The '*BEANS*' Model: Bio-diversity Evaluation of Alien & Native Species.

Computational modelling and analysis providing insight into the impact of invasive species on native ecosystems

Section 1: Problem Statement:

1.1 Background & Motivation:

Western Australia is home to one of the world's most diverse and flourishing natural ecosystems. At almost 3 million square kilometres it is home to a variety of subclimates, ranging from snow-capped mountains to harsh desert. Pre-colonisation, over 11,000 endemic species suited to these unique landscapes thrived here, with millions of years of evolution to adapt to their surroundings. However, the arrival of colonists in recent times brought with them a host of foreign plant species, which were introduced without proper consideration of the possible impact on the ecosystem. Introduced species have proved incredibly destructive to the balance of the natural landscape, with 444 of these native species currently listed as threatened, a further 143 endangered, and dozens extinct [11]. As longtime residents of Western Australia, our team was inspired by this matter to help reduce the catastrophic impact of invasive species on natural ecosystems.

In this model we examine the influence of different attributes of plant species and their environment on the balance of an ecosystem. We run a number of simulations, focusing on modelling existing cases of foreign flora introduction. We aim to reveal helpful patterns of specific cases we will simulate, allowing us to create real and helpful strategies for improving balance in these environments. Insights we extract from our model and its simulations could also assist in generating useful advice for scientists and ecologists, which can be applied to relevant ecosystems around the world and reduce the disastrous impact of invasive species.

1.2 Suitability for Agent-Based Modelling:

This case is extremely suitable for an Agent-Based Model (ABM), as it fits all the criteria of these. We interpret ABMs to have three essential components: **Agents**, an **environment**, and **interactions** (both between agents, and between an agent and its environment). In this situation, each plant is an agent. There will exist different classes of plant agents, representing different species, both invasive and native. The environment will be the habitat of plants, which houses all plant agents. Interactions are present in our case, as plants often indirectly interact with each other when competing for limited resources, often leading to plant death. Plants also interact with their habitat, obtaining natural resources, spreading their seeds to reproduce and growing. As this case can be modelled in this way, we believe ABM to be an ideal method of simulating competition between species of plants.

1.3 Complexity of the Case for Simulation:

The interactions of different species of plants in a habitat is a naturally complex phenomenon, with a range of factors all influencing species' survival and reproduction. Some of the most important factors we have identified are genetic traits of plant species themselves. These include how fast a plant grows, and subsequently its size. It similarly includes a plant's current age, and resultantly lifespan, as older and younger plants react differently to the same conditions. The rate at which a plant reproduces, or spreads seeds was also highlighted, as well as how far away it is capable of spreading these. Finally, we determined the resilience of a plant to adverse conditions such as limited resources to be of importance, a high degree of this evident in a cactus for example. All of these traits of plants were analysed to be of importance to our model, and will be quantified as properties of our plant agent.

This case was also seen to be impacted by conditions of the environment in which the plants exist. Notably, the availability of natural resources, such as nutrients and fresh water. Habitats with a high water availability, and nutrient dense soil will mean that native and invasive species can coexist more, without having to compete as much for the same resources. This will be quantified in our model as a property of the environment in which the agents exist. A final characteristic we determined to be important was the individual relationships between plant species. Some plants thrive more in the presence of other species, while some compete for the same resources and cannot coexist in the same environment without extinction. This was quite a unique characteristic, and will be encoded as a property in plant agents, referred to when these agents interact with each other. The many unquantifiable intricacies and randomness of nature also plays a major role in this case. This will also need to be encoded in our model, to ensure some element of chance plays a role in the interactions, reproduction and growth of plants.

The complexities of plant interactions in a habitat, including genetic traits, environmental conditions, and species relationships, make this case a valuable subject to analyse. By understanding how these parameters interact, we can gain insights into the intricate balance that governs ecosystem dynamics, and subsequently outline patterns which can generate valuable knowledge on the subject. This understanding can help in conservation efforts, predicting ecosystem responses to environmental changes, and foster biodiversity.

Section 2: Model Design

2.1 Design of Model:

Plant Class: This Class helps to model the unique behaviour of each species in a specific ecosystem. Plant objects are created with two parameters, a tuple containing the (x,y) coordinates of the plant in the Ecosystem, and a dictionary containing all of its 'genetic' parameters. The parameters are:

- **Plant Type:** Used as a label to differentiate between different species (e.g. 'Sunflower')
- **Min/Max Lifespan:** How many iteration steps a Plant can 'live' before it dies.
- **Min/Max Factor of Resilience:** This attribute is used to determine how likely a Plant is to survive when competing with another plant for resources. A higher resilience constant would mean a plant is less likely to die in overcrowded conditions.
- **Min/Max Growth Rate:** The amount in which a Plant grows each step.
- **Min/Max Reproduction rate:** The likelihood of a plant to reproduce each step.
- **Reproduction radius:** The grid distance from the agent in which it can reproduce. This is used to model the difference between tall tree seed dispersion, and grass seed dispersion.
- **Friends:** This attribute contains information on the relationship of a Plant species with other species. This will determine if a plant thrives or struggles in the presence of another Plant.

Many of these genetic attributes are passed as minimum and maximum values, with a final constant value being assigned to a random number between the two. For example, this means that despite different instances of Plants of the same species having the same 'genes', and subsequently the same min/max lifespan values, they will likely be initialised with different lifespans. This simulates the real world randomness of nature, specifically in lifespans, fertility, growth rate and resilience. In addition to these 'genetic' attributes, Plants also have variable attributes age and size which are increased at each step (size is increased by the growth rate).

Ecosystem Class: This Class houses all Plant agents, which interact with, move around, live and die within the 'Ecosystem'. An Ecosystem is visualised as a discrete, square, 2D grid with each square being occupied by 0 or 1 Plants. 2+ Plants cannot occupy the same square. One Ecosystem is initialised per simulation, with two parameters: an integer stating the length (and width) of the grid, and a constant determining the availability of resources in the Ecosystem. This is so Ecosystems with different water, nutrient and light availabilities can all be modelled. The properties of an Ecosystem class include these, as well as locations of agents and occupancy on the grid. This class contains a host of methods for executing a simulation.

Model Configuration: This model is configured by first setting up the Ecosystem, with a desired size and resource availability. Next, species of plants should be defined, with genetic attributes outlined appropriately. Instances of different Plant species can be added to the Ecosystem at desired times, reflecting the desired situation to simulate. Following this, the model can begin to simulate 'steps'

Rules: For each step executed, the Ecosystem object follows these rules for each Plant within it:

1. Increase a plant's **age** by 1. If it grows past its **lifespan**, it dies.
2. Increase a plant's **size** by **growth rate**.
3. Check neighbours of the plant, considering **resource scarcity**, **relationship** of plants and an element of random chance to decide whether a 'competition' should occur between two neighbours
    a. A competition occurring means one plant in a pair of neighbours must die
    b. A competition is won by the neighbour with the highest combination of **resilience** and **size**, to simulate real world competing plants
4. Attempt to reproduce to empty cells with '**reproduction area'** as maximum distance from the plant.
    a. Likelihood of a reproduction occurring in an available and in-range cell is set by a Plant's **reproduction rate**
    b. Successful reproduction creates a new Plant in the ecosystem, with the same genetics as its parent. However, due to randomisation within minimum/maximum values, its final attributes will likely end up being different
5. Repeat steps 1-4 for each plant currently alive

2.2: Complexity Reflection:

As our chosen case is one of great complexity and many intricacies, we added a number of attributes to plant agents to ensure these were well represented. One of the most important in determining a plant's attributes is the previously mentioned randomness factor. This factor allows both the inheritance and predictability of genetics to be represented, while also representing the genetic variation found in real world DNA. The continuation of species with favourable genes also mimics the complex phenomenona of **natural selection** and **evolution**. Different species of plants behave in vastly different manners, and as such we defined a large number of attributes for plant agents. Unique attributes of lifespan, resistance, reproduction rate and radius, growth rate are able to form complex representations of plants with interesting behaviour.

Our environment instances are designed to capture the complexity of natural habitats. They feature a 'resource scarcity' constant, which emulates the difference in behaviour of agents in resource dense environments when compared to resource scarce environments. Rules prompting the coexistence of plants determined to have a high 'friend' constant, and the competition of those with a low one were also implemented. This helps to simulate more of the otherwise unaccounted for complexities of plant/habitat interaction, such as symbiotic relationships with nitrogen-fixing plants, which enrich the soil, allowing other species to prosper.

Our model also simulates dynamic feedback loops, demonstrating how ecosystems shift to approach a state of equilibrium. An example of this could be seen in a plant with a high reproduction rate being introduced, increasing the competition and triggering a process of natural selection, improving the average attributes of all remaining plants. This feature adds complexity by emulating how a change to one element of the system can trigger shifts in the entire ecosystem, demonstrating the emergence of these natural systems.

Section 3: Simulation Results and Analysis

For our simulations, we have identified 3 cases in which ecosystems of native plants are currently threatened by invasive plants around the world, examining how each introduced species' specific attributes have allowed them to out-compete native species.

3.1 Visualisation:

Drummond Wattle (*Acacia Drummondii*) Vs Eastern States Wattle [Cootamundra wattle *(Acacia baileyana)*, Sydney golden wattle *(A. longifolia)* and Flinders Range wattle *(A. iteaphylla)*]: The Drummond wattle is a native wattle to Western Australia, whereas the Eastern States Wattles are invasive species. The Eastern State wattles are inhibited in their native habitats by seed eating insects [2], and without these reproduce rapidly in WA. These wattles ravish native ecosystems throughout the state, also acting as ***nitrogen fixers**,* fertilising the soil in which they grow. This newly fertilised soil subsequently becomes vulnerable to disturbances which allow foreign grasses to thrive. These grasses dry out in the summer, acting as fuel for bushfires, helping to germinate the Eastern wattles, creating a destructive feedback loop [2]. This scenario has been visualised in Figure 1.

Eucalyptus (*Eucalyptus Globulus*) vs Fynbos Trees (Many): The Fynbos is a group of trees native to South Africa, an environment with many climatic parallels to southwestern Australia. The introduction of Eucalyptus trees for the forestry industry has caused the Fynbos population to deteriorate rapidly [5]. The Eucalyptus is a fast growing plant which does not require particularly fertile soil, thus is an excellent pick for industrial tree farming. However, the Eucalypts' resilience and ability to grow in poor conditions has adverse effects on native flora within the region. Its high growth speed for a tree also means that it begins to develop a canopy cover quickly, blocking native plants from absorbing sufficient sunlight. These properties allow them to outcompete native plants for limited resources. The following simulation shows how even one Eucalyptus tree can quickly take over an entire habitat with its species. The visualisation of this simulation can be seen in Figure 2.

Scalesia Trees (Many) vs Hill raspberries (*Rubus Niveus*): The Scalesia forests are collections of endemic Scalesia Trees native to the Galapagos Islands, which are currently under threat by Hill raspberries. The Hill raspberries' dense, shallow bush structure causes two major problems. Firstly, they inhibit the native Scalesias from regenerating roots and finding sufficient resources. As well as this, these bushes also inhibit birds from germinating Scalesias, as these dense bushes prevent birds from foraging nearby as they cannot reach the ground to hunt for insects. The result of this simulation can be seen in Figure 3.

3.2 Parameter Impact

Drummond Wattle vs Eastern States Wattle: The introduction of Eastern States Wattles into bio-diverse Western Australia raises great concern about the future of native species in the southwest, particularly rival wattles such as the Drummond [1]. These invasive wattles outcompete native species due to their superior reproduction rates, which is abnormally high due to a lack of seed-eating insects [2]. These insects typically balance the germination of new seeds in the ecosystem, thus we aimed to emulate the artificial introduction of these insects into our south-west to do this in Western Australia, a proposed solution to this issue. The goal of this introduction would be to decrease the ability of Eastern Wattles to reproduce, while maintaining the population of native species. We modelled the effects of this circumstance by decreasing the Eastern States Wattle reproduction rate and area parameters. We similarly decreased the reproductive rate and area of the native species, as the insects will also be eating their seeds. The native Drummond wattles are able to maintain their populations throughout the invasion, as the reproductive advantage of the Eastern Wattles is less apparent due to the reduction of parameters. This allows the Drummond Wattles' superior resilience to have a greater impact, as Drummond Wattles outcompete their Eastern counterparts when not overrun by reproduction. The native plants have the additional advantage of maturation prior to the invasion, and are able to establish dense networks to help their chances of species survival. The modified version of this simulation is visualised in Figure 4.

Eucalyptus vs Fynbos Trees: The invasion of this species is a prevalent issue in parts of Southern Africa with destructive impact on local ecosystems, so finding a solution is of great importance. Nicola Froeschlin's 2022 study researched the impact of two types of restoration with the hope of reducing invasive species cover in this area: Active ("clearing followed by sowing of native species and soil restoration treatments") and passive ("clearing and burning, only") [4]. Disappointingly, both of these methods did little to reduce Eucalyptus cover, despite improving native species diversity. With this in mind, we opted for a different approach to tackle this issue, as it is clear that the superior genetic traits of Eucalyptus trees means environmental shifts will not be enough. Mangachena and Geerts' 2019 paper found that the invasion and overpowering of Eucalyptus trees in South African environments led to a dramatic impact on bird populations [10]. While **insectivorous** birds continued to thrive as their habitat shifted to Eucalyptus dominant forestry, **nectarivorous** bird species in particular were completely eradicated in the recorded area (Figure 5). This data suggests that while many birds can comfortably survive in Eucalyptus trees, nectarivorous birds much prefer the native Fynbos trees as a habitat. We suggest an introduction of a large volume of native nectarivorous birds, and culling of insectivorous birds when introducing Eucalypts into Fynbos forests. As Eucalyptus trees will have less birds nesting in them, they will have less vectors of reproduction, leading to a decreased reproduction rate and area. Conversely, Fynbos trees will have more birds nesting in them, leading to increased reproduction rate and area. These parameters were halved in Eucalyptus trees and doubled in Fynbos trees, generating the following modified simulation seen in Figure 6. These parametric changes dramatically reduce the destructive impact of Eucalypts, with Fynbos populations withstanding their introduction in this simulation.

Scalesia Trees vs Hill raspberries: Reducing the proportion of raspberry to Scalesia Tree population is of utmost importance to the Galapagos Islands' ecosystem. It is important to note that trees are not being wiped out in our initial simulations, but instead prevented from spreading further and held to a constant population. A solution to this issue could be found in increasing the nutrient density of the habitat of these plants. Although this would lead to more reproduction of Scalesia trees, it would also lead to more reproduction of raspberries, which seemingly opposes our goal. However the initial increase in density of the Scalesia population creates a stronger structure, preventing invasive reproducing raspberries from penetrating the forest of Scalesia trees. As Scalesia trees are almost always superior when directly competing for space, due to a higher lifespan and growth rate, trees gradually gain ground previously held by raspberries, and maintain a dense coverage over the majority of the ecosystem. This shift could be achieved in a real situation through continuous distribution of compost and mulch to the forest floor, artificial irrigation or introduction of nitrogen fixing species. This change in conditions can be parametrically reflected by reducing the resource scarcity constant from 0.5 to 0.2 of the Galapagos ecosystem. The results of this shifted simulation can be seen in Figure 7.

3.3 Quantitative Analysis:

Drummond Wattle vs Eastern States Wattle: The differences in genetic parameters had a profound impact on the final system. As the results show in the initial configuration, the Eastern States Wattle populations significantly increase over time, whereas the native Drummond populations decrease over time, seen in Figure 8. The relationship between the Eastern States and Drummond Wattles' populations is due to the superior reproductive rates of the invasive wattle. The ability to bolster their population allows the invasive wattles to engage in a war of attrition, with the native wattles dying out due to a lack of reproductive capability. This is supported by the data shown in Figure 9, as the Eastern States Wattles have significantly higher death rates than the native species during the initial confrontation between the species, but then begin to die less and less as the simulation progresses. The effect of the high reproduction rates can be seen when we decrease both wattles' reproduction rates. The reproductive advantage the invasive species holds is now less significant, letting the native species' resilience help it to flourish within its given environment, having a significant impact on the population proportions. Figure 8's second column shows the native species in the altered model with a greater population stability, even increasing slightly. In Figure 9, the altered model lacks the rising death count which previously signalled eradication of the species.

Eucalyptus vs Fynbos Trees: As can be seen in Figure 10, the control model of Eucalyptus vs Fynbos trees resulted in an eventual population domination by Eucalyptus trees after their introduction. In the second graph of the same figure, it can be seen how the introduction and culling of certain species of birds dramatically altered this, with Eucalyptus populations unable to take off after being introduced and dominated by Fynbos populations. In the altered model, the Fynbos has superior reproductive attributes to the Eucalyptus, so can therefore outnumber the invasive species dramatically. Even though Eucalypts still held many superior attributes, which allowed the few remaining plants to win many of the direct competitions they are part of, the overwhelming outnumbering of Fynbos proved insurmountable. Eucalyptus trees had a much higher average age in this model, seen in Figure 11, a statistic that actually proves a negative for the survival of the species. This high average age shows the Eucalypt's lack of ability to reproduce, despite the resilience of the few existing plants which persist to old age, as they are so overrun by Fynbos. The average age of Fynbos plants is much lower and more stable, evidence of the continuous reproduction of these trees, resulting in a large number of young plants. Another telling feature of this graph is the disappearance of the Eucalypt average age line around 50 steps, as this is the point in the simulation where the last Fynbos tree is wiped out. Comparing both graphs in this figure supports the surprising finding that a population which is younger on average tends to be dominant in this model.

Scalesia Trees vs Hill Raspberries: The initial conditions for the Scalesia Tree vs Hill Raspberry simulation resulted in an overpowering of the Scalesia population by raspberries, while the altered conditions resulted in a stronger persistence against the fast-spreading raspberries by the Scalesia trees. This is quantified in Figure 12, as the control simulation eventuates in a higher raspberry population, which continues to rise as the Scalesia population falls. Contrastingly, the altered simulation begins with a period of simultaneous population growth, but ultimately approaches an equilibrium as Scalesia population steadily grows and raspberry population steadily shrinks. These changes in population proportion are due to the increased resource availability in the environment, allowing both plants a boost in reproduction. This evidently benefits Scalesia plants more than raspberries, as despite both plants' reproduction capacities being increased by the same amount, the ratio of raspberry reproduction to Scalesia reproduction is not as high. This allows the other genetic superiorities of Scalesia trees a greater chance to emerge, including higher lifespan and growth rate, leading to increased Scalesia victories when competing with raspberries. More victories results in more space available within the Scalesia structure for reproduction, and less for raspberry reproduction, creating a powerful feedback loop. This can be further visualised in Figure 13, as the modified model features a lower average Scalesia age than the control model, and vice versa for raspberries. This is further evidence of increased reproduction of Scalesia trees, and decreased reproduction capacities of raspberries.

3.4 Real-World Reflection:

The above simulations, parameter impact evaluations and modifications provide valuable insights into ecological mitigation strategies which can be implemented in the corresponding scenarios. Although we believe the general trend of these ecosystems will be faithful to our model's results, our model is not an exact replica of all environmental conditions. As such, these strategies will likely have slightly different impacts on the environment than what our simulations show. We also urge potential actors of these strategies to do further research into other environmental impacts of our environmental modifications, such as impacts on erosion, local fauna, soil fertility and habitat loss before implementing any changes.

Section 4: Conclusion

4.1 Summary:

This model simulates the impact of introducing one or more invasive species of flora into an existing environment containing a species of native flora. We used a number of plant and ecosystem attributes to accurately represent complex real-world situations and all the intricacies of these. We analysed three cases of species introduction in detail: The Drummond Wattle vs Eastern States Wattles in Western Australia, The Eucalyptus vs Fynbos trees in South Africa, and Scalesia trees vs. Hill raspberries in the Galapagos Islands, Ecuador. These simulations, when paired with effective parameter analysis, helped us generate strategies to mitigate the impact of introduced species by reducing their population proportion in each case. These strategies were to introduce natural inhibitors such as seed-eating insects, alter populations of birds with different diets and enhance nutrient density in affected areas respectively. Our model can have significant positive impacts on damaged ecosystems if used correctly, providing recovery strategies for these three cases, and potentially many other applicable situations. We hope that these strategies can be implemented in habitats to create constructive change, and ultimately help mitigate the global epidemic of native flora eradication.

4.2 Limitations & Future Improvements:

Our model's main limitation was its implementation of the local environment. In order to more effectively simulate real world examples of flora competition, we would need to find a method to more effectively mimic real life environments.. Each environment has a unique combination of temperatures, climates, weather patterns, nutrients, seasonal changes and natural disasters, among other factors, but our model expresses this through a single 'resource scarcity' constant. We could also create more complex representations of resource availability to allow more intricate competition between plants to occur, such as featuring varying resource density depending on the location in the ecosystem. This could be more representative of complex environments such as desert oases, or river deltas. If we were to recreate this model with a greater time allotment and project scope, we would implement a more complex Ecosystem class to properly express this, rather than primarily focusing on representation of different plant species.

The representation of plants could also be further developed in the future, given a larger scope of project. Some potential improvements which could be made to representations of plants could include varying water requirements, nutrient requirements and light requirements (even featuring specific calculations of shade and foliage density). We assessed this as less of a limitation to our results, as our plants already featured a large number of attributes to ensure a high degree of customisation.

Section 5: References (IEEE Format)

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Section 6: Appendix

Figure 1

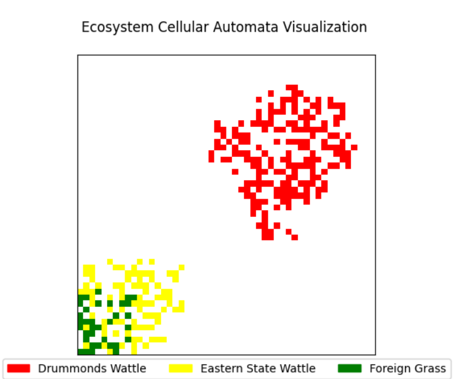
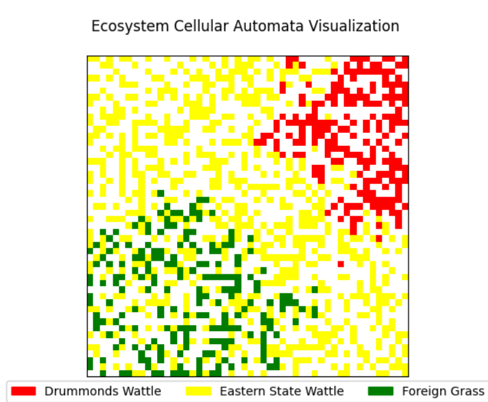
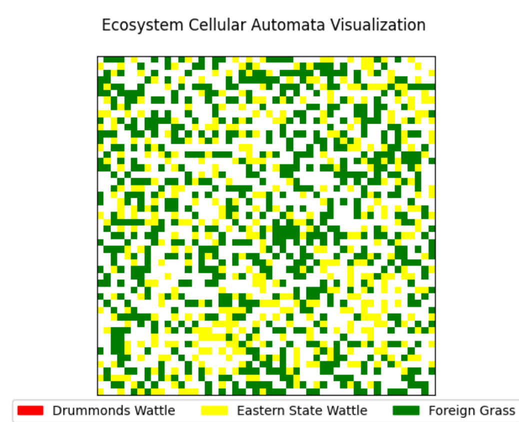
Time step: 25	Time step: 50	Time step: 100
		

Figure 2

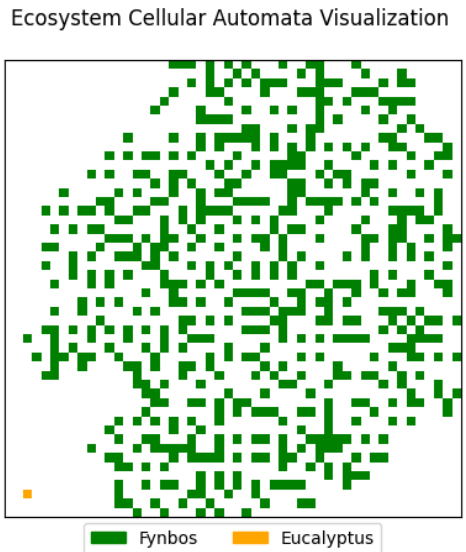
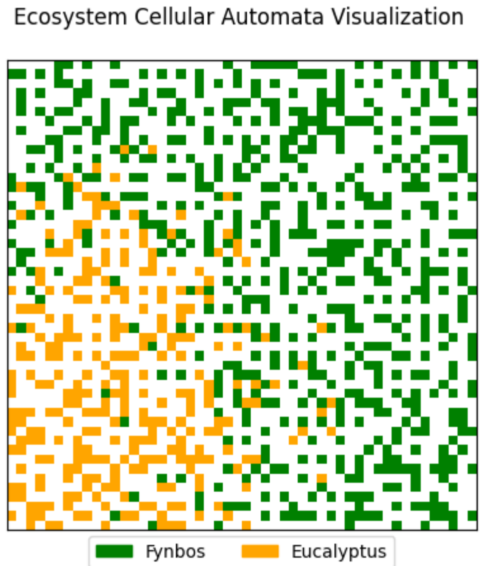
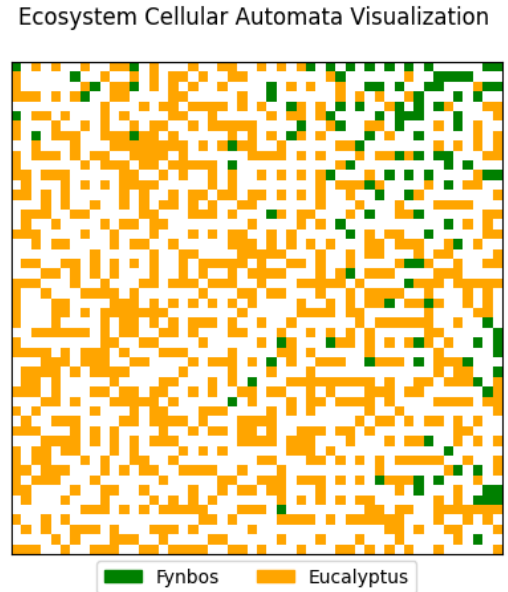
Time step: 25	Time step: 50	Time step: 75
		

Figure 3

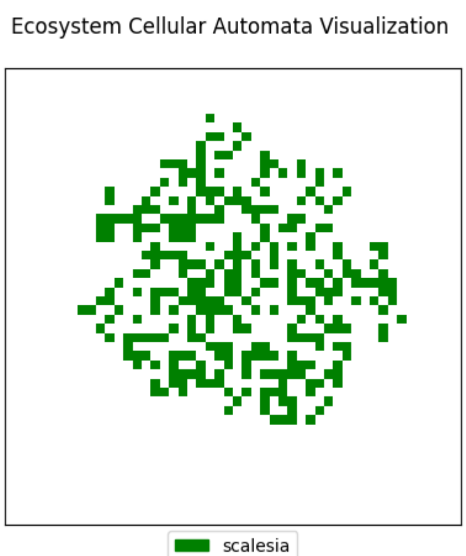
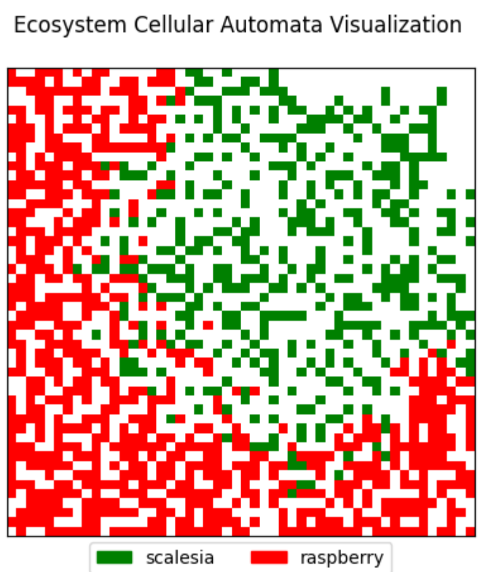
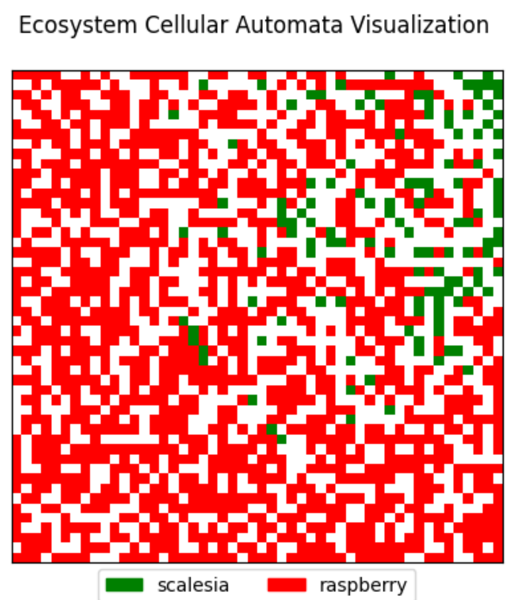
Time step: 40	Time step: 60	Time step: 100
		

Figure 4

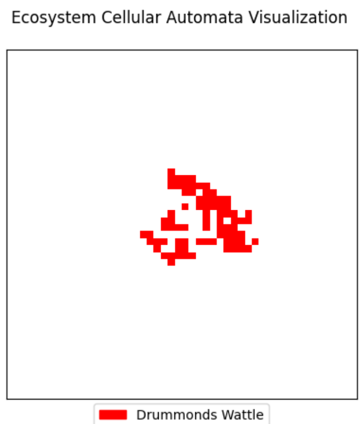
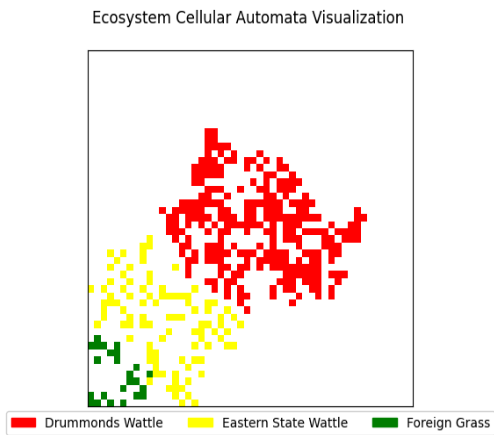
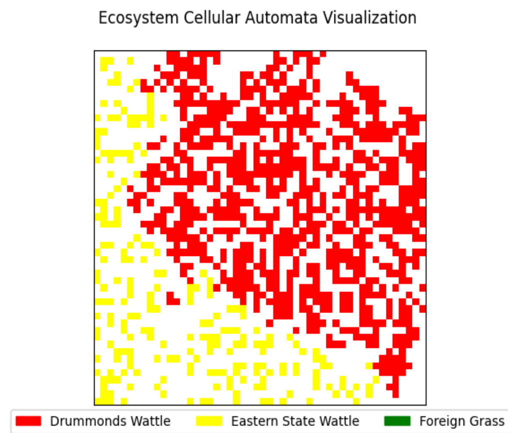
Time step: 20	Time step: 40	Time step: 80
		

Figure 5

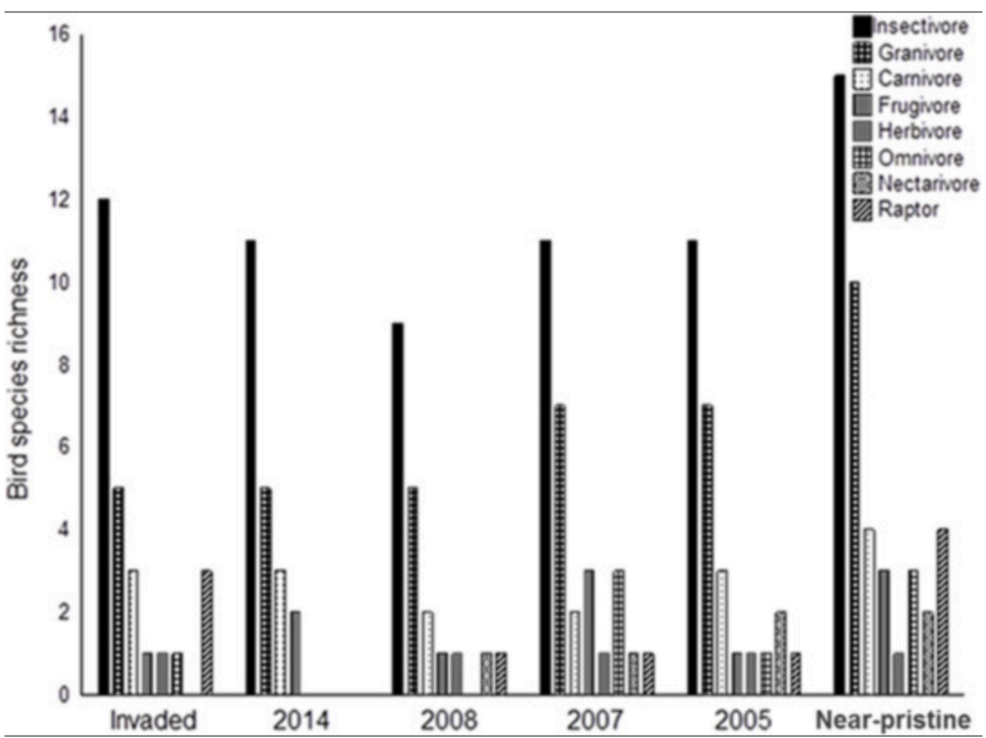


Figure 6

Time step: 5	Time step: 30	Time step: 55
		

Figure 7

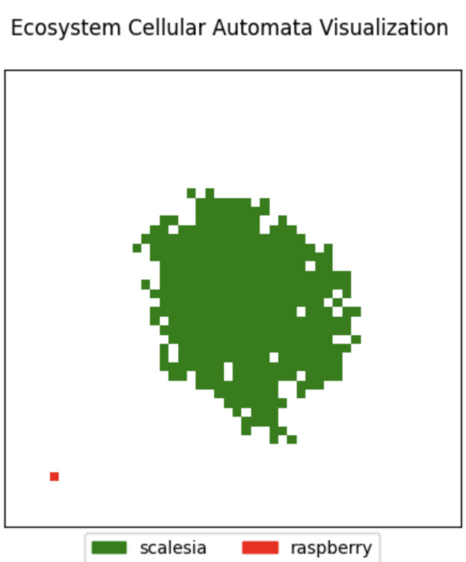
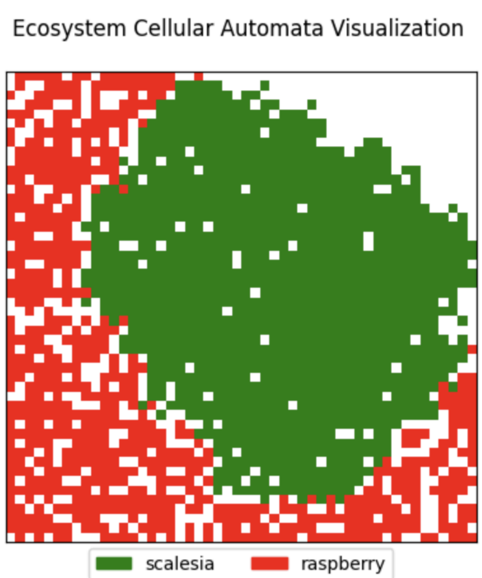
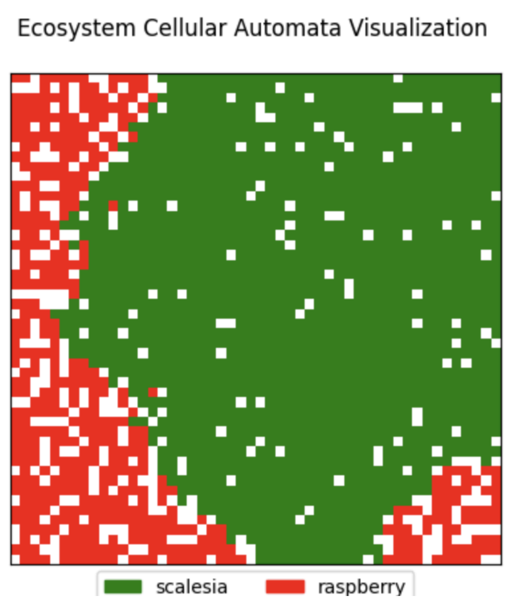
Time step: 20	Time step: 40	Time step: 80
		

Figure 8

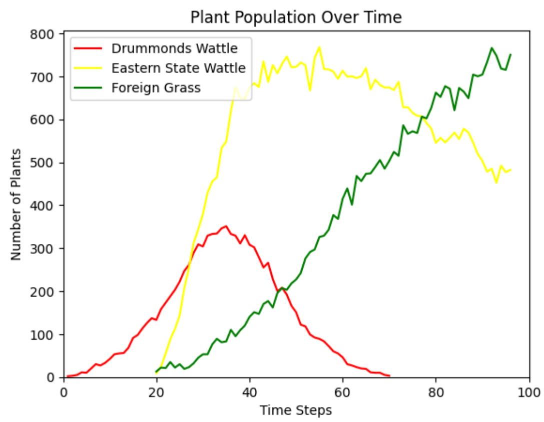
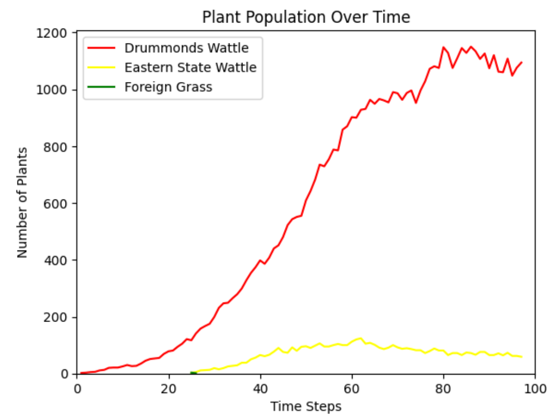
Drummond Wattle Control	Drummond Wattle Altered
	

Figure 9

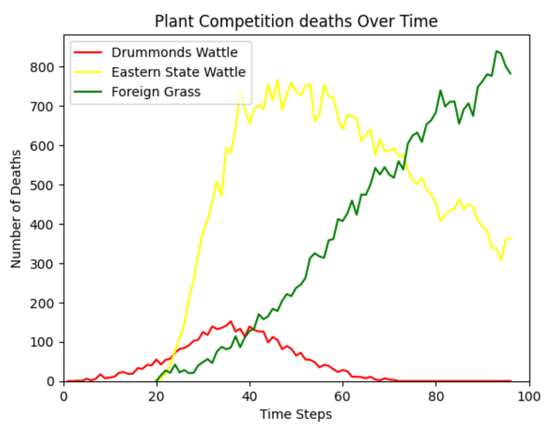
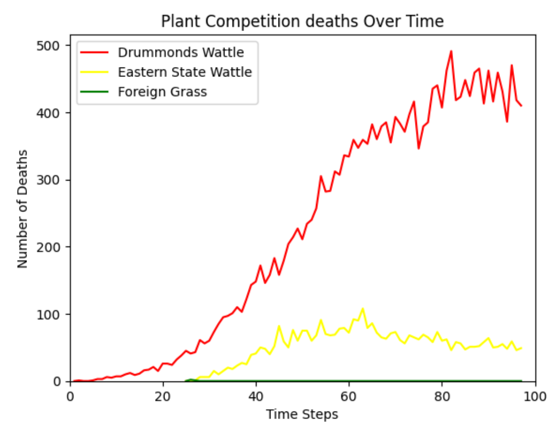
Drummond Wattle Control	Drummond Wattle Altered
	

Figure 10

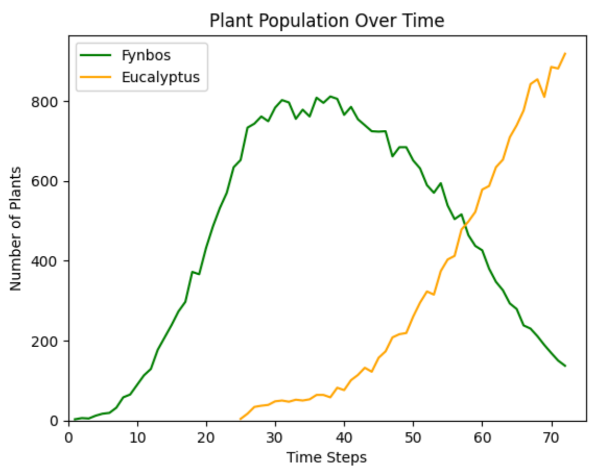
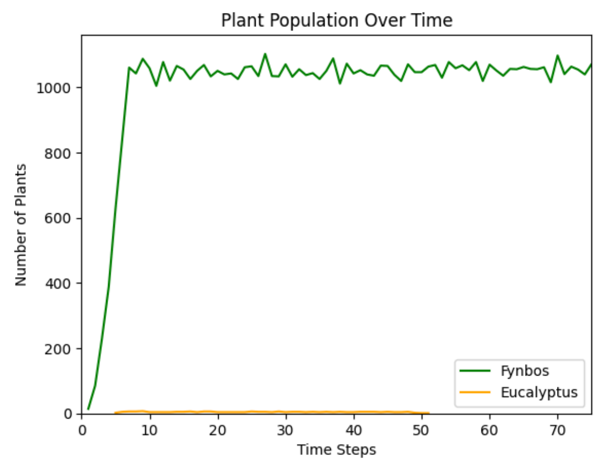
Eucalyptus vs Fynbos Control	Eucalyptus vs Fynbos Altered
	

Figure 11

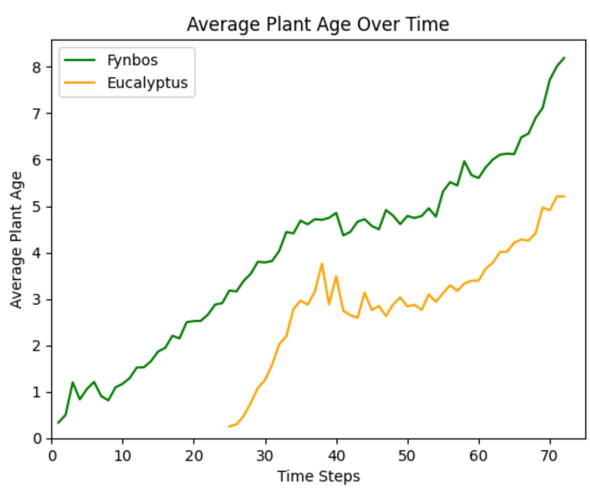
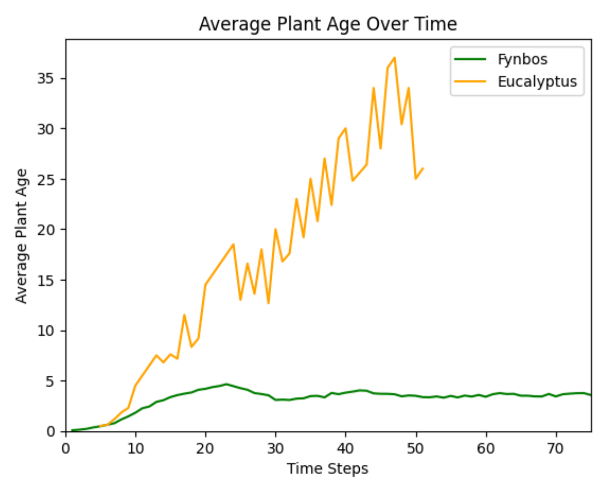
Eucalyptus vs Fynbos Control	Eucalyptus vs Fynbos Altered
	

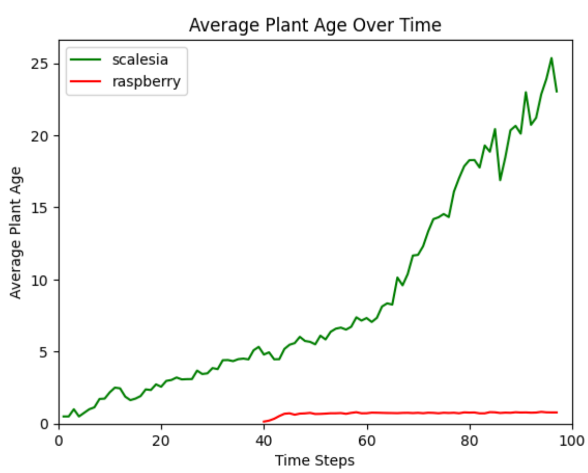
Figure 12

Scalesia vs Raspberry Control

Scalesia vs Raspberry Altered

Figure 13

Scalesia vs Raspberry Control



Scalesia vs Raspberry Altered