Scientists on Gaia

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Mechanisms for Stabilization and Destabilization of a Simple Biosphere: Catastrophe on Daisyworld

The Daisyworld model of Watson and Lovelock (1983) illustrates a mechanism by which a simple biosphere, consisting of black and white daisies, regulates the planetary temperature. Recently, Kirchner (1989) has shown that a modified Daisyworld model can exhibit "pathological" behavior in the presence of climate changes. My purpose here is similar, and I will show that a modified Daisyworld can lead to a global catastrophe in the presence of evolutionary changes.

For these calculations, I used the original model with only one modification: in addition to black and white daisies, I introduced a third species, kudzu. Like black daisies, kudzu has an albedo of 0.25, and its growth curve is the same amplitude and shape as that of the daisies; however, its optimum growth temperature is 33°C. The optimum growth temperature of white daisies and black daisies remains at 22.5°C. For all the other model parameters, I used values from figure 1 in Watson and Lovelock (1983).

Let us consider a particular scenario for the succession of life on Daisyworld. This scenario uses a solar luminosity corresponding to $L = 0.75$ (i.e., 75% of the present luminosity on earth). We start by introducing a 1% coverage of black daisies onto a barren planetary surface. The daisies spread, thereby warming the planet, until a steady state is reached (figure 13.1A). Next, we add a 1% coverage of kudzu. The kudzu slowly replaces the black daisies, eventually driving them to extinction (figure 13.1B). Finally, after the black daisies are totally extinct, we add a 1% coverage of white daisies. Because they cool the planet, the white daisies initially compete well against the kudzu. However, once the planet cools beyond a certain point, the kudzu dies off catastrophically. The temperature plunges, eventually cooling to below the tolerance limits of both species. In the end, all that remains is a barren planet (figure 13.1C).

In order to understand the mechanism of this catastrophe it is helpful to introduce a few simple concepts. First, we define the *generation range* of a species as that range of external conditions (e.g., solar luminosity) over which an arbitrarily small population of the species will propagate. Second, we define the *survival range* of a species as that range of external conditions over which some finite population is capable of surviving. Because a species at least must be able to survive where it can propagate, it follows that the generation range is a subset of the survival range. Finally, we define that part of the survival range which lies outside of the generation range as the *marginal-stability range*.

Figure 13.2 shows the steady-state solutions to the equations for (1) area covered and (2) effective temperature as a function of luminosity for each species growing without any other species. From the area-versus-luminosity curves, the generation range can be identified as the range where the solution with zero area is unstable (i.e., where the zero solution is represented by a dashed line). The marginal-stability range corresponds to the range spanned by the overhang in the area-versus-luminosity curves. For white daisies, for example, the generation range extends from $L = 0.833$ to 1.208, and the survival range extends from $L = 1.208$ to 1.559. Note that the existence of a marginal-stability range depends on strong feedback between the area of surface covered and the temperature. For example, if the albedo of the daisies is sufficiently close to that of bare ground, a marginal-stability range will not exist.

The key to understanding the catastrophe described above is to note that a solar luminosity of $L = 0.75$ lies within the generation range for black daisies, within the marginal-stability range for kudzu, and outside both the generation and marginal-stability ranges (i.e., outside the survival range) for white daisies. Whereas the black daisies could have survived any perturbation that left a finite population remaining, the kudzu is eliminated by any perturbation that reduces their area to below the dashed line in figure 13.2C. The introduction of white daisies is sufficient to trigger this instability.

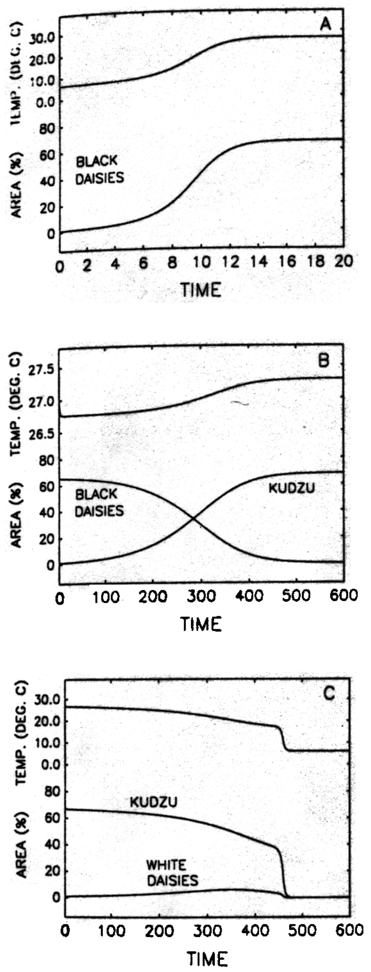

Figure 13.1 Three sequences in the scenario for the succession of life on Daisyworld. **A,** Black daisies propagate on a barren planet. **B,** Kudzu replaces black daisies. **C,** White daisies and kudzu annihilate each other. Time is in model units.

The scenario demonstrates (1) that it is possible for a species in its marginal-stability range to drive a species in its generation range to extinction, and (2) that it is possible for a species outside its survival range to drive a species in its marginal-stability range to extinction. In either case the more fit species is actually categorically less robust than the eliminated species in the sense that it is one step further removed from its generation range. In the latter case the more fit species is left outside its survival limits, so it also dies out.

It is worth considering the question of whether the presence of daisies stabilizes the temperature with respect to luminosity changes. This idea, which is the principal conclusion of Watson and Lovelock (1983), is true if we define net stabiliza-

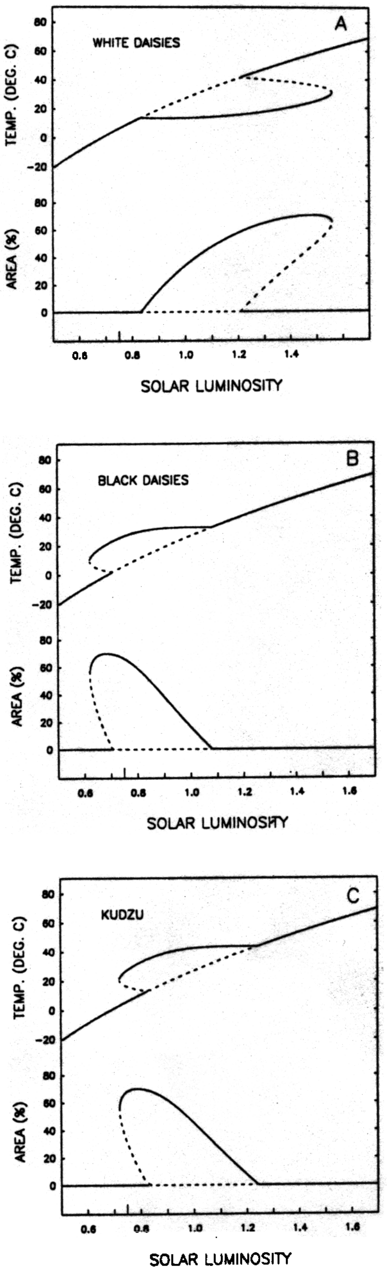

Figure 13.2 Steady-state solutions to the Daisyworld model for effective temperature and area covered. Stable steady-state solutions are represented by a solid line, unstable solutions by a dashed line. **A,** Solutions for white daisies. **B,** Solutions for black daisies. **C,** Solutions for kudzu. Stable solutions were found by numerically integrating the equations forward in time. Unstable solutions were found by integrating the equations backwards in time. The extra tick mark at L = 0.75 indicates the luminosity used in the catastrophe scenario.

tion in terms of the extension of the survival range beyond the generation range. From figure 13.2 it is clear that this definition is equivalent to requiring that the average slope of the temperature-versus-luminosity curve over the survival range is less with daisies than without daisies. The above scenario suggests, however, that the same feedback mechanism that extends a species' survival limits with respect to the external environment (e.g., luminosity) can reduce its survival limits with respect to competing species.

One possible objection to this catastrophe scenario is that the evolutionary sequence is imposed a priori, so that it is not clear if such a sequence is probable, or even possible, in a biosphere whose evolution is under the control of variation and natural selection. It should be noted, however, that the original Daisyworld model can be criticized on the same grounds. The regulation of planetary temperature on Daisyworld also requires a specific evolutionary sequence, namely, once the two species of daisies have formed, no further evolutionary changes are allowed. In this sense the original and modified Daisyworld models are both teleological in that they require manipulation of the evolutionary process to produce a desired effect. It might be possible to overcome this objection by constructing a Daisyworld model that allowed for realistic natural variations. This suggests a direction for further work.

Another possible objection to the catastrophe scenario is that it depends on the assumption that the earliest life forms, black daisies, are driven to complete extinction. In contrast, anaerobic bacteria, among the earliest life forms on earth, are still abundant today. Here it should be pointed out that the succession of black daisies by kudzu is not essential to the catastrophe: any process that drives the biosphere into a marginally stable state would suffice. For example, the catastrophe scenario could have started with a solar luminosity of $L = 1.0$, with kudzu populating a barren planet. A cooling of the sun to a luminosity of $L = 0.75$ would then put the biosphere in the same state as existed prior to the introduction of white daisies. Neither catastrophe scenario has any obvious relevance to the earth. It is conceivable, nevertheless, that the increase in the solar luminosity over geological time could drive (or could already have driven) the earth's biosphere towards a marginally stable state. This is an issue that, perhaps, deserves closer examination.

In summary, a scenario for evolution on a modified Daisyworld illustrates how a simple biosphere can destroy itself if the wrong sequence of evolutionary changes takes place. The self-destruction occurs after a stable environmental feedback loop has been established. The catastrophe is possible because, by modifying the physical environment, a species accomplishes two distinct ends: (1) an extension of its survival limits and (2) the elimination of competing species. Furthermore, the same modification that succeeds at eliminating competing species may fail at maintaining the environment within critical tolerance limits. Perhaps there is a lesson for humans here.

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