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Modeling the effects of Greenhouse Gases in the Daisy World

Greenhouse gases are widely understood to be one of the main drivers behind modern-day climate change. Gases like carbon dioxide, methane, and nitrous oxide trap heat that is leaving Earth. In a balanced atmosphere, this ensures that surface temperatures are conducive to life. However, as human activity has added more greenhouse gases to the atmosphere, an associated rise in temperature has been recorded. This rise has come with many harmful changes to Earth's climate, impacting animal ecosystems, global economies, and human lives.[1]

In this project, I attempt to model the Greenhouse Gases in a simpler system, to understand its potential effects on a planet's ecosystem and potential mitigation strategies. The simpler system that I use is the Daisy World, a model developed by A. Watson and J. Lovelock that tracks two species, Black Daisies and White Daisies, on a hypothetical planet where the surface is entirely covered of those species or barren ground. In an ideal scenario, these two species self-regulate and establish a steady state, based on the solar energy that the planet receives. However, by introducing the Greenhouse Effect, we observe that the cover fractions can change over time in a variety of different ways.

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[1] "Basics of Climate Change." *Climate Change Science*, United States Environmental Protection Agency, 19 August 2022, https://www.epa.gov/climatechange-science/basics-climate-change.

Section 1: Deriving Mathematical Equations

The state of the Daisy World is calculated at each timestep, which I denote as 1 Daisy-World-year. While a tedious description of the exact calculations will not be provided, a quick review of the calculations is enough for a general understanding. The cover fractions are initialized to 90% barren ground, 5% Black Daisies, and 5% White Daisies. The Albedos, which measure the reflection of solar heat, are fixed at 0.5 for barren ground, 0.2 for Black Daisies, and 0.8 for White Daisies. The planet's albedo is calculated by a sum of these albedos, scaled by their respective cover fraction. The atmospheric temperature is calculated from the planet albedo and several solar constants, which is then used to calculate the overall surface temperature, the temperature by surface type, and the birth rate for each population of daisies. The death rate is always calculated as 30% of the current population. These values are synthesized in the differential equation below, which I model in my code using a 2-step Runge-Kutta method.

$$\frac{dC_i}{dt} = b_i C_i(t)[1 - C_i(t) - C_j(t)] - DC_i(t)$$

To introduce the Greenhouse Effect, I use the following equation from a 2014 article in Biosystems [2] that calculates E, the alteration of the thermal balance by the Greenhouse Effect, where a represents emission of Greenhouse Gases, b represents absorption of Greenhouse Gases, and Aw and Ab are albedos for White Daisies and Black Daisies.

$$\frac{dE}{dt} = a - bE(A_w + A_b)$$

[2] Paiva, Susana et al. "Global warming description using Daisyworld model with greenhouse gases." *Biosystems*, vol. 125, 2014, pp. 1-15. https://doi.org/10.1016/j.biosystems.2014.09.008.

I discretize this using a Forward Euler scheme, and for purposes of my experiment with modeling man-made Greenhouse Gas increases, I hold E to be non-negative in my code — if E is ever calculated to be negative, I revert it to 0. Since the article uses a different set of equations for the Daisy World, I created my own synthesis of this equation and the aforementioned calculations. The Greenhouse Effect affects the entire planet's temperature, and I wanted the increase of E to have a positive linear effect on this temperature. So, I modified the calculation for atmospheric temperature to include a "+ E" term. This integrates the Greenhouse Gas calculation into the Daisy World, and all the other calculations can remain the same.

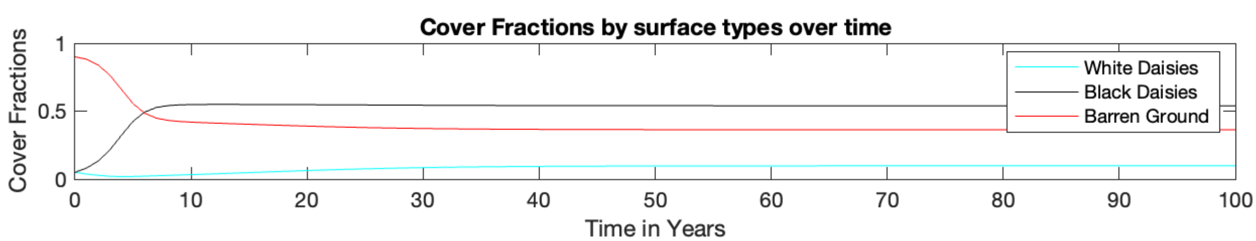
Section 2: Results from Scheme #1

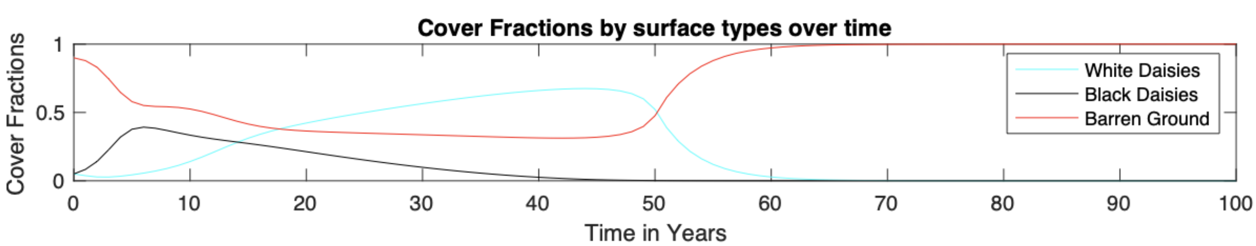
The following figure represents various graphical representations of the above scheme, for different values of a and b. Experimenting with these values provides insight into the mechanics of this scheme. For each set of values, I graph the cover fractions over 100 years.

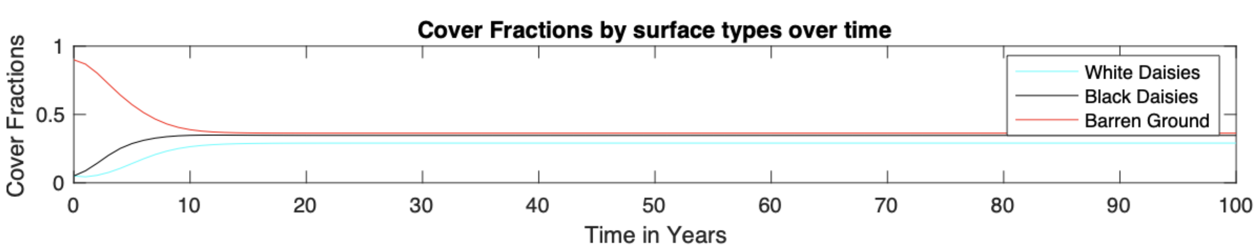
First, I start with a = 0, b = 0, and initial E = 0. This represents the base case where there is no Greenhouse Effect. The Daisy World behaves normally, reaching its steady state in about a decade, with Black Daisies being the dominant species.

Next, I set a = 1, b = 0, and initial E = 0. This represents a constant rate of emission, with no absorption. Over the first 5 years, the Daisy World appears to behave normally, with the Black Daisy population rising quickly. However, after this, the increased temperature becomes more conducive to White Daisy growth, so the Black Daisy population falls and the White Daisy population rises. After about 45 years, the White Daisies reach their peak population while the Black Daisies are extinct. However, the continued temperature increase grows to be too much for the White Daisies too, and they go extinct in roughly a decade. This graph generates a useful insight that applies to Earth - species that are unable to cope with higher temperatures will die off sooner than species that can handle these higher temperatures. However, once the temperature grows to be too hot, all life will die out.

In my final graph under this scheme, I allow both emission and absorption of Greenhouse Gases to occur: a = 5, b = 0.5, and initial E = 10. This represents an equal amount of emission and absorption, so the Greenhouse Effect is a constant 10, which is added to the baseline temperature. Essentially what we create is a regular Daisy World, just with a higher temperature. Like the first graph in this section, a steady state is reached in about a decade. Since the temperature is now a bit more favorable towards White Daisies, we see that the population of the Black Daisies and White Daisies are relatively equal.







Section 3: Building a better scheme: Emitters and Absorbers

One of the limitations of the scheme in this paper is that b is multiplied by E. At first this makes sense - absorption should be a fraction of the Greenhouse Gases currently in the atmosphere. However, since I interpret E to be the effect of those Greenhouse Gases rather than their concentration, this reasoning is unnecessary, especially because I coded the non-negative condition as previously described. The issue that results is that many combinations of a and b end in a steady state, since as emission adds to E, on the next step a larger amount is absorbed, preventing other interesting scenarios from arising. In my improved scheme, I remove this E.

Another limitation is that the model assumes that emission and absorption is done equally by both species on the planet. In my new scheme, I use cover fractions for the daisy populations, not their albedos. I also sought to assign roles to these species. In Earth's ecosystem, humans are the polluters of Greenhouse Gases, and plants are often absorbers of these Greenhouse Gases. To recreate this in the Daisy World, I let White Daisies be the emitters, and let the Black Daisies be the absorbers, and multiplied their cover fractions to a and b respectively.

Finally, I sought to study the effects of the polluters enacting mitigation strategies to reduce their emissions. This mirrors the effects of human activities like carbon capture, clean energy investments, and other environmental policies. So, I introduce a variable R to represent the polluter's reduction in emissions. R starts at 0, increases as the White Daisies work to reduce their emissions, and decreases as the White Daisies uninvest in these efforts.

With all this, my new and improved scheme is modeled by the following equation:

$$\frac{dE}{dt} = a(1 - R)(C_w) - b(C_b)$$

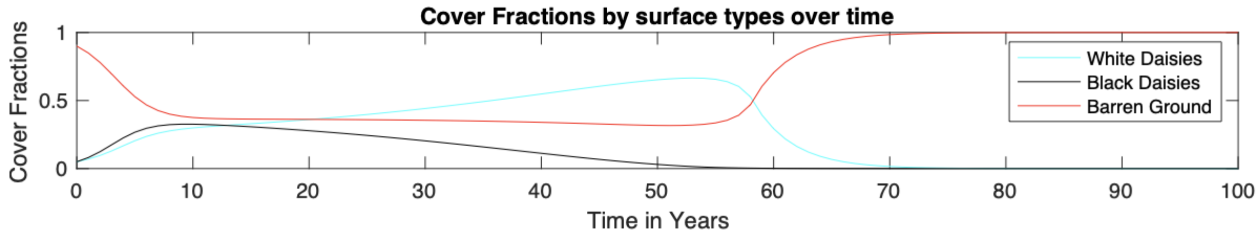
Section 4: Results from Scheme #2

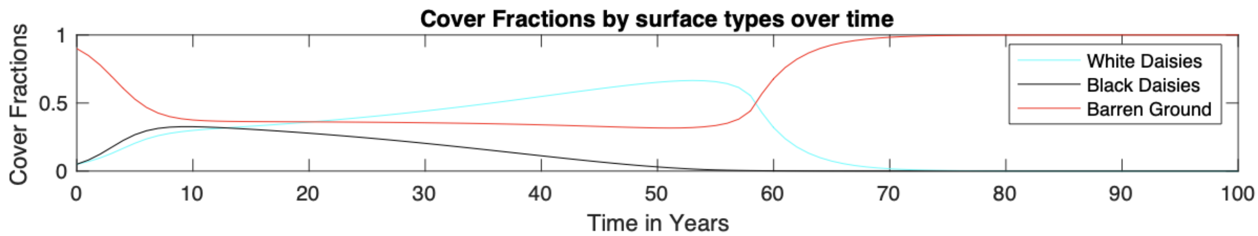
The next figure represents various graphical representations of the second scheme. I fix the values a = 2, b = 1, initial E = 10, and vary R. For each result, I graph the cover fractions over 100 years.

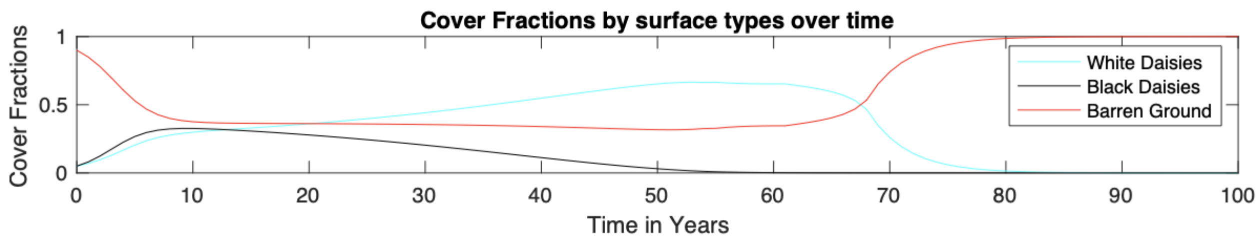
First, I fix R = 0. This is a baseline for the roles of White Daisies as emitters and Black Daisies as absorbers, with no mitigation strategies. We see a result similar to a constant rate of emission from the previous scheme. Over the first decade, the Black Daisies and White Daisies grow. Over the next four decades, the Black Daisies go extinct as the White Daisies continue to grow to their peak. Unfortunately, over the next decade the White Daisies die out too.

To begin varying R, I set the condition that the White Daisies will begin taking action when they see that their population is decreasing. Each year that their population decreases, R will increment by 0.1. For example, after 4 years, the White Daisies will only emit 60% of their baseline emissions. If their population begins increasing, they will abandon their mitigation strategies, and R will revert back to 0.

I had hoped that this would cause the temperature increase to stabilize, and for the population of at least the White Daisies to stabilize. Unfortunately, this doesn't occur, for a fairly obvious reason — by the time this emissions reduction begins, the Black Daisies are already extinct. No more absorption is taking place, so even though the emissions are shrinking, the value of E continues to increase. There is essentially no change in the graph.

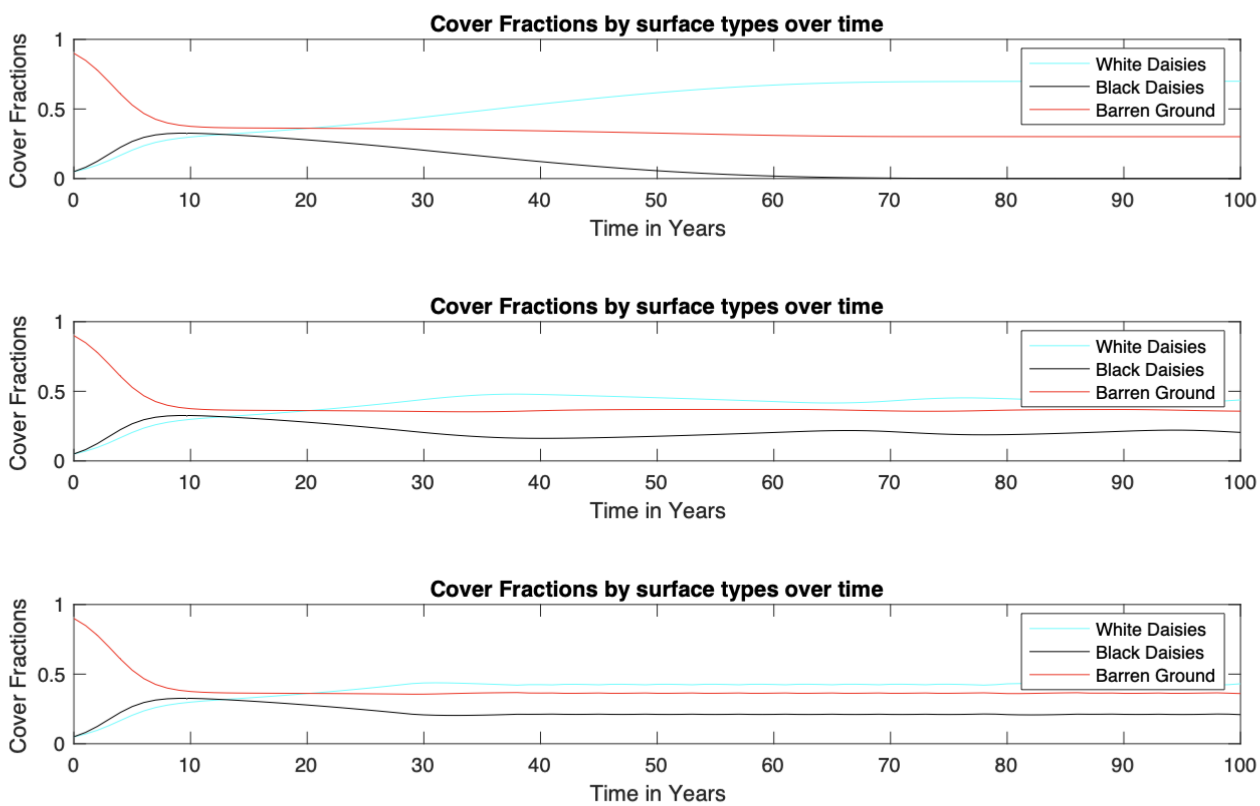






I increased the R increment to 1, to see if rapid (and practically unreasonable) action could save the White Daisies. If the emitter's population declines, R is set to 1, and all emissions cease. If the emitter's population begins to rise again, R goes back to 0, and all emissions begin again. Unfortunately, even this immediate action can't save them. For about a decade after their population begins to decline, the temperature stabilizes. However, following this decade the atmospheric temperature rises again and grows out of control, killing the White Daisies once again. This is a valuable lesson that can be applied to Earth as well: if humans wait until our population is declining before we take action, it is most likely too late — population collapse will occur.

With this lesson in mind, I changed the trigger condition to be that the White Daisy population is more than double the Black Daisy population. I also changed the un-investment case, so that rather than decreasing R back to 0, it decrements R by the same mitigation rate. I tested 3 different rates, which each resulted in different outcomes. At a slow rate of +2% and -2%, the White Daisies reach a steady state of about 70% cover, although the Black Daisies go extinct. At a moderate rate of +10% and -10%, the Black Daisies are able to rebound, and the two species oscillate. At a rapid rate of +100% and -100%, the daisy populations reach a relatively steady state, although the atmospheric temperature experiences regular sharp oscillations. These graphs are in the figure below.



Section 5: Analysis

While this model is already fairly complex, there are always more improvements that can be made. One improvement could be to describe the varying effects of different Greenhouse Gases, like carbon dioxide and methane, by having them be emitted by White Daisies at different amounts and having their concentrations affect the value of E differently. Alongside this, I could also model how different plants are affected differently by these gases. For example, since many plants breathe in carbon dioxide, I could integrate this into the calculations. Finally, I could introduce evolutions by the different daisies. If their albedos adapted over time to the rising temperatures, perhaps they could survive longer.

However, even with the above experiments in applying Greenhouse Gases to the Daisy World, we can already draw multiple conclusions that apply both to the Daisy World and our current climate issues on Earth.

The first conclusion is that even small changes in atmospheric temperature can have drastic effects on the survival of different species. All of the temperature changes in these experiments are in double-digits or less, and yet these changes can determine a daisy population's survival or extinction. On Earth, with our complex web of ecosystems, decreasing populations of important species by even just 10% or 20% could have catastrophic effects. Scientists generally hold 1.5ºC to be the maximum allowable global warming above pre-industrial times, before catastrophic events like food insecurity and ecosystem collapses occur. These small changes in temperature can affect our planet in surprisingly large ways. [3]

Fortunately, we can also conclude that mitigation strategies are feasible and effective. In the Daisy World, by decreasing the White Daisy population's emission of Greenhouse Gases, we

[3] "Global Warming of 1.5 ºC." Intergovernmental Panel on Climate Change, 2018, https://www.ipcc.ch/sr15/.

were sometimes able to return to a steady state, where both populations were able to live in significant numbers. On Earth, the same should be possible - by decreasing humanity's net emission of Greenhouse Gases, we should be able to mitigate the damage that we've done to Earth, and ensure the survival of Earths' fragile ecosystems. These adaptations can include electrification alongside green production of electricity via solar panels or wind turbines, agricultural reform that helps use water efficiently and protects land so it can be farmed on for generations to come, reducing personal carbon footprints by eating foods with lower emissions and using less energy, or even carbon capture technologies that reduce our net emissions. All of these mitigation strategies are worth investing in, because a combination of all of these will be required in the coming years.

That being said, the last conclusion is the most important — humanity must act sooner rather than later, and these actions must be taken decisively. In both cases where the White Daisies only acted once their population was impacted, neither species survived. The White Daisies could only save themselves by acting once the Black Daisies were significantly impacted, and even still the Black Daisies died if the emissions reduction wasn't significant enough. Humanity cannot wait for our own species to suffer before acting on climate change. We must diagnose the issue quickly, develop mitigation strategies, and take strong international action. This will be necessary to ensure the stability of human life and society, as well as the survival of the many vulnerable species and ecosystems on Earth.

Works Cited

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