Invaders on Daisyworld: A Computer Simulation of Invasive Species

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Keywords: TODO

ABSTRACT GOES HERE TODO

1 Introduction

A healthy ecosystem exhibits homeostatic properties[1] that maintain an environment hospitable to the native species, allowing for a stable system in situations where life may not normally exist. External pressures such as climate change may cause an ecosystem to collapse given there is a large enough change that the system cannot react in time[2]. If the change is not large enough so that the system can adapt, the additional stress of the introduction of a non-native species can cause the adaptation to fail and the collapse of the ecosystem's homeostasis[3].

To explore the extent of which an ecosystem can adapt to a changing environment, a computer simulation of DaisyWorld[4] was developed. This model is *Agent based*[5], where the ecosystem is simulated by aggregation of many simple autonomous agents that perform simple tasks. By being made up of these agents the system can exhibit complex behaviour through their interactions.

In the original specification of Daisyworld, there are only two kinds of daisies, black and white. These two daisies flourish at the same temperature, only differing by the amount of incident radiation that they absorb. It is this difference in albedo that causes either type of daisy to warm or cool it's local environment. As the local temperature strays from the optimal growing temperature of the daisies, the chance of that daisy dying increases. Hence daisies that cause the temperature to deviate from their optimal temperature die more often, causing the global temperature to converge to the daisies growing temperature.

This paper tests the introduction of a third type of daisy with the same albedo as the “black” variant of daisy, but with a higher optimal temperature. It can therefore warm up it's environment and overtake the two native species in certain conditions, much like an invasive species in real life.

TODO: describe what happens?

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This paper is split up into the following sections, each discussing different parts of the aforementioned system.

- Method
- Results
- Analysis and discussion
- Future work
- Conclusion

2 Method

This agent based model of daisyworld is implemented on a two dimensional grid, with opposing sides connected to one another (the surface of a torus in 3d space). This grid is split up into tiles, that may or may not contain a daisy. Each tile modifies it's local temperature at each time step based on the albedo of the object at it's location and the current incident radiation. This incident radiation is controlled by a sun object that updates the solar luminosity at each time step.

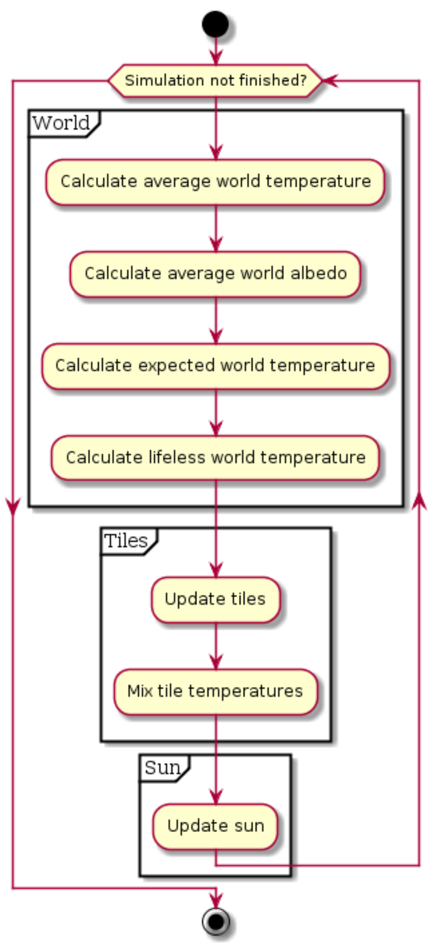

Figure 1: World update program flow

2.1 World

The world is implemented in a two dimensional grid, with opposing sides connected to one another. Each tile in this grid has it's own local temperature and object that lives at that location. It is this object that defines the albedo of the tile. At each iteration or timestep the following is calculated and written to file for later processing.

2.1.1 Average Temperature

This is calculated by the following equation for a world that has dimensions m by n.

$$T_{av} = \frac{1}{mn} \sum_{i=1}^{m} \sum_{j=1}^{n} T(i,j) \tag{1}$$

Where

Where $T(i,j)$ is the temperature of the tile located at coordinates (i,j).

2.1.2 Average Albedo

The following equation is used to calculate the average albedo of a world of dimensions m by n.

$$A_{av} = \frac{1}{mn} \sum_{i=1}^{m} \sum_{j=1}^{n} A(i,j) \tag{2}$$

Where $A(i,j)$ is the albedo of the tile located at coordinates (i,j).

2.1.3 Expected temperature from average albedo

This is the expected temperature of the world, if the only updates to the system was to the temperature, the global average would eventually converge to this value.

$$T_{ex} = \sqrt[4]{\frac{S \cdot L \cdot (1 - A_{av})}{\sigma}} + 273 \tag{3}$$

Where:

- S is a constant having units of flux
- L is the luminosity of the worlds sun
- σ is Stefan's constant
- A_{av} is the average albedo from the previous section

Note that this is equation **(4)** in [4] reordered to make T_e the subject.

2.1.4 Expected temperature of a lifeless world

This is the expected temperature of the world at the current amount of incident radiation for a world where life does not exist. Since the albedo of bare ground is 0.5[4] this temperature can be defined by:

$$T_{nl} = \sqrt[4]{\frac{S \cdot L \cdot 0.5}{\sigma}} + 273 \tag{4}$$

Where:

- S is a constant having units of flux
- L is the luminosity of the worlds sun
- σ is Stefan's constant
- A_{av} is the average albedo from the previous section

Note that this is equation **(4)** in [4] reordered to make T_e the subject.

2.1.5 Amount of each type of daisy

The amount of each type of daisy is calculated by iterating over every tile and incrementing a type-specific counter, outlined in *Figure* 2.

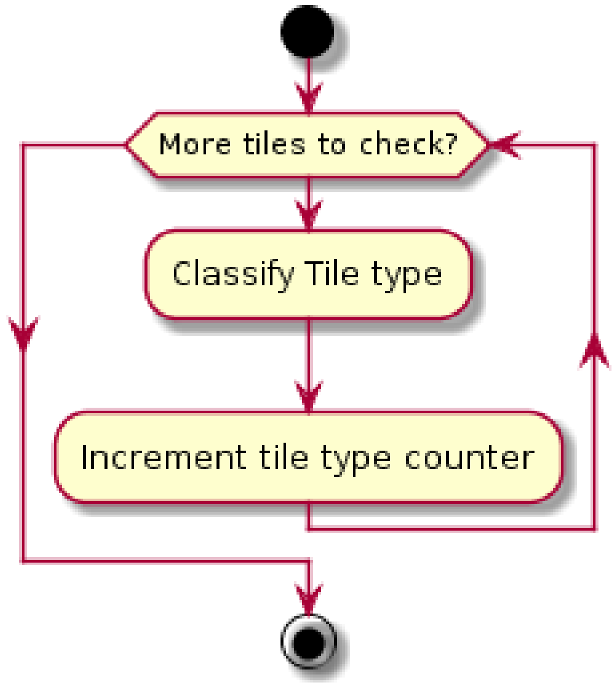

Figure 2: Sequence diagram for counting tile types

2.1.6 Tile update

After calculation of the world attributes, each tile is then allowed to update it's own attributes. Details into this process are in *Section* 2.2.

2.1.7 Temperature mixing

Temperature mixing is implemented by taking the average temperature of adjacent tiles and adding 20% of the difference to the current tile. Mathematically, this can be expressed as:

$$\Delta T = \frac{1}{4}\left(T(i-1,j) + T(i+1,j) + T(i,j-1) + T(i,j+1)\right) \tag{5}$$

Where $T(i,j)$ is the temperature of the tile at coordinates (i,j). This “wraps around” the grid, so $T(-1,-1)$ is equivalent to $T(M,N)$ for a M by N grid.

2.2 Tiles

Each tile has attributes consisting of temperature and albedo. The albedo is dependent on not only what type of daisy lives at that point, but whether or not there is a daisy at all. If no daisy exists at a timestep, the default albedo of bare ground (0.5) is used instead.

2.2.1 Updating

At each timestep each tile updates each of it's individual components. This comprised of the current local temperature, whether or not a daisy exists at the current tile and the type of that daisy.

2.2.1.1 Temperature

For each tile, a portion of the difference between the ideal temperature of the tile (calculated via the *Stefan-Boltzmann law*) is added to the current temperature of the tile.

Expressed formally:

$$\Delta T_{t+1} = \alpha \cdot \sqrt[4]{\frac{S \cdot L \cdot (1 - A_t)}{\sigma}} + 273 - T_t \tag{6}$$

Where:

- T_t is the temperature at the current timestep
- T_t is the temperature at the next timestep
- σ is Stefan's constant
- S is a constant having units of flux
- L is the luminosity of the worlds sun

- A_t is the albedo of the tile at the current timestep
- α is a constant between 0 and 1 to indicate the amount of difference to add to the T_t

For this model, α was chosen to be 0.01.

2.2.1.2 Germination

The type of daisy to spawn is based on the daisies in adjacent tiles, diagonal exclusive. If no daisies exist an adjacent tile, it contributes a small chance for any type of daisy to grow.

The chance to attempt to spawn a type of daisy can be expressed by:

$$S_t = \frac{C_t + W \cdot C_b}{4} \tag{7}$$

Where:

- S_t is the chance to attempt to spawn that type of daisy
- C_t is the count of adjacent daisies of that type
- C_b is the count of adjacent blank tiles
- W is a constant defining blank tile contribution to any tile.

W is defined as 0.05. This means that a tile surrounded by blank tiles has a 20% chance to attempt to spawn any type of daisy.

If a daisy does not successfully spawn, the next type is randomly chosen to spawn off (after exclusion of any previously attempted types).

2.3 Daisies

Daisies have two attributes, albedo and optimal growing temperature. These are static from life until death from the perspective of the daisy.

2.3.1 Albedo

The albedo is used to calculate the amount of energy reflected back from the surface of the tile. A value close to 0 corresponds to a large amount of energy being absorbed, while a value close to 1 indicates the opposite.

White daisies correspond to an albedo of 0.75, while black correspond to an albedo of 0.25.

2.3.2 Optimal growing temperature

Optimal growing temperature is where the chance of spawning the selected daisy at a given tile is 1. Following the original Daisyworld model, this is defined as:

$$\beta = \begin{cases} 1 - 0.0003265(T_{opt} - T_t)^2 & -17.5 + T_{opt} \leq T_t \leq 17.5 + T_{opt} \\ 0 & \text{Otherwise} \end{cases} \tag{8}$$

Where:

- β is the spawn chance or growth rate
- T_{opt} is the optimal growing temperature of the given type of daisy.
- T_t is the current temperature of the tile attempting to spawn a daisy.

Note that the death rate (γ) of the daisies was modified to be $1 - \beta$ from the original model. This reflects the agent-based implementation of this system, as a daisy located in a hostile environment will be more likely to die compared to one in a friendly environment.

The "native" daisies given in the original daisyworld and mirrored here both have an optimal growing temperature of 22.5 degrees Celsius.

2.3.3 Invasive species

The modification introduced is a new type of black daisy with a different - higher - optimal growing temperature to "native" daisies.

This is an attempt to emulate a new species that modifies it's environment in a way that native species can no longer grow, hence barring the native species from growing in the same area.

The general intention of this is if the invasive daisies out-compete the natives to a high enough degree, homeostasis will be broken and the ecosystem will collapse, much like real life ecosystems.

2.4 Sun

The sun only has one attribute, the incident solar luminosity on the world. This is normalized so that if the luminosity is 1 and the world is lifeless, the average temperature should be 22.5 degrees Celsius.

3 Results

The simulation was run for 100000 timesteps, on a grid of 50 by 50 tiles. Once each simulation was completed, 95% confidence interval is calculated of all simulations so far of that type and is held against the following conditions:

- The confidence interval is less than 0.5 degrees
- The confidence interval does not overlap the confidence interval of adjacent parameters unless it converges to less than 0.5 degrees.
- There has been a minimum of 10 simulations of that parameter
- There has been a maximum of 30 simulations of that parameter

Once all of these conditions are met for all simulations, plots are made and simulation stops.

The parameter varied between runs was the optimal growing temperature of the invasive daisies, from 22.5 to 60.5 in 1 degree steps.

On the left is the global temperature vs solar luminosity. Blue is the average global temperature with error bars indicating the 95% confidence interval. Red is the expected temperature for a lifeless planet.

On the right is the global amount of each type of daisies.

- Blue is the amount of blank tiles
- Black is the amount of black daisies
- Green is the amount of white daisies
- Red is the amount of invasive black daisies

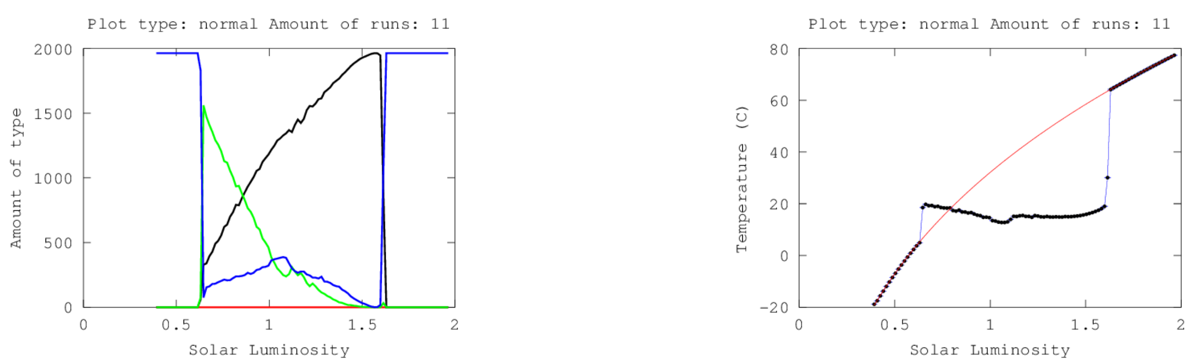

Figure 3: Normal simulation

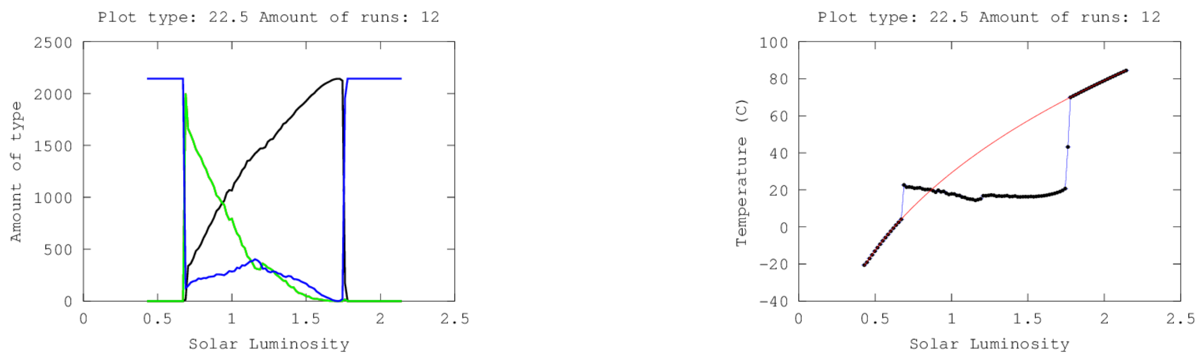

Figure 4: Simulation with invasive blacks at 22.5 degrees

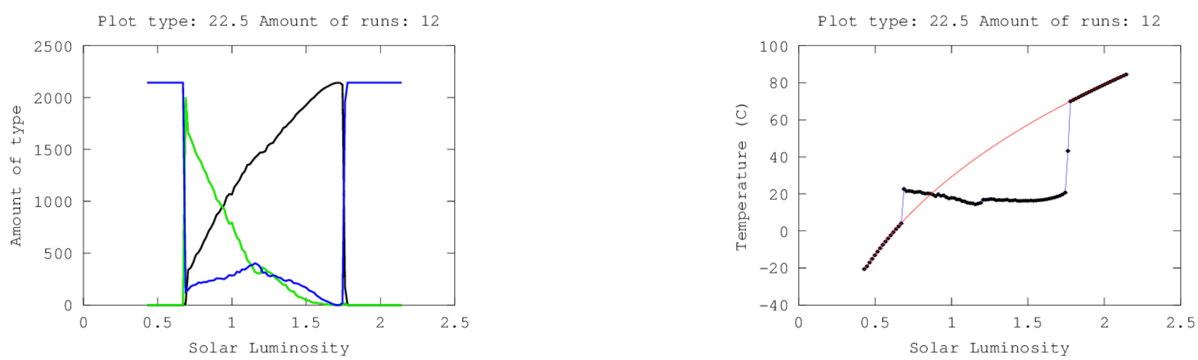

Figure 5: Simulation with invasive blacks at 22.5 degrees

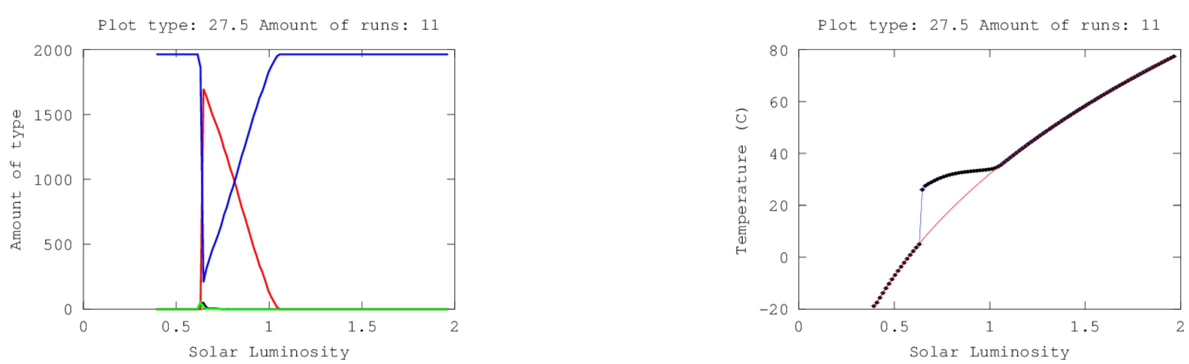

Figure 6: Simulation with invasive blacks at 27.5 degrees

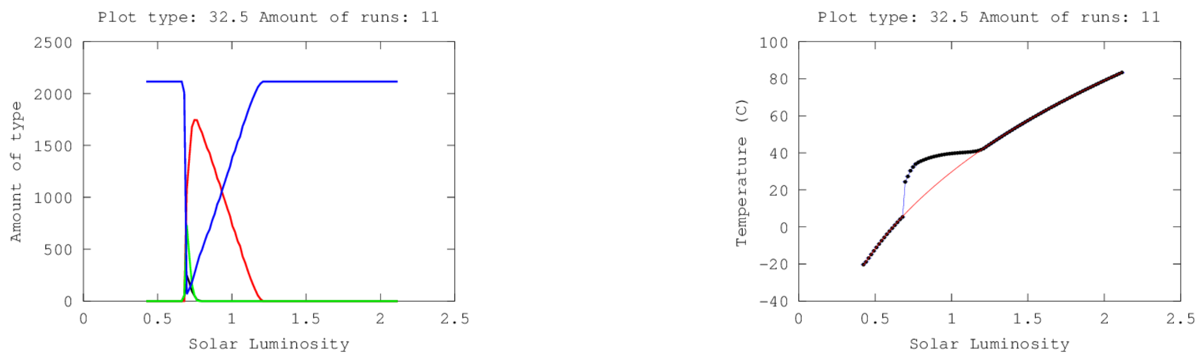

Figure 7: Simulation with invasive blacks at 32.5 degrees

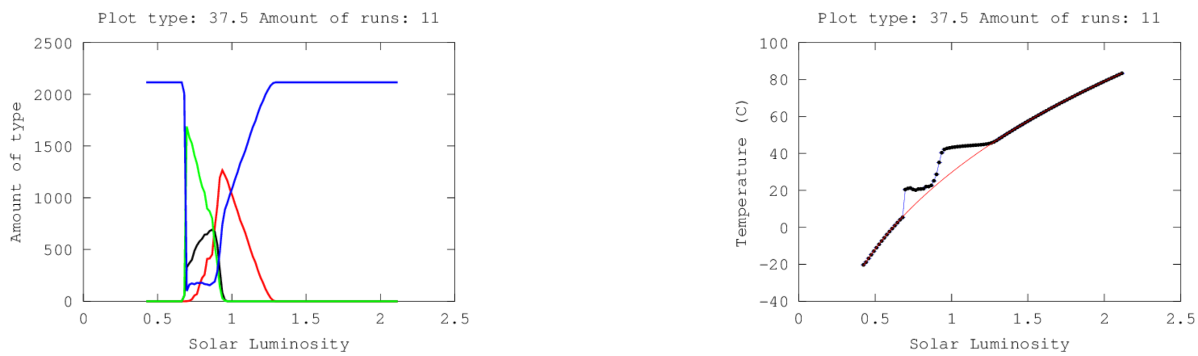

Figure 8: Simulation with invasive blacks at 37.5 degrees

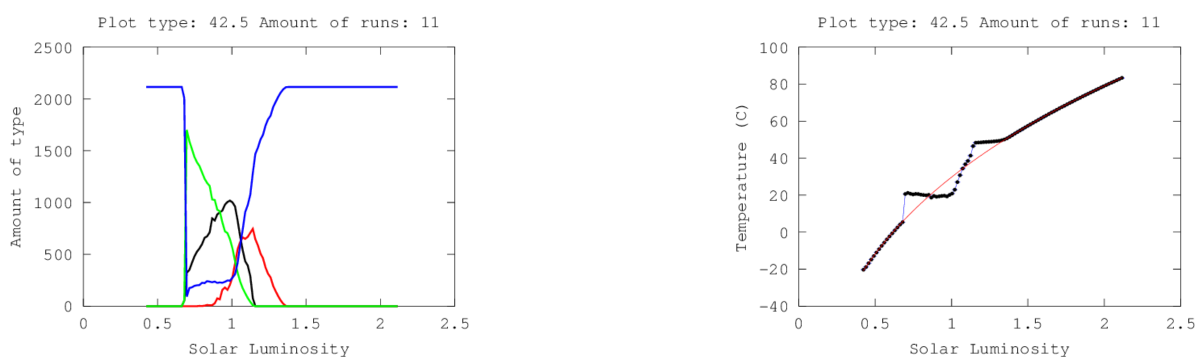

Figure 9: Simulation with invasive blacks at 42.5 degrees

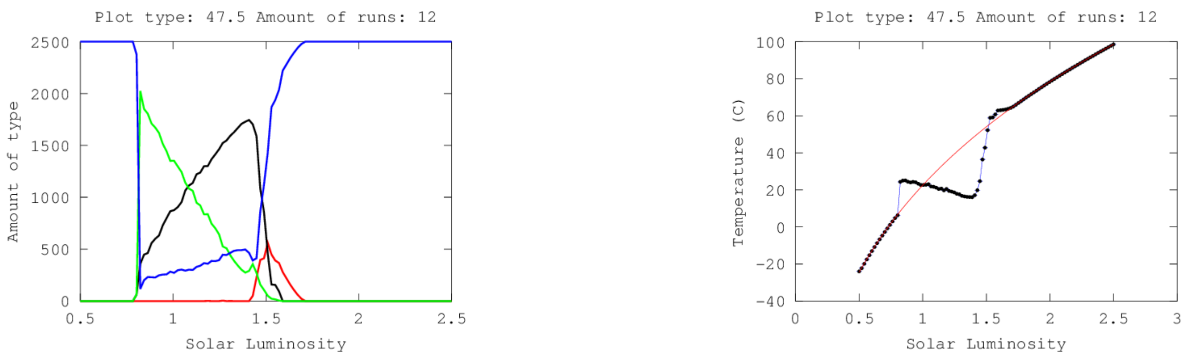

Figure 10: Simulation with invasive blacks at 47.5 degrees

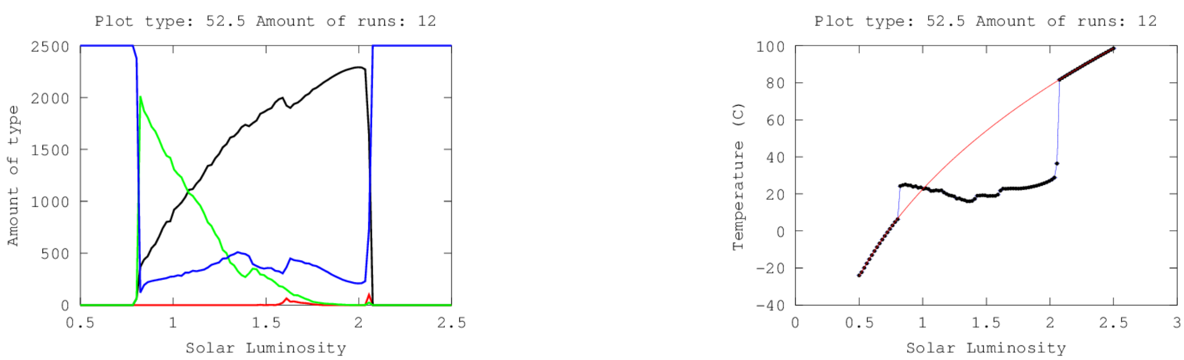

Figure 11: Simulation with invasive blacks at 52.5 degrees

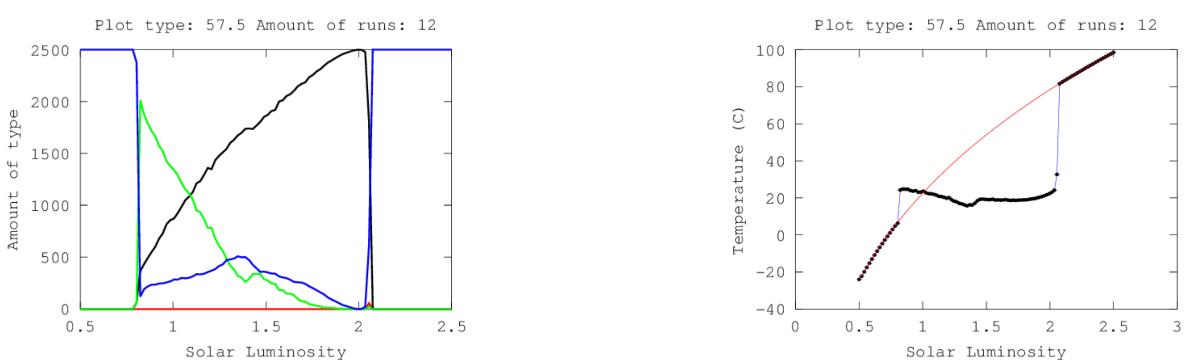

Figure 12: Simulation with invasive blacks at 57.5 degrees

4 Analysis & Discussion

There seem to be three behaviours of the system with these parameters:

- Maintained homeostasis
- Immediate homeostasis breakdown
- Held-off homeostasis breakdown

These are explored in the following sections.

4.1 Maintained homeostasis

When the introduced species is extremely similar, or extremely dissimilar, to the native species, homeostasis is maintained. This could be the result of either of two cases:

4.1.1 Extreme similarity

The similarity between the introduced species and the natives means that all species are attempting to keep their environment at the same temperature (or close enough to maintain homeostasis). This can be seen in graphs with optimal growing temperature of 22.5 to 25.5 degrees Celsius.

4.1.2 Extreme dissimilarity

The dissimilarity between the native species and the introduced means that the new species never actually gets to grow at any stage when the system is in homeostasis. The parameters that exhibit this behaviour is 54.5 degrees Celsius and upwards.

Some analysis of the optimal growing temperature and it's range fully explains this behaviour. Since the native daisies can only grow in the range of 22.5 ± 17.5 degrees, the upper temperature limit of 40 degrees is very much below the 54.5 degrees where this behaviour starts.

4.2 Immediate homeostasis breakdown

This is seen in optimal growing temperatures 26.5 to 31.5 degrees Celsius. An explanation of this is that when the system first attempts to establish homeostasis the invasive daisies take over immediately and quickly make the environment too hot for the natives.

The initial establishment of homeostasis is not a valid state of an ecosystem on earth in current times, hence this region is a candidate for further exploration, although it may be very similar to the next Sexton.

4.3 Held-off homeostasis breakdown

This is a very interesting region, occurring in the temperature range of 32.5 to 53.5 degrees Celsius. Homeostasis is established, but as the sun grows hotter and forces the system to adapt, the invasive species takes hold and breaks homeostasis.

This mirrors ecosystems on earth, where an environment that would normally be able to fend off an invasive species cannot due to external stresses[6].

5 Future work

A more in depth exploration of the three regions (especially the “Held-off homeostasis breakdown” and the “Immediate Homeostasis breakdown”) regions. Specifically:

- What conditions are required for the invasive species to take hold
- Why does the system sometimes not collapse for the same parameters, what is the difference?
- How does the invasive species actually take hold?

- How much of the world is required to be invasive species before homeostasis breaks down?
- What would the difference be for a invasive species that cools a warming daisyworld as opposed to warming it?

6 Conclusion

A healthy ecosystem that may normally be able to withstand an invasive species can succumb when put under excessive stress, such as climate change. This simulation exhibits behaviour similar to ecosystem breakdown in these conditions. Hence it may be an effective tool in the future exploration of the effects of ecosystem collapse due to the introduction of invasive species.

References

[1] Ernest, S. and Brown, J. (2001). Homeostasis and Compensation: The Role of Species and Resources in Ecosystem Stability. Ecology, 82(8), p.2118.

[2] Barry, G. (2014). Terrestrial ecosystem loss and biosphere collapse. Management of Env Quality, 25(5), pp.542-563.

[3] Rapport, D., Regier, H. and Hutchinson, T. (1985). Ecosystem Behavior Under Stress. The American Naturalist, 125(5), p.617.

[4] Watson, A. J. and J. E. Lovelock, 1983: Biological homeostasis of the global environment: the parable of daisyworld. *Tellus*, **35B**, 284–289.

[5] Gilbert, G. (n.d.). Agent-based models.

[6] Alpert, P., Bone, E. and Holzapfel, C. (2000). Invasiveness, invasibility and the role of environmental stress in the spread of non-native plants. Perspectives in Plant Ecology, Evolution and Systematics, 3(1), pp.52-66.