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CS 361
2025.6.9

Final Report

Summary of Methodology

Daisyworld is an artificial life dynamical system simulation created by Watson & Lovelock (1983), intended to understand climate feedbacks and stabilization. The researchers simulate a simple artificial ecology. *Daisyworld* is populated by two kinds of daisies, black ones and white ones. Each has a growth function that is maximum at a temperate temperature. Black daisies raise the global temperature by absorbing more sunlight, and white daisies, conversely, lower it. Watson & Lovelock simulated the response of the daisies to changing solar luminosities to investigate how the daisies would stabilize the temperature of the planet. We successfully replicated this experiment. Additionally, we extend this experiment by adding neutral daisies that coexist with black and white ones, and by implementing a round planet with different solar luminosities at various latitudes.

Summary of Results (Original Paper)

The original Daisyworld paper presents the relationship between luminosity, temperature, and the proportion of flowers within Daisyworld. The original paper presents these results for four different experiments: only neutral daisies, only black daisies, only white daisies, and a mixture of white and black daisies. Given the varied albedos of each daisy, their proportions within Daisyworld follow predictable patterns.

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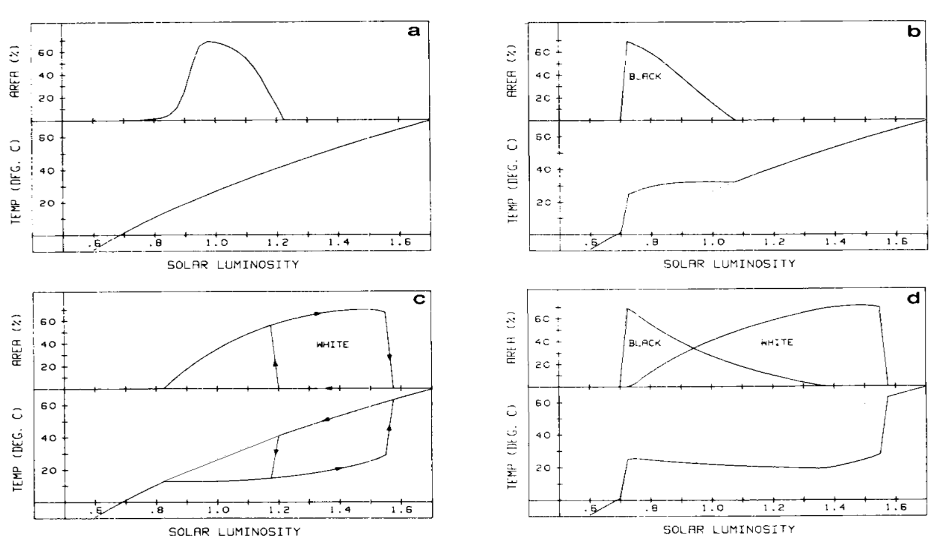

Fig. 1. Steady state responses of daisyworld. Areas of black and white daisies and effective temperature are plotted against increasing values of the luminosity parameter L. Dotted lines indicate the temperature of the planet without life. Fixed parameters used in generating these curves were: γ in eq. (1), 0.3; P in eq. (2), 1.0; S in eq. (4), 9.17×10^5 ergs cm^{-2} s^{-1}; albedo of bare ground, 0.5; q' in eq. (7), 20. (a) For a population of "neutral" daisies, albedo 0.5 (dotted and solid temperature curves are coincident). (b) For a population only of black daisies, albedo 0.25. (c) For a population only of white daisies, albedo = 0.75. This figure also shows that the effect of decreasing luminosity. Note that the system exhibits hysteresis. (d) For a population of both black and white daisies, albedos 0.75, 0.25.

Reimplementation Description

The *Daisyworld* paper provided the dynamical system equations, which we straightforwardly implemented in code. The world tracks only two variables, the populations of black and white daisies, rather than being an agent-based simulation. At each time step, the simulation calculates the planet's temperature using simplified thermodynamic laws and then allows both types of daisies to grow based on their populations and the temperature. We investigate the behavior of the system at multiple solar luminosities, following the approach of Watson & Lovelock (1983), by allowing the system to reach a steady state and then incrementing or decrementing the solar luminosity by a small amount. We did not make any significant changes to the original implementation, thanks to its simplicity and the thoroughness of the paper.

Equations

First, we calculate the global temperature of the planet

$$T_e = \sqrt[4]{\frac{SL(1-A)}{\sigma}} - 273$$

(equation 4 of Watson & Lovelock, 1983). L is the solar luminosity factor, about 1, $S = 9.17 \times 10^5$ and $\sigma = 5.67 \times 10^{-5}$ are constants, and A is the average albedo over the planet, where bare ground has albedo 0.5, black daisies have albedo 0.25, and white daisies have albedo 0.75. Next, we calculate the local temperature over black and white daisies individually with equation 7 of Watson & Lovelock (1983),

$$T_{b,w} = q'(A - A_{b,w}) + T_e,$$

where $q' = 20$ is a constant and $A_{b,w}$ represents the albedo of black or white daisies. Daisies then grow at a logistic rate related to their local temperature, equation 1 of Watson & Lovelock (1983),

$$\frac{da_{b,w}}{dt} = a_{b,w}\left(x\left(1 - 0.003265(22.5 - T_{b,w})^2\right) - \gamma\right),$$

where $\gamma = 0.3$ is the death rate and x is the amount of bare ground. Daisies can grow from temperatures 5°C to 40°C, growing the fastest at 22.5°C. The last two equations imply that daisies respond to both their local and global conditions. Thus, daisies that produce a more comfortable local temperature will be rewarded, and this local temperature will extend to the global temperature.

Identically to Watson & Lovelock (1983), we raised the solar luminosity from 0.5 to 1.7 in increments of 0.01. At each luminosity, the world had 500 time units to reach equilibrium, and the dynamical equations were applied 50,000 times, with a time step of 0.01. If daisies went extinct, their population was boosted to 0.01 once the luminosity changed to give them a chance to return.

Replication Results

We successfully replicated the original results of *Daisyworld*. Our first results, comparing only gray daisies, only black daisies, only white daisies, and white and black daisies, are below. The behavior of daisies in our experiments is quantitatively and qualitatively identical to that in Watson & Lovelock (1983).

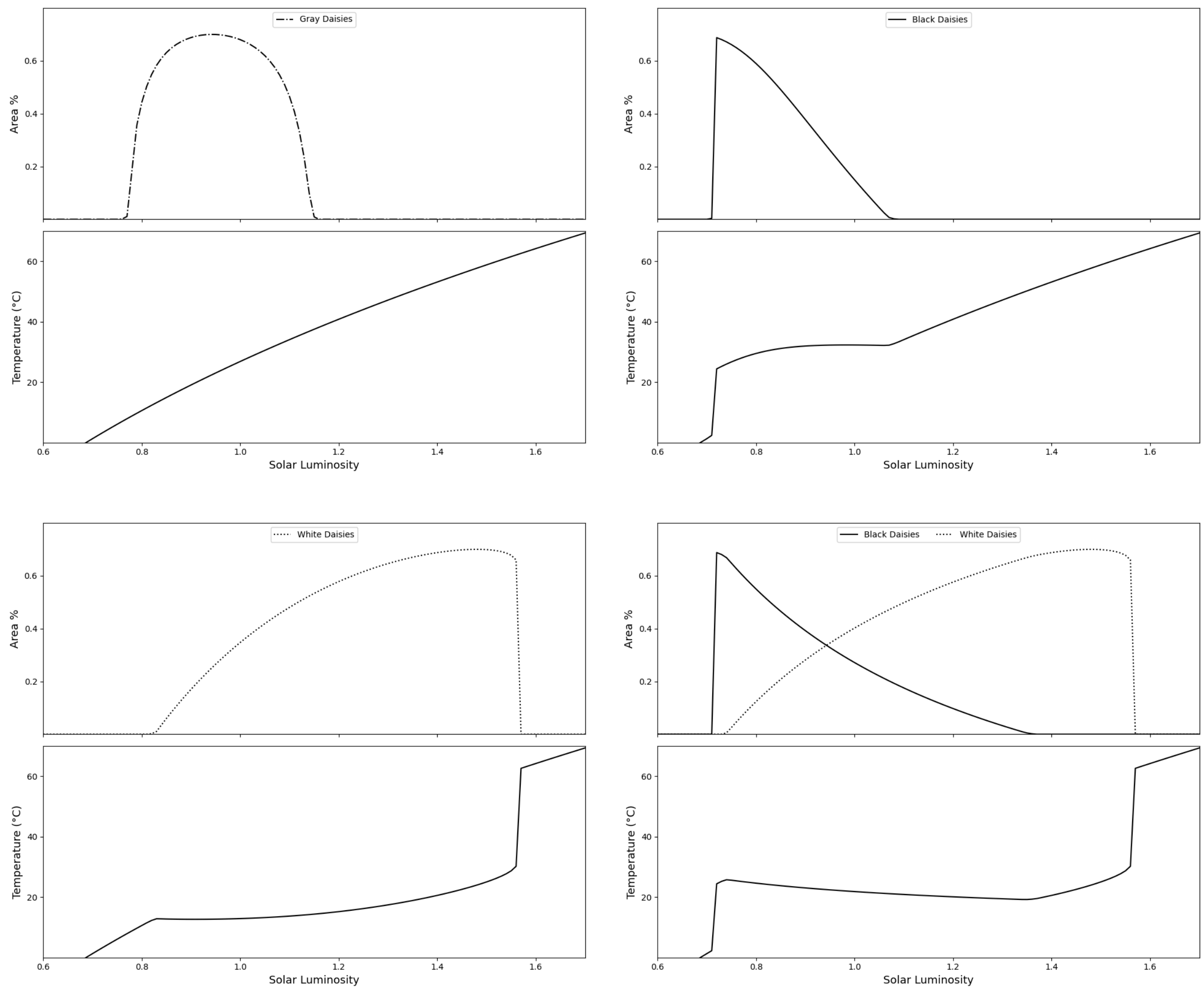

Figure 2. Replicating the experiments from Watson & Lovelock (1983). Upper left: a world with only gray daisies. Upper right: a world with only black daisies. Lower left: a world with only white daisies. Bottom right: a world with both black and white daisies. Note the proficiency of black and white daisies combined at keeping the temperature stable for a wide range of solar luminosities. Thermodynamic values are identical to Figure 1.

Extension 1

We extended the results of Watson & Lovelock (1983) by introducing a gray, neutral daisy. While the original Daisyworld paper introduces the concept of a neutral daisy, they do not simulate its coexistence with the other flowers.

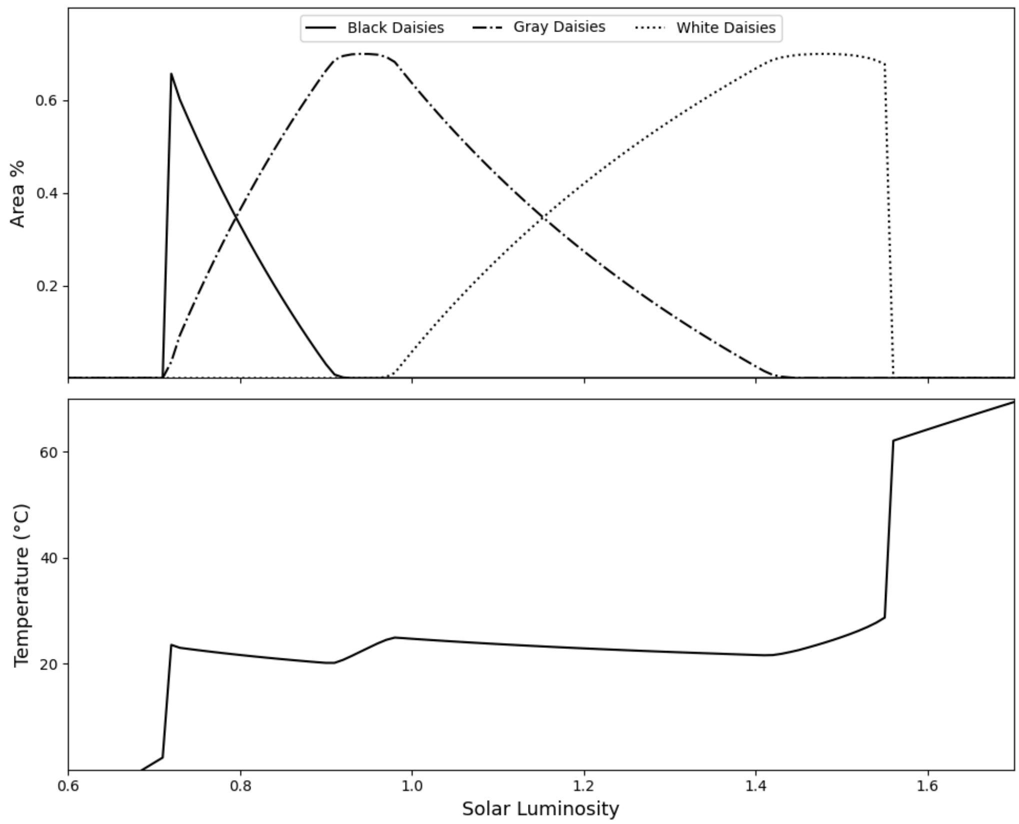

Figure 3. Daisyworld when it has white, black, and gray daisies. Apart from the presence of gray daisies, all other values are identical to the experiments in Figure 2.

Like the simulations in Watson & Lovelock (1983), the global temperature of the planet stays very stable for a wide (almost identical) range of solar luminosities. However, at higher solar luminosities, the temperature of this test exceeds the temperature on the white and black tests, and conversely for lower solar luminosities. We interpreted this as gray daisies taking up the space that would otherwise be occupied by white daisies, lowering the white daisies' ability to effectively cool the planet, and conversely, for black daisies.

In both the white+black and white+black+gray trials, at least two types of daisies have appeared by the time the solar luminosity is 0.74, and at least one type persists until the solar luminosity is 1.55. Over this range, the average temperature was 22.1°C in the white+black trial and 22.9°C in the white+black+gray trial (the optimal temperature for daisy growth is 22.5°C). The standard deviation in temperatures over this range was 2.2°C for the white+black trial, and 1.6°C for the white+black+gray trial. This indicates that the presence of gray daisies kept the global temperature closer to the ideal daisy growth temperature.

Extension 2

Watson & Lovelock (1983) acknowledge the limitation of their simulation taking place on a flat world and mention possible additional real-world feedback effects that could come from plants populating and depopulating polar regions. To investigate this, we implemented a round world. The world contains 90 latitudes, each of which models its daisy populations via dynamical systems.

Equations

Each latitude receives a different proportion Σ_e of the overall solar luminosity because of the obliquity of the sun. We modeled this as varying linearly from 1.7 at 0° latitude to 0.6 at 90° latitude. This kept the overall sunlight hitting the planet approximately the same as the flat planet tests.

We first calculate the average amount of sunlight absorption over the planet, instead of its average albedo, with

$$B = \frac{1}{90}\sum_{y=0}^{90}(1 - A_y)\Sigma_y.$$

This can then be inputted into the equation for global temperature to yield

$$T_e = \sqrt[4]{\frac{SLB}{\sigma}} - 273.$$

The local temperature over either black or white daisies is calculated with

$$T_{b,w} = q'(\Sigma_y(1 - A_{b,w}) - B) + T_e,$$

and from there, each latitude has its own growth rate for black and white daisies based on the local temperature of each type, as above.

Results

We simulated the same tests on the round world as the flat world.

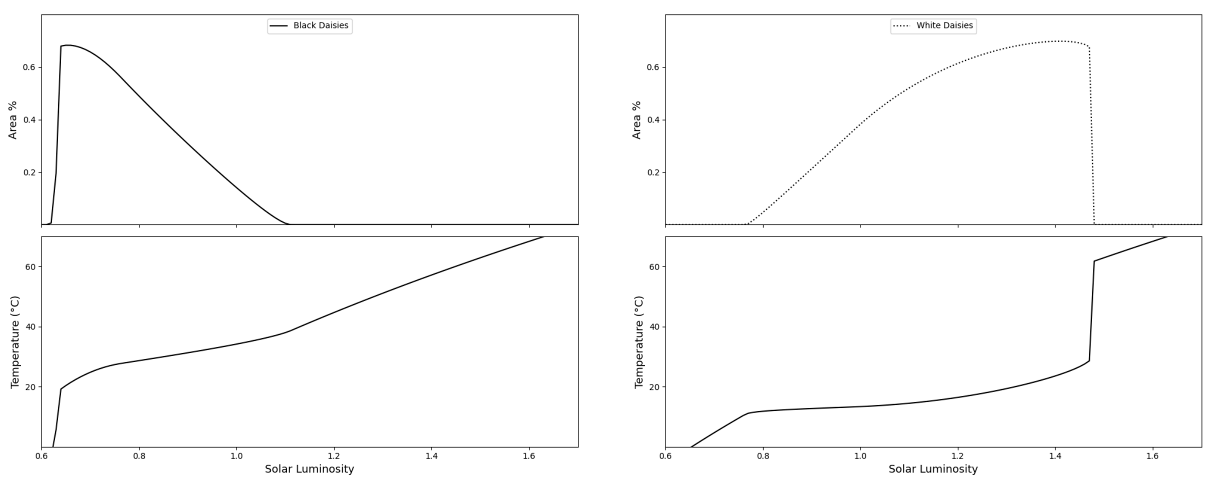

Figure 4a: Proportions of daisies for changing solar luminosities on a round planet. Left: only black daisies. Right: only white daisies.

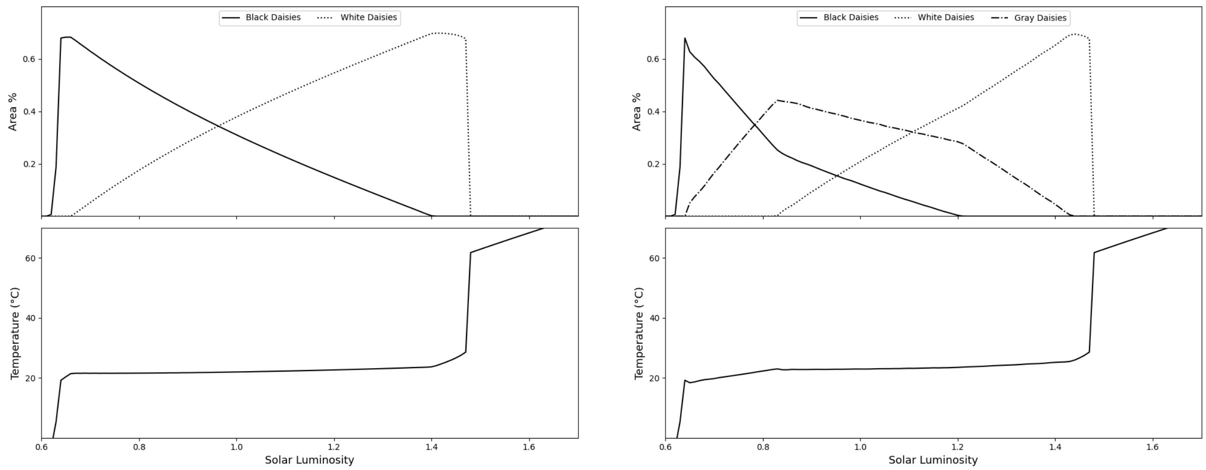

Figure 4b. Left: black and white daisies. Right: black, white, and gray daisies.

In all four of these simulations, daisies started growing about 0.09 solar luminosity before the corresponding flat simulation, but died off about 0.08 solar luminosity sooner as well. This indicates that having multiple latitudes and thus multiple environments to support daisies does not help them survive over a longer range of solar luminosities. The combination of white and black daisies kept the planet's global temperature remarkably stable. Over solar luminosities 0.67 to 1.47, from when at least two daisy types existed to when the last daisies died, the global temperature was on average 22.6°C with a standard deviation of only 1.3°C. White, black, and gray daisies together had a similar effect as they did on the flat planet.

Habitats of daisies on a round planet

We tracked the latitudes where each color of daisy existed on the round world. We found that daisies rarely coexisted on the same latitude. When both black and white daisies existed, on average, only 5% of the latitudes had daisies of both colors. At least some daisies populated every latitude while both populations were stable. This indicates that daisies competed with each other for space, and the population of any specific latitude did not matter much to the daisies that lived there because their temperature comes from the global temperature. An interesting extension would be to have the local temperature over each type of daisy to be affected by both the global temperature and the average temperature of that latitude. We hypothesize that this would cause daisies to exist at the same latitudes more frequently.

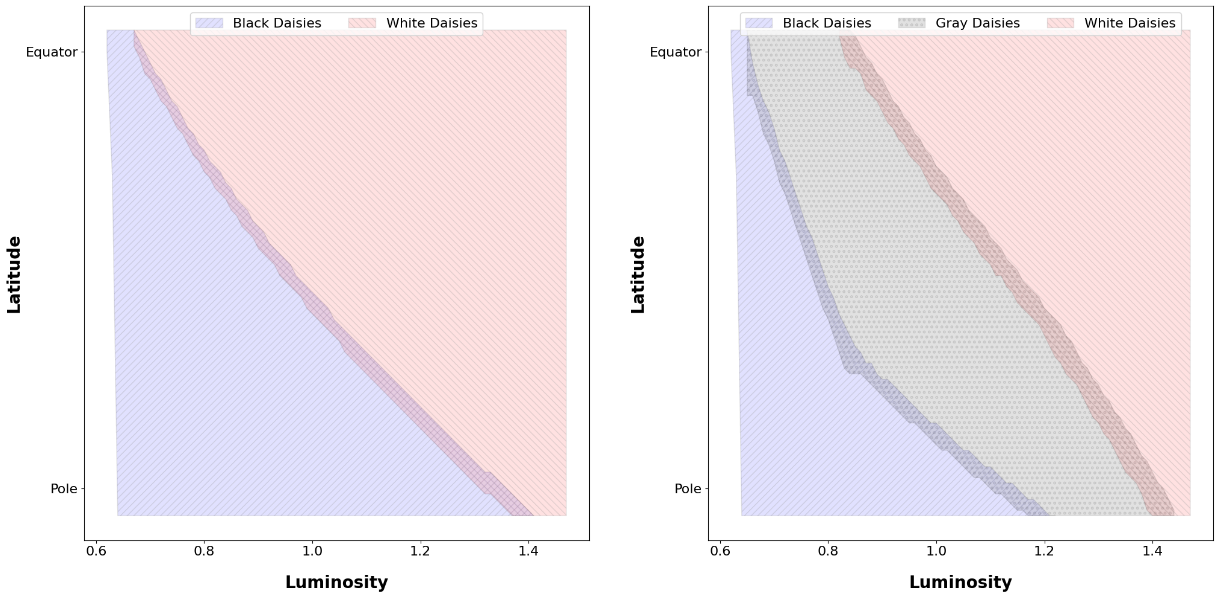

Figure 5. Habitats of each type of daisy. Black daisies existed closer to the poles as they can induce a higher local temperature, and conversely, white daisies. Left: black and white daisies. Right: black, white, and gray daisies.

Limitations and Road Bumps

We have successfully implemented all of the main tests from the Daisyworld paper and achieved the same quantitative and qualitative results. One limitation in our approach is that for the first test, when the world contains only gray daisies, our graph of gray population versus luminosity is a different shape from that in Watson & Lovelock (1983). This is because we let the simulation run for longer at each luminosity value in order to come to a steady state before increasing the luminosity. When the simulation is run for less time, as it was in Watson & Lovelock (1983), the gray daisies have more memory of their population from previous luminosity values, leading to lag. This was confirmed qualitatively by adjusting the parameters in our simulation.

Works Cited

WATSON, A.J. and LOVELOCK, J.E. (1983), Biological homeostasis of the global environment: the parable of Daisyworld. Tellus B, 35B: 284-289. doi.org/10.1111/j.1600-0889.1983.tb00031.x