shown in Figure 1 begins with 10 humans, 400 hares, and 40 lynxes, and a hare breeding frequency of 15 weeks. At the end of this period, there are 11,005 agents - roughly 59 of which are lynx, 10 are human, and the remaining are hares. A breeding frequency slower than this (e.g. every 16 weeks) would cause the hares to die out, as their birth rate is lower than their death rate. This test demonstrates a 208-iteration simulation, with each iteration representing one week.
The agents in this scenario have clustered in one corner of our 60km^2 model environment. This is the result of the emerging behaviour of the hares attempting to avoid the lynx over time; however subsequent simulations may have varying results due to the stochasticity which is shown in Figure 2 where run 3 and 4 resulted in the population of the lynx dying prematurely. This is a result of the agents being initially distributed across the environment in random positions, hence perhaps they did not form colonies far apart enough to survive the attacks from the lynx.



(a) Test 1 Model



(b) Test 1 Graph

Figure 1: Test 1 Results
(Blue = Lynx, Red = Hare)

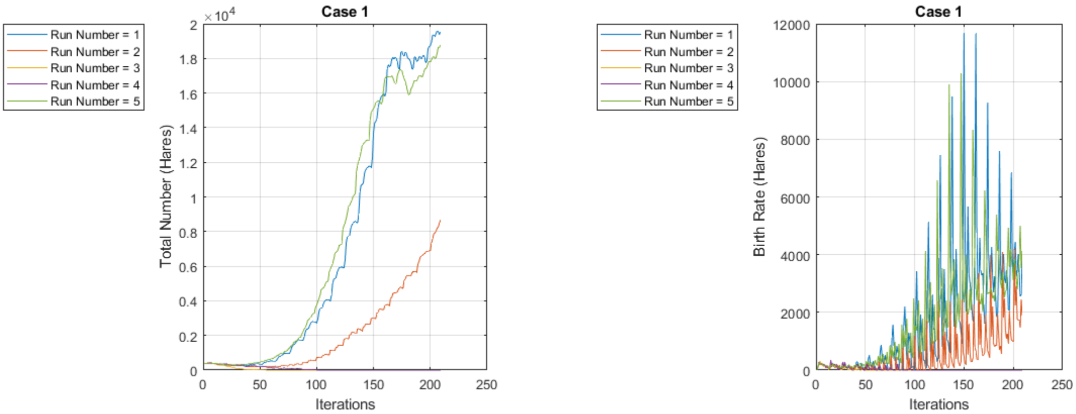
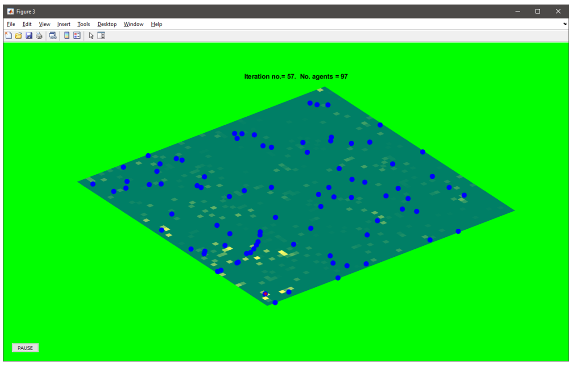


Figure 2: Case 1: Optimal values for the populations

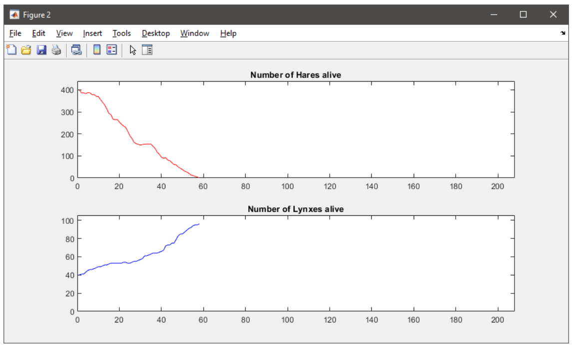
4.2 Case 2: Low birth rate of hares

Number of hares: 400; Number of lynxes: 40; Number of humans: 10

As discussed beforehand, and demonstrated here in Figure 3, keeping all initial parameters the same but slowing the breeding frequency of hares by one week (from 15-week to 16-week periods) results in death of all hares. Should the simulation be allowed to continue further, all lynx would also subsequently die out due to the removal of their singular food source. This is shown in Figure 3b). We see that when starting with a population of 400 for the hares, they die out after 58 weeks. (Which each iteration representing a week). Further generated graphs that display the birth rate for this case can be seen in Figure 7 from the appendix.



(a) Test 2 Model



(b) Test 2 Graph

Figure 3: Test 2 Results
(Blue = Lynx, Red = Hare)

4.3 Case 3: Low initial lynx population

Number of hares: 400; Number of lynxes: 10; Number of humans: 10

When considering a lower initial number of lynxes, the birth rate of hares increases over the first 100 weeks as shown in Figure 4, this being followed by a rapid decrease until week 130 after which it fluctuates around a constant value. This is particularly interesting as we know that after 100 weeks the lynx population becomes extinct due to humans so the hares will multiply out of control until they will run out of food due to abnormal number of agents in the environment.

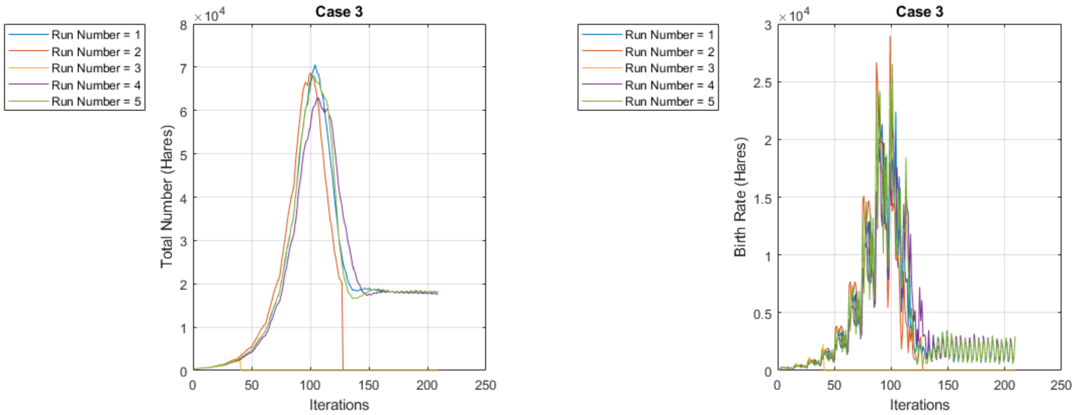
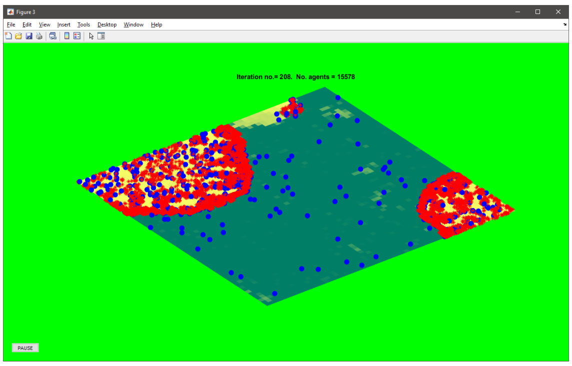


Figure 4: Case 3: Low lynxes population

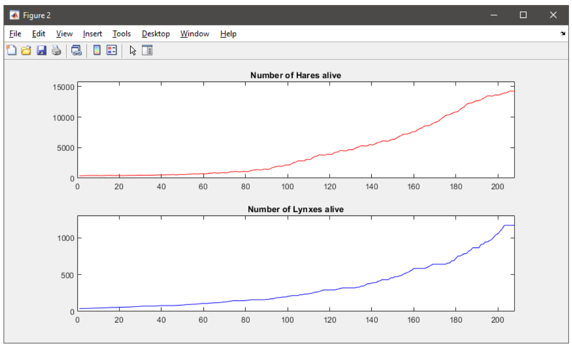
4.4 Case 4: No human agents included

Number of hares: 400; Number of lynxes: 40; Number of humans: 0

In Figure 5, we tested the effects of removing humans entirely from our model. This meant that no lynx would die from unnatural causes, and thus they have free reign on hunting hares, and the breeding frequency of hares must be increased accordingly. We found that for the hares not to die out as a result of being hunted by the lynx, they must have their birth frequency increased nearly 40%, going from every 15 weeks to every 9 weeks. Running the simulation again with a birth frequency of any slower than every 9 weeks would cause the hares to die out. Further generated graphs that display the birth rate for this case can be seen in Figure 8 from the appendix.



(a) Test 3 Model



(b) Test 3 Graph

Figure 5: Test 3 Results
(Blue = Lynx, Red = Hare)

4.5 Code efficiency analysis and improvements

Regarding our results, the biggest issue we had was the number of agents alive, and thus being modelled, towards the end of the simulation. This caused a bottleneck on MATLAB's side, which we believe is due to how MATLAB runs on a single core unless there will be any gain.
We began with these parameters as they were the most representative from the literature which we read. If repeating the experiment, we would likely choose to scale these down in order to limit this computational bottleneck, and ideally have at most half of the 11,005 agents alive, as at the end of Test 1.

The model could also benefit from further improvements in regard to the execution of the agents. Currently each agent is executed in turn in order to apply their functions (eating, breeding, migrating, etc.). This could result in some agents being given an unfair advantage that is not a result of their ability to kill but as a result of the execution of the program. As an example, if two agents compete for the same resource then the agent which is executed first will take ownership of that resource, rather than the skill of said agent being considered when deciding this.

5 Discussion

From our investigation, we carried out numerous tests to evaluate our system. We were able to find a sustainable system where the hares can reproduce at a steady rate, without being truly affected by the environment and especially by the population of the lynxes. We see that even though the population of the hares grows exponentially, the population of the lynxes tends to stay at a constant population. From literature we know that the population of hares tends to fluctuate between 10000-25000 in an area[4] whilst lynx populations tend to stay at a constant population of about 40[5]. From this we can see that the hares will most likely have a more unreliable population, even though our model starts with a low population of hares we can see they quickly reach a number which best represents that of the natural world; about 10000. It was difficult to simulate a large population at initialisation due to lack of computational power, but we were able to successfully model the number of lynxes with roughly the same area 40 lynxes would operate in. However, some unreliability is introduced into the system due to the exponential rate of the population, we did not have enough computational power to observe this exponential rate become a constant rate. However, we can assume that this stage will eventually be reached as in our model we introduced a grass which will be their source of food, if the population reaches a stage where only a discrete amount of food can sustain such a large population then the population of the hares should abide to that population of the literature as there will not be enough food for all hares causing a proportion of them to die out.

From our results we elucidated that the breeding rate of the hares, the human agents, and the lynx agents can have detrimental effects on our model when altered. We discovered that the breeding rate for the hares is very important, without a high and constant rate of breeding the hares will die out very quickly due to constantly being hunted. They must produce a lot of offspring in nature to survive, multiple litters with multiple offspring are the common occurrence for the hares over a year[4]. This is mirrored in our model. In nature the agents have seasonal breeding, however, to introduce simplicity, we constructed a system which allows breeding at any point in time if the agent's food parameter is over a specific threshold. Our agents also reproduce asexually, meaning there is no concept of sex and no two agents have to come together to produce offspring. An implementation to ameliorate our model would be introducing to the agents a probability of being female or male but also restricting the agents from multiplying until certain seasons by allowing breeding only during certain iterations. If a low number of lynxes are in an area, the population of the hares is seen to grow out of control due to there being a low chance they get killed by a predator. However as mentioned previously, we know that when the population reaches a high enough number, it will eventually decrease as food for the hares will run out of food in the neighbourhood. A reason for this occurring in our model is due to the way we model our environment. In our model we assume that everything is edible by the hares, we assume that food available will always be plentiful and that is why the population initially grows at such a high rate due to the high amount of food available. To avoid this, we could model the environment to be more realistic by adding uninhabitable parts, such as lakes or even introducing urbanisation or deforestation as more factors that could affect the population of the hares. However due to us modelling a predator-prey model we decided it would be best to find out how the food chain directly affects the hares by simplifying our environment. To add complexity into our system we introduced a human agent which will hunt the lynxes, this had a big effect when removed or added. When removed, the lynxes were not being hunted and therefore resulted in the population of the hares dying out very quickly. However, when we added more human agents in our environment, we saw that more lynxes were killed. As mentioned before, when the population of the lynxes is low, this will directly cause the population of the hares to increase very rapidly. However, these findings might be unreliable due to the assumptions applied to our human agent. We simplify our humans by modelling them to not die, not reproduce and constantly hunt for lynxes which is not the case in the natural world. An improvement to our human agent would be to introduce a more complex system where the human might be able to place traps and have an expanding area of where it operates, where any lynxes in that certain area will automatically be found and hunted due to being tracked rather than what we model in our ABM system.

Comparing results simulated by our system to that of the literature [1] we see some differences and similarities. Initially we see a major difference between the actual simulation, with the time available for this project we could only model 208 iterations whilst in paper [1] 7112 iterations were modelled. with the time available in this paper they were able to better model a natural system whilst in our system, we were restricted by our results due to not being able to run our model for a long time. Results from this paper show how the agents in the system depend on each other in the modelled environment. For example, it is noted that when a population of preys is high then the population of predators will also be high. When the population of both specified agents are high, the amount of grass decreases. This shows similarities to our paper: results obtained examples of the lynx and hares directly relying on each other to control their population. If the population of the hares is low then the lynx population will also be low due to not having enough of a food source, this is also true when the hare population reaches an enormous number which can no longer be supported due to food running out and hence population decreases in the system.

Our ABM system has its advantages and disadvantages. As mentioned frequently in our report. ABMs are prone to be computationally intensive. Problems arise when modelling an environment with a high number of agents, such as our own. This could be tackled by modelling our environment to be smaller, or maybe representing each agent as ten agents however this moves away from the purpose of ABMs, to represent each agent as an individual. Representing each agent as an acting individual in the environment allows the system to be more natural and represents a more realistic view of the world as all of the agent's behaviours are modelled as closely as possible to their emergent behaviour in nature. This allows for a system which captures the essence of what a single hare might do as opposed to a cellular automata model which will model how a group of hares might act instead.

6 Conclusions

To conclude our findings, we were able to successfully construct a model that would imitate a real life predator-prey natural systems. Even though the model that is presented in this report is a simpler model in comparison to other papers which have been analysed such as the one presented in [1] where a Fuzzy Cognitive Map is used as the environment map as well as more complex agents behaviour, we were still able to gather reliable results and have been able to observe complex behaviour of agents.

Our results show that the human agents do indeed affect the balance of the natural system that is presented in the report. By eliminating all the human agents for one of the experiments conducted we have been able to notice that the system would be in equilibrium with the correct parameters used. However, the introduction of the humans has benefited the hare population indirectly through hunting their predators (the lynxes). As a result of adding humans into the ecosystem the rate of birth required for the hare population to sustain the balance in the ecosystem by supplying a reliable source of food for the lynx population is lower in comparison to the rate of birth without the humans. This is due to lynxes having a fairly long breeding frequency (every 42 weeks) as shown in Table 1 included in the appendix. Through the addition of humans into the system the number of lynxes can be regulated easier and be kept under control as by the time the agents are due to breed, some of them would already be dead therefore they will not exponentially multiply to highly threaten the hare population.

The rate of birth of the hares at which they can be a sustainable food source for the lynx population and maintain the balance in the ecosystem is when their breeding frequency parameter is set to 16 weeks, with the human agents included in the simulation. Any number higher than this would result in decreasing the breeding frequency and cause the hare population to die prematurely as they will be consumed by the lynx agents. As mentioned above, the humans agents aid the hare population as in the case where humans are not included in the simulation the breeding frequency parameter of the hares is set to 9 weeks which is a about a 40% increase from the simulation where humans are involved.

References

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A Tables

Parameter	**Units**	**Value**
Hare speed	km/week	26
Lynx speed	km/week	18
Human speed	km/week	16
Hare breeding frequency	weeks	To be investigated
Lynx breeding frequency	weeks	42
Hare death food threshold	weeks	0
Lynx death food threshold	weeks	0
Hare maximum age	weeks	365
Lynx maximum age	weeks	834
Human kill efficiency	units	10
Grass regrowth	units/week	10
Environment size	km^2	60
Timestep	weeks	Simulation time chosen

Table 1: Summary of parameters used within the model

B Figures

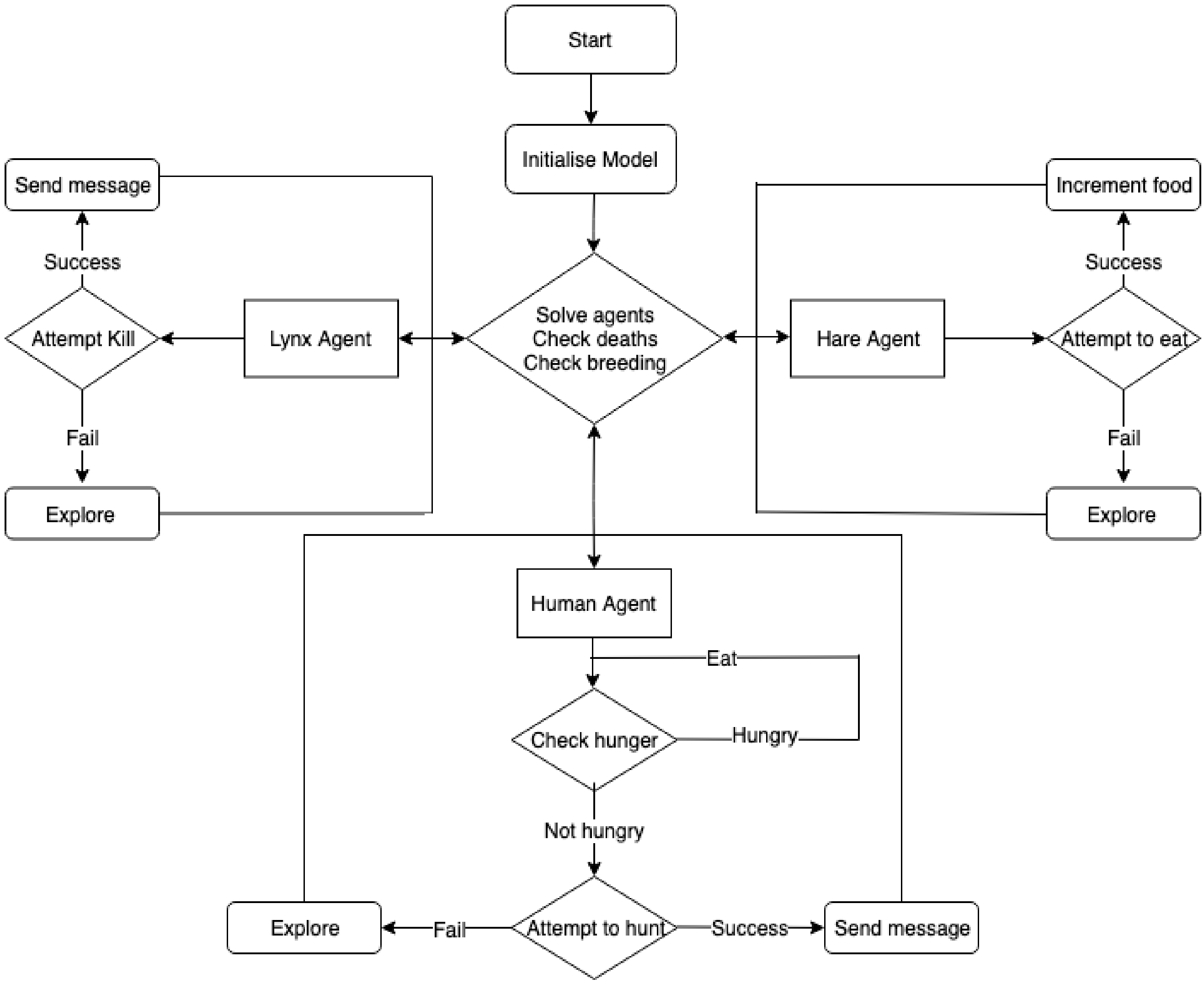

Figure 6: Flow Chart Diagram of Model

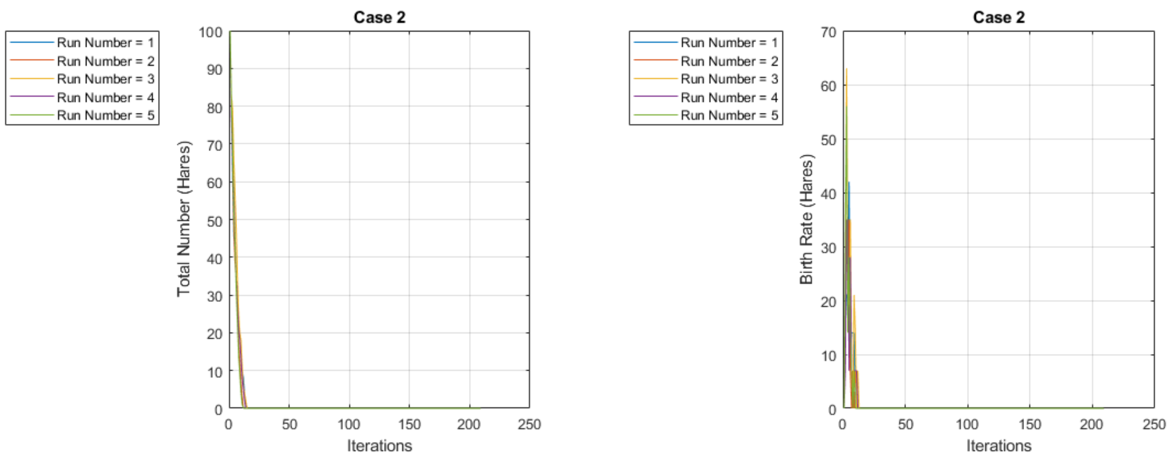

Figure 7: Case 2: Low birth rate of hares

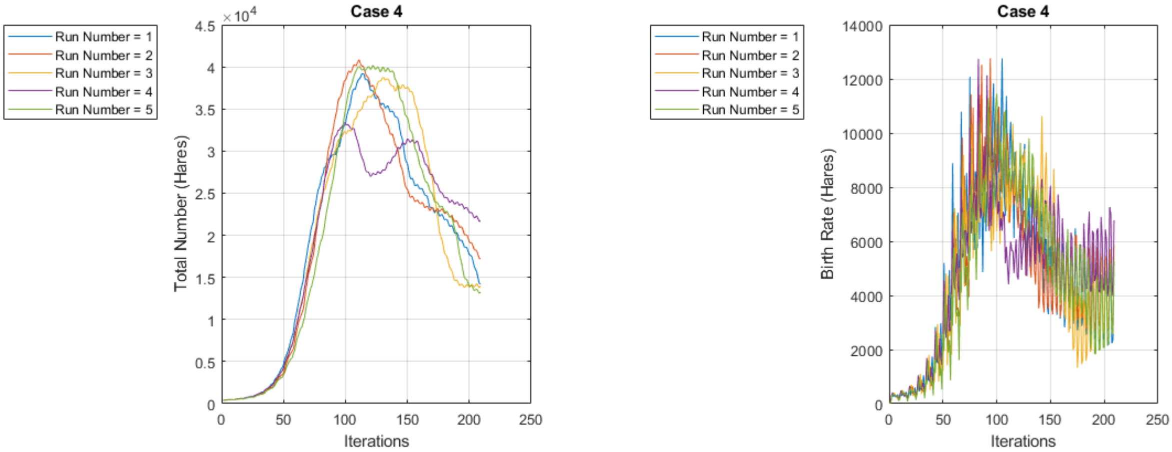

Figure 8: Case 4: No human hunting