# Modelling the Gaia Hypothesis: Daisyworld

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*Abstract*— **The Gaia hypothesis examines the global effects of local interactions among organisms. A model commonly used to examine the global emergent properties proposed by the Gaia hypothesis is Daisyworld. The original Daisyworld relies on a deterministic set of equations to determine the outcome of the model. This project develops a two dimensional cellular automata (CA) representation of Daisyworld. By using a cellular automata and incorporating stochastic effects into the model, this project is able to develop a Daisyworld that takes into account both the spatial and stochastic characteristics of natural ecosystems.**

**The model developed is found to closely resemble results produced by a mathematical Daisyworld. The effects of death rate and solar luminosity on the CA Daisyworld are examined. It is found that lower death rate causes the daisies to adjust to varying solar luminosities more slowly, but it also enables them to survive longer when the solar luminosity is extremely high. The model is found to be able to adjust to changing solar luminosity and maintain a temperature that is close to the optimum temperature for daisy growth. Finally, the model is extended to include four species of daisies. The general properties of the four species Daisyworld are studied as well as the impacts of solar luminosity on this variant of the model.**

## I. Introduction

The Gaia hypothesis postulates that life on Earth works as a collective unit to ensure that conditions on Earth remain conducive to life. Some forms of the Gaia hypothesis attribute the maintenance of conditions on Earth to a macro-organism [1] and as a result the hypothesis has been somewhat controversial. However, principles at the core of the Gaia hypothesis are undeniable with applications across several disciplines of science.

The global regulation suggested in the Gaia hypothesis results from interactions between organisms and the environment. These interactions lead to the formation of feedback loops that control concentrations of various chemicals on Earth. The cycling of water, carbon, nitrogen and many other chemicals are natural examples of feedback loops that regulate concentrations of chemicals on Earth. As a result of these cycles, concentrations of chemicals on Earth are not consistent with the concentrations that would be observed on a planet at equilibrium, instead chemicals are present in concentrations that are suitable for life on Earth. For example, on a planet at equilibrium all oxygen would be bound in molecules with other elements, as a result there would be no oxygen left in the atmosphere. In contrast, the average amount of oxygen in the atmosphere of Earth is $21\%$. This can be attributed to the oxygen cycle maintaining concentrations of oxygen in the atmosphere at a level that is suitable for life.

Underlying the Gaia hypothesis is the idea of emergence on a global scale. Similar to the way ants can assemble complex structures without centralized control, organisms are able to produce a global environment that is conducive to life through interactions with other organisms and the abiotic environment. These simple interactions can have global impacts on conditions on Earth. For example, nitrogen fixing bacteria in soil fix nitrogen gas into inorganic compounds that can be used by plants to synthesize amino acids. This simple interaction is a key component of nitrogen cycling on Earth and helps ensure that nitrogen in the atmosphere and soil are in a balance that is suitable for life. However, it is carried out autonomously by simple bacteria with no centralized control.

The emergent properties suggested by the Gaia hypothesis can be observed in Daisyworld. Daisyworld is a model in which the Daisyworld planet orbits a sun that is warming slowly over time, similar to Earth. Life on Daisyworld is simplified to only include two species, black daisies and white daisies. The black daisies reflect less light back into space than the white daisies, this causes them to increase the global temperature. Similarly, white daisies reflect more light back into space, decreasing global temperature. These effects can be quantified by the albedos of each species of daisy. The albedo of the planet is calculated based on the quantities

of black and white daisies present on Daisyworld. This is explained further in Section II.

The original Daisyworld [2] is modelled using a deterministic set of differential equations. The model does not take into account the stochastic or spatial nature of interactions in a two dimensional or potentially three dimensional environment. With these considerations in mind, this project develops a two dimensional cellular automata (CA) that takes into account both spatial and stochastic elements of the Daisyworld model. Cellular automata have been previously used to model Daisyworld in [3], [4], [5], [6].

## II. Methodology

Daisyworld begins as a planet that is uninhabited by daisies. As the sun increases in intensity the temperature on Daisyworld increases. The temperature of the planet is impacted by the amount of light reflected by the planet back into space and the luminosity of the sun. The amount of light reflected back into space by the planet is determined by the albedo of the planet, which is impacted by the amount of black and white daisies on its surface. This section describes the equations that control the dynamics of Daisyworld and how they are applied to create a two dimensional cellular automata of the planet. The variant of Daisyworld described is from [7].

### A. Temperature

Temperature of Daisyworld is influenced by the albedo of the planet and the luminosity of the sun, it is governed by the following physical laws. Temperature of Daisyworld is calculated using the Stephen Boltzmann Law:

$$E_{em} = \epsilon \sigma_{SB} A T_p^4 \tag{1}$$

Where $E_{em}$ is the amount of energy emitted by the planet, $\sigma_{SB}$ is the Stephen Boltzmann constant, $A$ is the surface area of the planet and $T_p$ is the temperature of the planet. The value of the Stephen Boltzmann constant is 5.67e-8 J/sec $m^2K^4$. Also, surface area of the planet, $A$, is taken to be a unit value of 1.

It is assumed that the planet is in radiative equilibrium. Thus it follows that $\epsilon$ will be a unitless constant. The following equality also holds:

$$E_{em} = E_{abs} \tag{2}$$

Where $E_{abs}$ is the amount of energy absorbed by the planet. By using knowledge of physical systems it follows that:

$$E_{abs} = E_{rec} - E_{ref} \tag{3}$$

Where $E_{rec}$ and $E_{ref}$ are the amount of energy received and reflected by the planet, respectively. By the laws of physics these quantities can be described by:

$$E_{rec} = S \times L \tag{4}$$

$$E_{ref} = E_{rec} \times \alpha_p \tag{5}$$

Where $S$ is the solar flux constant with a value of 917W/$m^2$, $\alpha_p$ is the planetary albedo and $L$ is the solar luminosity. Solar luminosity for the above equation may be calculated in one of two ways. The first method is to use an automatic linear increase in luminosity at each time step in the simulation. Also, a manual method to adjust luminosity is provided in this project.

By substituting Equations 3, 4, and 5 into Equation 2 the following equation can be derived:

$$E_{em} = S \times L(1 - \alpha_p) \tag{6}$$

After substituting Equation 6 into Equation 1 and simplifying, the following formula for temperature is reached:

$$T_p = \sqrt[4]{\frac{S \times L(1 - \alpha_p)}{\epsilon \sigma_{SB}}} \tag{7}$$

It remains to be shown how the albedo of the planet, $\alpha_p$, is calculated in the above equation. Planetary albedo is determined by the following formula:

$$\alpha_p = \alpha_w a_w + \alpha_b a_b + \alpha_{un} a_{un} \tag{8}$$

where $\alpha_w$, $\alpha_b$ and $\alpha_{un}$ are the albedos of white daisies, black daisies and bare land, respectively. The percent of the planet covered by white daisies, black daisies and bare land are represented by $a_w$, $a_b$ and $a_{un}$. All of the albedo values are between 0 and 1. This formula effectively weights the albedo of each species by the amount of area it covers when determining the planetary albedo.

### B. Growth of Daisies

The area of land covered by daisies is governed by daisy growth. Daisy growth is modelled according to the following equations.

$$\frac{da_s}{dt} = a_s(a_{un} g_s - deathrate) + 0.001 \tag{9}$$

$$1 - \frac{4}{(40-5)^2}(22.5 - T_s)^2 \tag{10}$$

$$F_{HA}(\alpha_p - \alpha_s) + T_p \tag{11}$$

Where $\frac{da_s}{dt}$ is the change in area for daisy species $s$ in time $t$. The growth factor of the daisy species, $g_s$, is represented using a parabola with a maximum of 1 at

the optimal temperature for daisy growth. Growth may only occur in a limited range of temperatures, when $T_s$ is not between $5°$C and $40°$C growth will not occur. $T_s$ denotes the local temperature for each species of daisy. In this equation, $F_{HA}$ is the heat absorption factor that is set to 20.

### C. Cellular Automata Rules

Using the aforementioned equations, rules for a cellular automata (CA) Daisyworld are developed. These rules aim to capture some aspects of realistic daisy growth, while ensuring growth patterns follow the general pattern described by the formulas. Daisy growth is dictated by the following rules:

- If the change in area for a daisy species $s$, is greater than 0, daisies of this species will consider their neighbors.
  - If the amount of neighboring cells occupied by daisies (of any species) is less than a spreading threshold, then the bare neighbors of the current cell will grow daisies with probability, $p = c \times da_s/dt$.
  - If the number of neighbors occupied by other daisies is greater than the spreading threshold a new patch of daisy species $s$ will be started at a random location.
- If the change in area for species $s$ is not greater than 0, then daisies of species $s$ will die with probability, $p = -da_s/dt$.

In the above rules, $c$ is a constant value to help accelerate daisy growth. Before the addition of this constant the daisies were not able to grow fast enough to keep up with changing solar luminosity. This constant is currently set to 9. The spreading threshold helps avoid daisy growth being limited by over crowding and can be adjusted dynamically from within the model interface.

## III. Results

To evaluate the effectiveness of the two dimensional cellular automata (CA) Daisyworld, several tests were run. In each case various parameters were set to default values, unless otherwise specified by the experiment. The baseline parameters include an automatic linear increase of temperature. Death rate is set to 0.3, spreading threshold is set to 7 and optimal daisy growth temperature is set to $22.5°$C. The albedos of black daisies, white daisies and bare land are set to 0.25, 0.75 and 0.50, respectively.

Experiments run on the model attempt to verify the accuracy of the model as well as testing the effects of modifying parameters on the model. These experiments include a comparison with a mathematical Daisyworld with the same parameters as the CA model. The effects of solar luminosity and varying death rate are also explored. The two species CA Daisyworld is then extended to include four species of daisies. The effects of solar luminosity are further examined on the four species model.

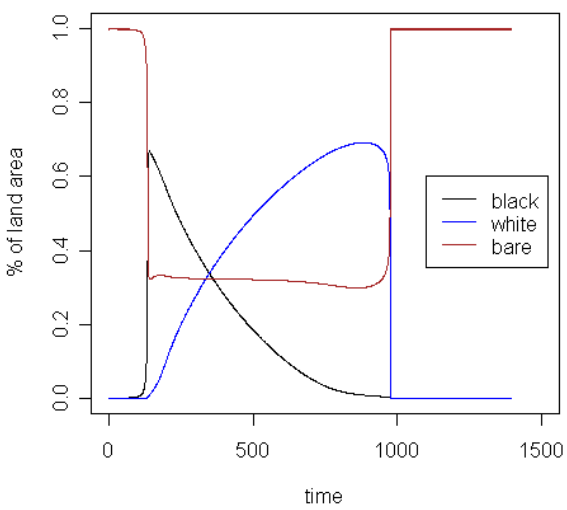
### A. Comparison with Mathematical Model

When compared with a mathematical Daisyworld with the same parameters, the CA model developed in this project produces similar results. Characteristics used to compare the two models include, area covered by each type of daisy, Figure 1, and temperature of Daisyworld, Figure 2.

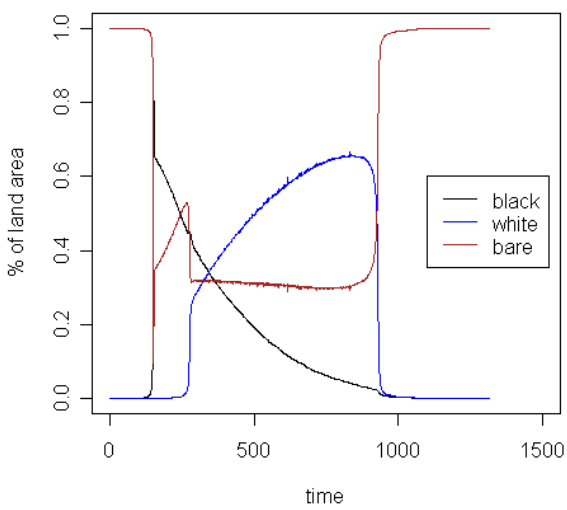
In the case of area covered by daisies, there is one main instance when the CA model does not match results reached in the mathematical case. This is at the beginning of the simulation when white daisies do not increase in area as rapidly as they do in the mathematical model. This problem is compounded by black daisies reaching a much higher initial peak in the CA model, as well as decreasing in area more slowly than they do in the mathematical model. As a result, the white daisies have to compete with more black daisies initially, this may be partially responsible for the delayed growth of the white daisies.

The impact of the higher initial peak in the amount of black daisies on temperature is illustrated in Figure 2 (b). Initially, the temperature is higher than the ideal temperature for the daisies. Then, as a result of the black daisies not decreasing in area as fast as they do in the mathematical model, the temperature remains above the ideal temperature for a longer period of time than it does in the mathematical model.

In both Figure 1 and Figure 2, the effects of randomness on the CA Daisyworld can be observed. The effects of using stochastic processes to control the growth and death of the daisies is evident in noise effects on the quantities of daisies. Despite the effects of noise on the system, both the mathematical and CA models show similar overall trends. This suggests that for the simple case, the mathematical model may be a good method to study the dynamics of Daisyworld. However, for examining more complicated situations on Daisyworld the CA model may prove to be more convenient and similar to natural processes because of its stochastic and spatial components.

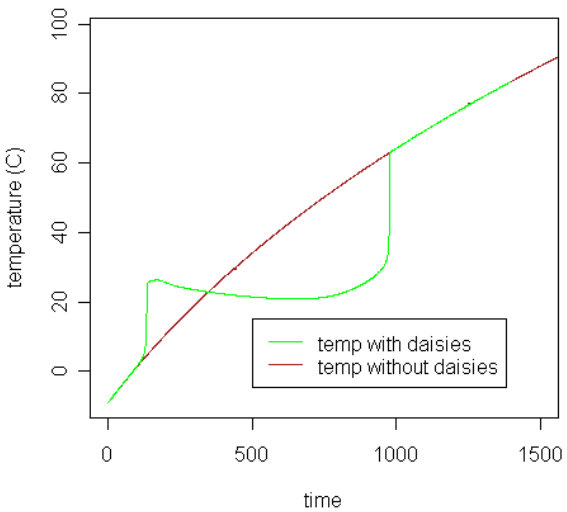



(a) Mathematical Model

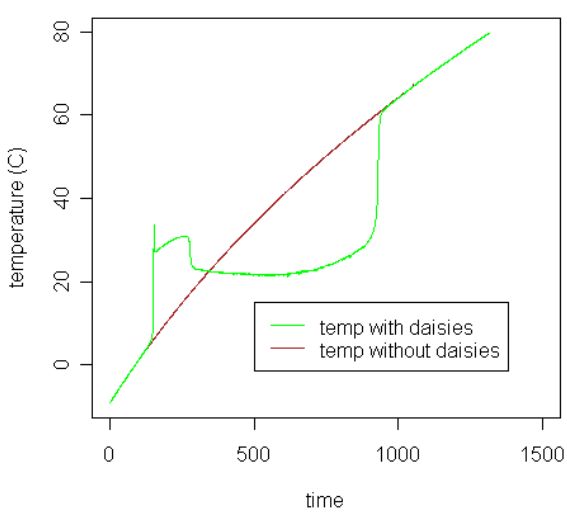



(b) CA Model

Fig. 1. Comparison of Area Covered by Daisies in the Mathematical Model to CA Model of Daisyworld

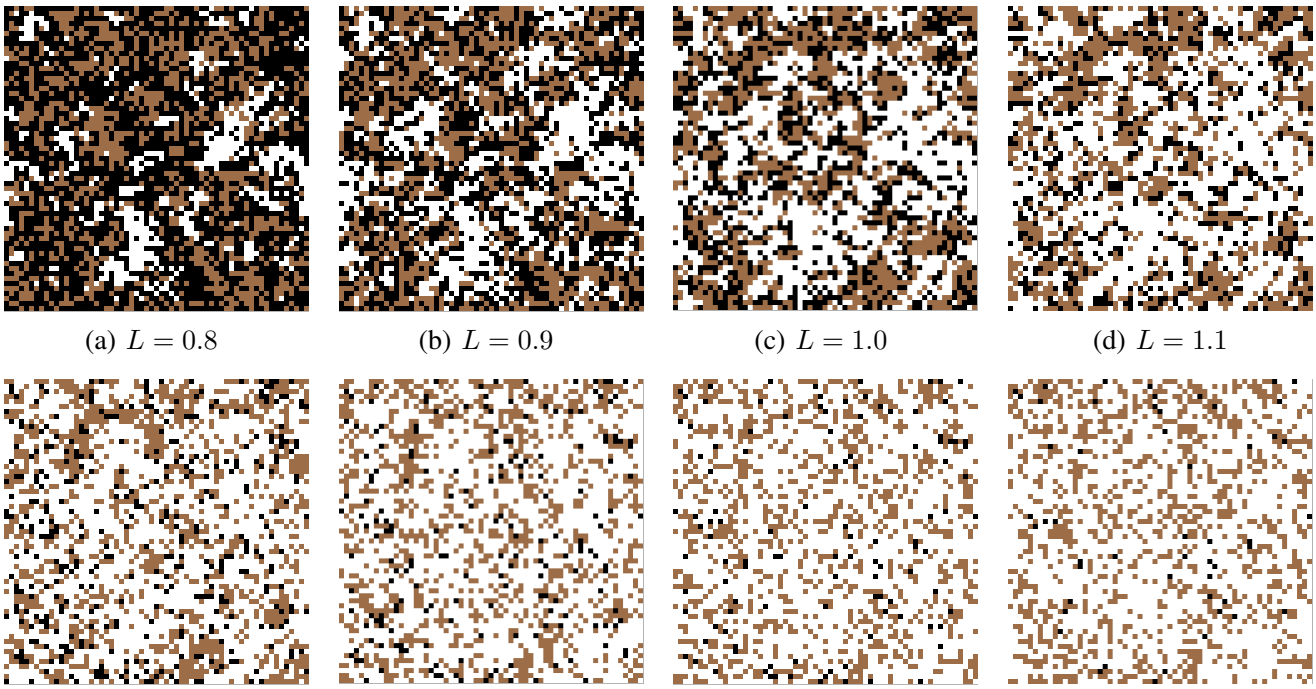



(a) Mathematical Model




(b) CA Model

Fig. 2. Comparison of Temperature in the Mathematical Model to CA Model of Daisyworld



(a) $L = 0.8$ (b) $L = 0.9$ (c) $L = 1.0$ (d) $L = 1.1$

(e) $L = 1.2$ (f) $L = 1.3$ (g) $L = 1.4$ (h) $L = 1.5$

Fig. 3. Effects of Solar Luminosity ($L$) on Two Species Daisy World

TABLE I
AVERAGE TEMPERATURE OF TWO SPECIES DAISYWORLD WITH VARYING SOLAR LUMINOSITY

| L | Avg. Temp (°C) |
|---|---|
| 0.6 | -9.066 |
| 0.7 | 1.803 |
| 0.8 | 23.725 |
| 0.9 | 22.416 |
| 1.0 | 21.343 |
| 1.1 | 20.507 |
| 1.2 | 20.000 |
| 1.3 | 20.529 |
| 1.4 | 23.111 |
| 1.5 | 27.204 |

### *B. Effects of Solar Luminosity on Daisyworld with Two Species*

To examine the effects of solar luminosity on Daisyworld the parameters of the model were set to the default values mentioned above. However, solar luminosity modification was set to manual. At each time step the solar luminosity was set to a specified value and the model was given time to adjust to the new solar luminosity. This was done by waiting until populations of each type of daisy reached a relatively constant value. Screen shots were taken for each solar luminosity (Figure 3) and average temperatures for each solar luminosity were recorded. Due to space constraints, only solar luminosities from 0.8 to 1.5 are illustrated in Figure 3. Outside of these solar luminosities there was no sustained daisy growth.

The self regulation of temperature by daisies on Daisyworld is illustrated in Figure 3. It is evident that in order to keep the temperature close to the optimal temperature for daisy growth, the amount of each species of daisy changes depending on the solar luminosity. This can be attributed to the feedback mechanisms employed in the Daisyworld system. If one species of daisies dominated, for example, white daisies, the overall temperature of the planet would decrease. Also, since the albedo of the white daisies is lower than the albedo of the planet, this would cause the local temperature of the white daisies to amplify their cooling effect. This would limit their growth and cause the area occupied by white daisies to decrease. This feedback mechanism guides the planet into a state where each species occupies an appropriate amount of land to sustain a planetary temperature that is ideal for daisy growth.

The average temperature recorded for each solar luminosity is very close to the optimal temperature for daisy growth, with the exception of when solar luminosity is 1.5. When the solar luminosity is 1.5, the intensity of the

sun is too high for the daisies to effectively regulate the temperature. At other solar luminosities, however, the emergent property of temperature regulation keeps the temperature of the planet close to the ideal temperature for daisy growth. The emergence of this temperature regulation should be emphasized, because the daisies do not follow any centralized control to reach the appropriate quantities to sustain an ideal temperature for growth. Instead they grow or die based on the feedback mechanism discussed above, as a result causing the temperature of the planet to stay within a suitable range for the daisies to survive.

### C. Effects of Death Rate on Daisyworld

The effects of varying the death rate of daisies is examined in Figures 4 and 5. Death rate was examined to determine its effects on how quickly the model can adjust to increasing values of solar luminosity. The automatic linear increase of solar luminosity was used.

Intuitively, the area covered by the daisies is impacted by varying the death rate of the daisies. When the death rate of daisies is lower, the planet is dominated by daisies and the amount of bare land is reduced. As death rate increases, the amount of land covered by daisies decreases.

Death rate also has impacts on how well the model can regulate temperature. This can be observed in the time that daisies stop being able to survive extremely high solar luminosity. In the case when death rate is equal to 0.1, the daisies are able to survive until approximately 1200 time steps. In contrast, when death rate is 0.5 the daisy population crashes well below 1000 time steps. When examining the temperature graphs, it is evident that when death rate is lower, it takes the model longer to adjust to non-optimal temperatures. In particular, when death rate is 0.1, the elevated temperature as a result of the initial spike in the black daisy population takes several time units to return to an ideal temperature. However, when death rate is set to 0.5 the initially elevated temperature is reduced more quickly. When the death rate is higher the daisies may be able to adjust to fluctuating solar luminosities more quickly. However, once solar luminosity is too high for the daisies to survive the higher death rate causes the daisy population to crash more rapidly than it would if the death rate is lower.

### D. Daisyworld with Four Species of Daisies

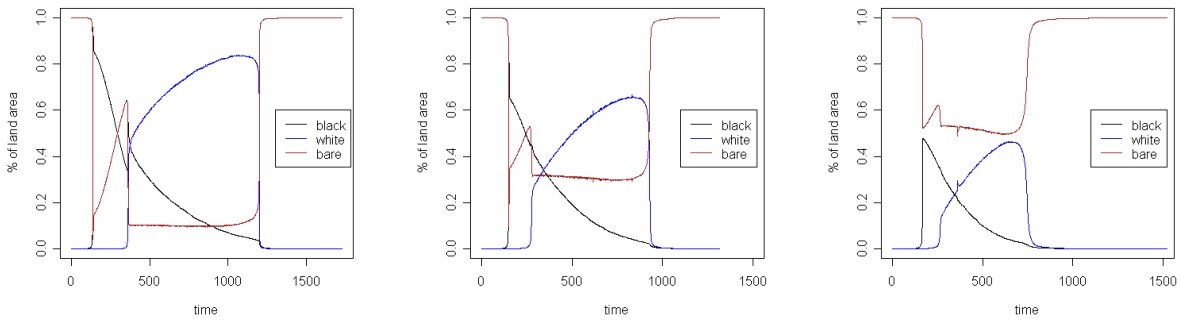
To gain more insights into the Daisyworld system the two species model is extended to include four species of daisies. The majority of the formulas for the original model remain unchanged. The calculation of the planetary albedo can be generalized to include more than two species as follows:

$$\alpha_p = \sum_{s \in \mathcal{S}} \alpha_s a_s + \alpha_{un} a_{un} \tag{12}$$

Where $\mathcal{S}$ is the set of all species and $\alpha_s$ and $a_s$ are the albedo and area of a species, respectively. Similar to the previous formula for planetary albedo, $\alpha_{un}$ and $a_{un}$ are the albedo and area of land not occupied by daisies. Also, in this new model the albedo of the species are set to 0.2, 0.4, 0.6 and 0.8 for red, orange, yellow and green daisies, respectively.

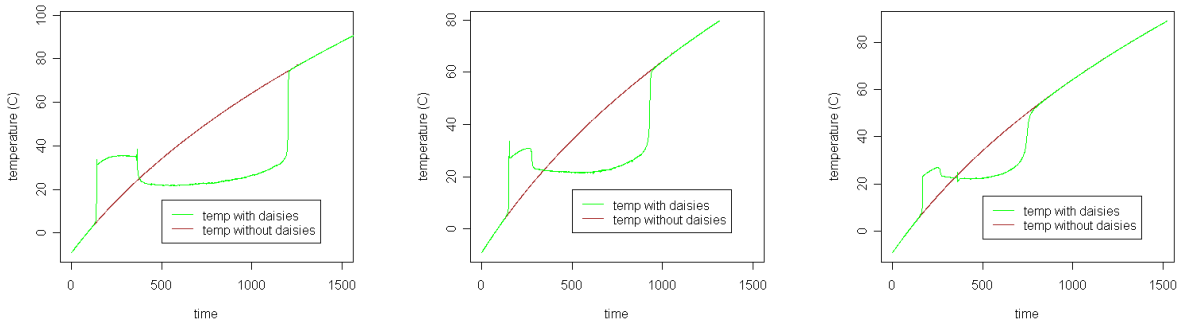
A motivation for including more species of daisies in Daisyworld is to explore what happens when the system has more species that it can utilize to achieve an optimal temperature. The base case, uses the default parameters described above, with the exception of albedos, which are modified for the four species case. In Figure 6 (a), the areas covered by each species of daisy during the simulation are plotted. Similar to the two species case, there are certain times in the simulation when specific species thrive. In particular, the daisy populations experience elevated populations in increasing order of their albedos. Also similar to the two species case, the lowest albedo species experiences a large spike at the beginning followed by a relatively slow decrease in population. The three higher albedo species experience a lag before they grow, during the spike and decrease period. One main difference between the two and the four species model, is the level of variability in the outcomes of the simulation. Although the red daisies experience a population spike first and the green daisies experience peak populations when solar luminosity is high, the quantities of orange and yellow daisies vary between trials. This can be attributed to impacts of using stochastic processes to control daisy growth on the simulation.

Since the growth factor of each species of daisy is calculated using Equation 10, the daisies still only grow in a narrow range of temperature with peak growth when the temperature is $22.5^{\circ}$C. As a result of this, the four species model does not provide any added benefit to the sustainability of optimal growth conditions on the planet, as illustrated in Figure 6 (b). Potentially if the species had different ideal temperatures this would not be the case.




(a) death rate $= 0.1$ (b) death rate $= 0.3$ (c) death rate $= 0.5$

Fig. 4. The Effects of Death Rate on Daisyworld




(a) death rate $= 0.1$ (b) death rate $= 0.3$ (c) death rate $= 0.5$

Fig. 5. The Effects of Death Rate on the Temperature of Daisyworld

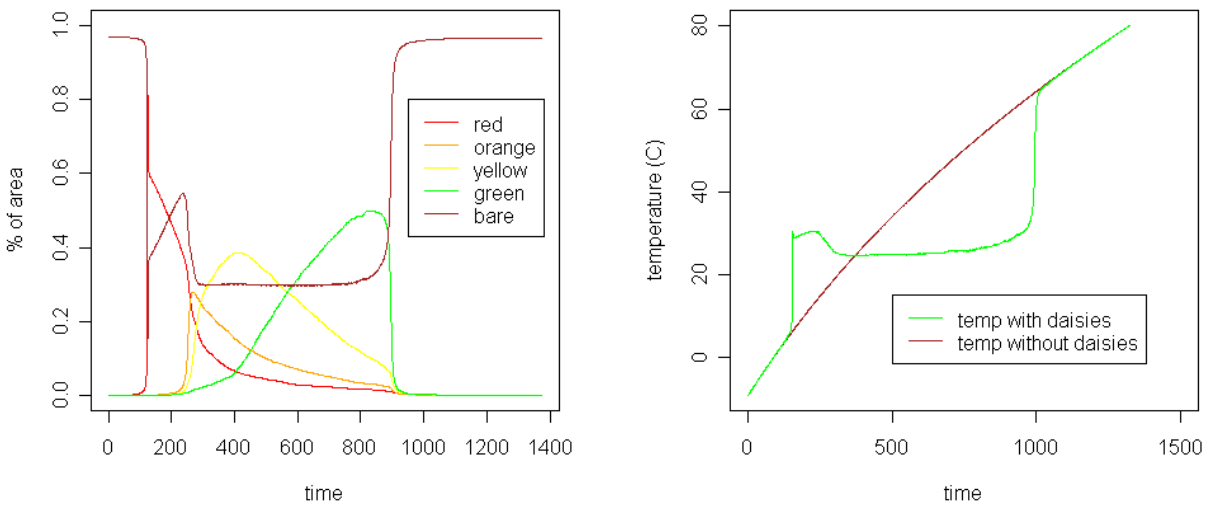
TABLE II
AVERAGE TEMPERATURE OF FOUR SPECIES DAISYWORLD WITH VARYING SOLAR LUMINOSITY

| L | Avg. Temp (°C) |
|---|---|
| 0.6 | -9.066 |
| 0.7 | 20.873 |
| 0.8 | 21.337 |
| 0.9 | 22.368 |
| 1.0 | 22.383 |
| 1.1 | 23.936 |
| 1.2 | 23.939 |
| 1.3 | 23.810 |
| 1.4 | 24.160 |

### *E. Effects of Solar Luminosity on Daisyworld with four species*

A study of the effects of changing solar luminosity is also carried out on the four species model (Figure 7). The average temperature for each value of solar luminosity is reported in Table II. Due to space constraints, images of Daisyworld are only included for solar luminosities between 0.7 and 1.4 inclusive. Outside of these solar luminosities the planet was not able to support daisy growth because the solar luminosity was either too high or too low.

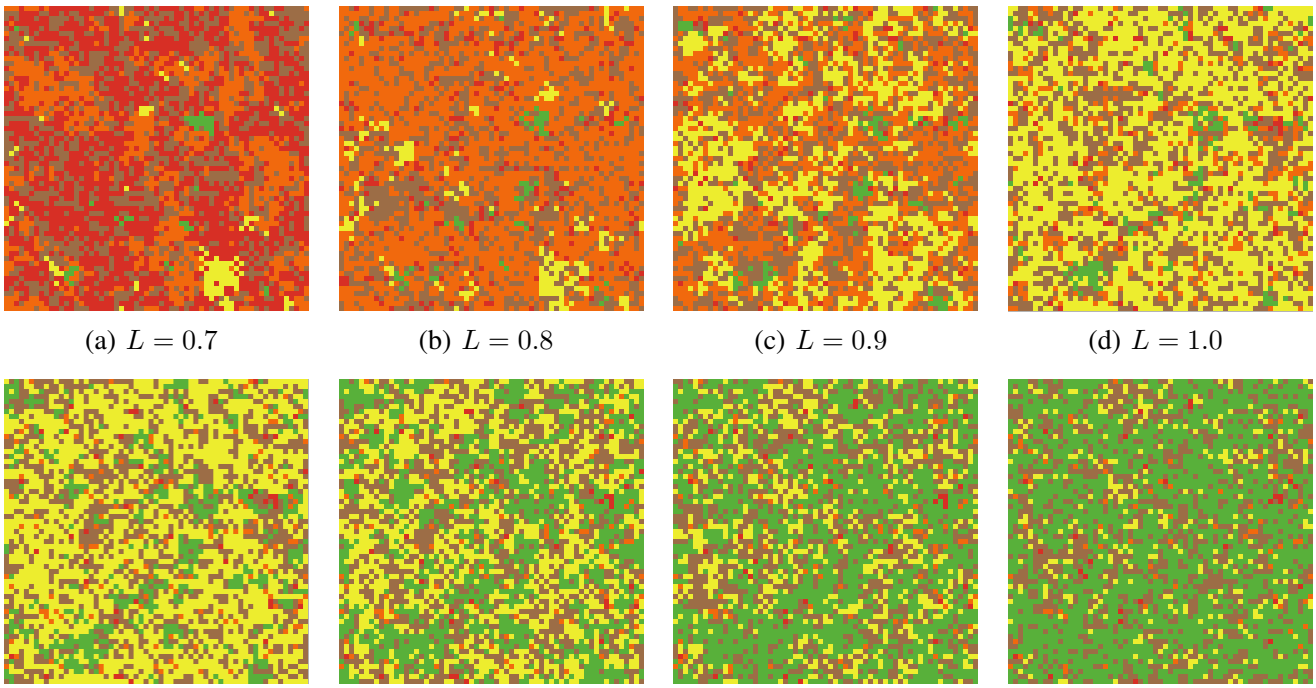
Similar to the two species model, the four species model of Daisyworld is able to keep the temperature of the planet ideal for life, despite increasing solar intensity. This is accomplished by varying the amount of each type of daisy to produce a global albedo that results in ideal global temperature for daisy growth. The continuous nature of the transition for each level of solar luminosity can be seen in the gradual change in dominance from the red to orange, yellow and eventually green daisies when the solar luminosity is very high. Depending on the previous conditions for each albedo there is potentially more than one stable state that will ensure temperature is




(a) Area Covered by Daisies

(b) Temperature

Fig. 6. Daisyworld with Four Species



(a) $L = 0.7$ (b) $L = 0.8$ (c) $L = 0.9$ (d) $L = 1.0$

(e) $L = 1.1$ (f) $L = 1.2$ (g) $L = 1.3$ (h) $L = 1.4$

Fig. 7. Effects of Solar Luminosity ($L$) on Four Species Daisy World

ideal for daisy growth. For this study of solar luminosity, the luminosity was gradually increased from 0.6 to 1.5. However, if solar luminosity had been adjusted in a different sequence the proportion of each type of daisy may have differed. Despite these potential differences though, the planet is still able to stabilize at a temperature that is very close to the optimal temperature for growth of daisies.

## IV. Conclusions

The goal of this project was to examine emergent phenomenon on a global scale. The Gaia hypothesis provides a framework for considering the Earth as a decentralized, self regulating unit. This project focused on a simple model of emergent properties on a global scale in the Daisyworld model. The deterministic nature of the original model, although true to physics, does not easily extend itself to making the model more characteristic of organisms in nature. To over come the limits of the mathematical system, this project represented Daisyworld using a two dimensional cellular automata that was able to capture both the spatial and stochastic properties of natural systems. The cellular automata approach is found to produce results that are comparable with the mathematical model and the effects of varying parameters on this model were studied.

Future work on this topic would include extending the basic model to include more characteristics of natural systems. For example, evolutionary algorithms could be used to allow the daisies to evolve to suit their environment. In particular, a daisy's fitness could be evaluated by how close its local temperature is to its optimal temperature. Using this measure the daisy's albedo could be modified to bring the local temperature closer to the optimal temperature.

Allowing daisies to have different growth temperature ranges would provide some interesting competition among species. Instead of working together to reach a common optimal temperature, the daisies would need to compete to bring the global temperature closer to the optimal temperature of their own species. There are several things to consider in a model where species have different optimal temperatures. These include the case where a high albedo daisy has a higher optimal temperature. In this case, if the species became overly abundant, it would decrease the temperature, causing its population to crash. Similarly low albedo daisies with low optimal temperature could be examined. There is also the case where high albedo daisies have a lower optimal temperature in this case the daisy would be able to move global temperature closer to its optimal temperature by reflecting energy back into space. In both these cases, competition and cooperation have the potential to emerge and it would be interesting to observe the effects of these different interactions on the planet's ability to maintain global temperature within a range that is conducive to daisy survival in general.

By developing a Daisyworld model that incorporates stochastic and spatial effects on daisy growth, this project provides a starting point for several lines of inquiry into global emergent phenomena. There is also potential to modify some of the core components of the model to increase its similarity to natural systems.

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