1.1: Daisyworld


Summary

Life and Earth have interacted over billions of years, with life profoundly changing environments on Earth. In turn, Earth provides the boundary conditions for life. Lovelock (1983) and Watson and Lovelock (1983) proposed that life and Earth be considered as two parts of a coupled system. This system is too complex to fully model, but some of the behaviors of the interactions can be explored with a very simple system proposed by Watson and Lovelock (1983): Daisyworld. Daisyworld is a biosphere consisting of two species of daisy with different colors. “The growth rate of the daisies depends on only one environmental variable, temperature, which the daisies in turn modify because they absorb different amounts of radiation.” These relationships produce feedbacks that can stabilize or destabilize the temperature, depending on the temperature growth preferences for the two daisy species. Temperature is stabilized when the growth-temperature curve is peaked with darker (more heat absorbing) daisies growing at lower temperatures than white (more heat reflecting) daisies. Watson and Lovelock (1983) propose that these sorts of feedbacks stabilize temperature on Earth.

Introduction

Environments on Earth are modified by living things at scales from individual chemicals to the oxidation state of Earth’s surface. Even the formation of granite has been proposed as due to biological carbon cycling (e.g. ref). “In turn, geophysical
and geochemical constraints have shaped the evolution of life and continue to dictate what type of life, and how much of it, can colonize” environments on Earth (Watson and Lovelock, 1983). Watson and Lovelock (1983) created a coupled system with two components: life and Earth. In their model, perturbations of life affect Earth and of Earth reflect life, leading to feedbacks between the two components. The coupling between the components may enhance a perturbation in a positive feedback or dampen it in a negative feedback.

Studying these feedbacks is difficult as demonstrated by the challenges of modeling climate change (e.g. refs). Non-linear feedbacks produce chaotic systems; for example the dynamics of the atmosphere led to the Lorenz Equations, which are a classic example of systematic behaviors but unpredictable results in detail. Consider a model that includes all of life and Earth processes over geological time; it is too complex to model in full. However, Watson and Lovelock (1983) proposed “an artificial world, having a very simple biota which is specifically designed to display the characteristic in which [they] are interested-namely, close-coupling of the biota and the global environment.” They proposed a few equations to capture this world and illustrate the importance of life-Earth interactions. The equations can be found in the original reference and are not reproduced here (yet) (Watson and Lovelock, 1983).

**Daisyworld Model**

Daisyworld is a planet colonized only by two species of daisy of different colors. One species is dark (called “black” here), and one species is light (called “white” here). Black daisies absorb more heat than white daisies do, so the parts of Earth covered by black daisies tends to warm up through time, whereas the parts covered by white daisies tend to cool down relative to bare ground. Watson and Lovelock (1983) propose a set of coupled differential equations to rigorously model the changes in temperature and to calculate the proportion of the planet covered with bare ground and each type of daisy. This model is fun to play with. However, it is also more complicated than we need to understand the feedbacks. Even a system as simple at the GEL 53 Geobiology Daisyworld Game produces interesting dynamics.

The key to understanding the feedbacks is to explore how the rules of the system either dampen or enhance perturbations. If black daisies grow better at lower temperatures than white daisies, cooler temperatures will lead to more black daisies, which will in turn increase the amount of heat absorbed. The absorption of more heat leads to warmer temperatures. As temperatures increase, more white daisies will grow, leading to less heat absorption and cooler temperatures. In this scenario, perturbations in temperature are dampened by the growth of the daisies, which is a *negative feedback*. In the full Watson and Lovelock (1983) model:

The “environmental feedback” in the model as described so far is strongly limiting on both species of daisy. Black daisies are warmer than white, and tend therefore to be favoured by cooler mean temperatures, yet an increase in the numbers of black daisies tends to warm the planet. The same goes in reverse for the white daisies. Under these circumstances it is perhaps not surprising that the system exhibits a stable point around which the daisies can successfully homeostat the temperature over a wide range of luminosities.

In contrast, if black daisies grow better at higher temperatures than white daisies, an increase in temperature will lead to more
black daisies, which absorb more heat, which increases temperature even more. In this scenario, perturbations in temperature are amplified by the growth of the daisies, which is a positive feedback. Watson and Lovelock (1983) show how this positive feedback can be countered by adding another negative feedback process to the system:

Owing to a subtle change of climate, clouds appear on daisyworld. The clouds are light in colour. We will assume that the clouds form only over stands of black daisies because of the rising air generated over these warm spots. Now, therefore, black daisies no longer tend to increase the temperature. Instead, more black daisies mean more white clouds and a colder planet.

However, this change in dynamics has a huge impact on white daisies. They end up going extinct in the Watson and Lovelock (1983) model:

White daisies were not deliberately suppressed, but became extinct of their own accord. White daisies fail because, in the battle for survival of the fittest, they are now distinctly less fit than the black daisies. An increase in either species now tends to cool the planet, but black daisies, being warmer than the mean, thrive better at low temperatures.

The conditions for daisy growth in their model are slightly different than that in the Daisyworld Game; it is not clear to me that white daisies can go extinct in our game without significant rule changes.

**Relevance to Earth**

The behaviors in Daisyworld are relevant to Earth even though the system is exceptionally simplified. Decades of improvements in climate models since the publication the Watson and Lovelock (1983) Daisyworld have demonstrated that feedbacks among the biosphere, hydrosphere, and atmosphere are complexly interrelated (e.g. ref). In particular, life has a substantial influence on Earth’s temperature through both the heat absorbed and the cycling of greenhouse gases. It is very interesting to read Watson and Lovelock’s original section on the relevance of Daisyworld to Earth in the context of our relatively poor understanding of greenhouse processes at that time. Here it is in its entirety:
5. Relevance to the earth

Extrapolation from daisyworld to the earth is, to say the least, rather tenuous at this stage. However, a peaked growth versus temperature curve is a universal property of living things. Furthermore, the biota may have a substantial influence on the earth’s temperature via the abundance of greenhouse gases in the atmosphere. Recently, Owen et al. (1979) and Walker et al. (1981) have speculated that the abundance of atmospheric CO$_2$ may have been dominant in determining the mean temperature of the earth through geological time, in which case the biota as a whole would appear to be depressing the mean temperature below that of the “sterile earth” by tending to reduce atmospheric CO$_2$ pressures (Lovelock and Watson, 1982). In the present context, neither the direction nor the mechanism whereby life affects the temperature are of themselves important---only the assumption that the biota influence the temperature is required. For the sake of illustration, however, let us suppose that the net effect of life on Earth is to reduce atmospheric carbon dioxide, and that the biota are temperature limited. Thus a decrease in temperature would lead to an extension of the barren polar regions and would decrease the average level of biological activity over the earth as a whole, while a temperature increase would have the opposite effect. But a decrease in biological activity as a whole would presumably also decrease those activities which tend to reduce atmospheric CO$_2$. Thus carbon dioxide would increase to oppose the original change. We then have the rudiments of a temperature stabilization system for the earth analogous to that on daisyworld. We can speculate that some such mechanisms may have played a part in regulating the temperature and other environmental variables over the long history of the earth.

References


