Poisoning the soil and recovering in Daisyworld

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Abstract

Until this date, the daisyworld model is used by researchers for educational means, but also for further investigations by extending the basic model. This article investigates such extension of the model of Watson and Lovelock (1983) by introducing an ever increasing poisoning of the soil on the surface of this imaginary planet. Furthermore, it investigates what might happen if this poison will be cleaned up. Will the natural world recover? And if the answer is yes, until what extend, or under what conditions, will this still be the case? Results show that within imaginary daisyworld the natural world can recover, but that this doesn't mean the human species can recover too.

1. Introduction

Daisyworld is a simple model introduced by Watson and Lovelock (1983), thereby demonstrating the Gaia hypothesis (Lovelock and Margulis, 1974; Lovelock, 1972) that life can, unconsciously, self-regulate Earth's environment. The original daisyworld is a zero-dimensional model consisting of a planet with transparent atmosphere exposed to evenly distributed solar radiation flux. The climate is represented by a single variable – the global temperature – that is a simple resultant of radiation balance on Earth. Life on this imaginary planet consists of two types of plants, black and white daisies, which differ only in their radiation reflectance (albedos), hence their relative cover areas affects the Earth's albedo and its global temperature. However, the growth rates of the two daisy populations depend on temperature, thus the cover areas and temperature are closely related by a feedback mechanism. With this intriguing model of an imaginary planet Watson and Lovelock illustrated the idea that the natural living world is tightly coupled with the non-living environment. The model shows how self-regulation of planetary temperature emerges out of this interrelation, or in their own words: biota have effected profound changes on the environment of the surface of the earth, and at the same time, that environment has imposed constraints on the biota.

The model was initially presented in defence of the Gaia theory, which suggests that the Earth can be seen as (or 'behaves' like) a single organism. The biosphere of planet Earth has a self-regulatory effect on its environment by regulating its temperature and chemistry to keep conditions suitable for life to thrive upon. Everything on earth is seen as interconnected within a single system: the natural world, atmosphere, oceans, the surface and crustal rocks. Lovelock used intuition rather than rational thinking to come to this hypothesis. Quite a few scientists, in particular the biologists Ford Doolittle, Richard Dawkins and Stephen Jay Gould, attacked this idea of Gaia forcefully, with Richard Dawkins writing the Extended Phenotype (Dawkins, 1982) mainly to prove his point. Lovelock however can be considered a free thinker, technician, maverick inventor and scientist with a more interdisciplinary view then most of this criticasters, I believe, looking beyond the scope of just biology or just ecology or any other discipline, and interestingly enough, we can only view climate change modelling of the earth as an interdisciplinary form of science as well. It can turn into a fierce philosophy of science debate whether or not one can investigate the Gaia hypothesis in a scientific way, but we can regard this concept as a worldview, as a way of looking that has benefits and flaws, rather than as a theory that can be falsified. The Gaia hypothesis inspired many to become an environmental activist, scientist or both, but believing in the hypothesis has consequences. In 1970s Lovelock argued that there was no need for taking action against the damage of the ozone layer by CFC's, which were produced and greatly used by us humans, since the natural world would correct this wrongdoing. This turned out to be false, apparently since there is a reinforcing feedback loop that was overlooked by Lovelock and/or because the scientific data collection was wrong at the time. This example shows us quite clearly how it can be dangerous to put too much trust in the self-regulation and homeostasis of the natural world. Or more in general terms: the resilience of nature towards manufactured chemicals might be limited, as manufacturing can be seen as something outside the scope of Gaia as natural system. On the other hand one could argue that for Gaia it doesn't matter when or at what expense humans will suffer from Ozon depletion.

Much like the original daisyworld model, climate change science suggests the tight coupling of vegetation with the global environment temperature. After rise of Earth's global temperature above 1.5°C for example, an expansion of desert terrain and vegetation would occur in Mediterranean biome, causing changes unparalleled in the last 10,000 years (Hoegh-Guldberg et al., 2019). It is now widely agreed upon that we have entered, or are entering the 'Anthropocene' – the age of humans – meaning that we as a species are having such huge impact on planet earth that it justifies naming this a new geology era. Lenton & Latour (2018) even propose a new fundamental state of Gaia, since humans are becoming aware of the global consequences of their actions, leading to the possibility of deliberate self-regulation: Gaia 2.0. But also when the Anthropocene as a new era will not yet be granted – it's still an ongoing investigation and debate among geologists – most scientists nowadays agree that we as humans have a profound impact on climate through the emission of extra greenhouse gasses, and many scientists believe that we humans are destroying large parts of the natural world as a result of our mere existence (population growth), our way of living (with an ever economic growth curve as central goal), our (monoculture) farming and our industrialisation.

Until this date, the daisyworld model is used by researchers for educational means, but also for further investigations by extending the basic model. This article investigates such an extension by introducing an increasing poisoning of the soil of this imaginary planet (as a metaphor for the impact we humans have on planet Earth's natural world). Furthermore, it investigates what might happen when this poison will be cleaned up. Will the natural world recover? And if the answer is yes, until what extend, or under what conditions, will this still be the case? To get a better idea on possible implications for our life on planet Earth, climate change is investigated using the Milankovitch cycles. We expect to find similarity with daisyworld's basic model, to improve our understanding of the boundaries of recovering from poisoning the soil and to learn more about limitations and difficulties regarding analysing climate data.

2. Model description

Life on our imaginary planet consists of just two types of plants, black and white daisies, who differ substantially in their reflectance of sunlight (albedos). Their cover areas around the planet affect the albedo and thereby indirectly its global temperature. Watson and Lovelock(1983) state that their idea of white and black daisies doesn't necessary mean the flowers are totally black nor white. Their albedo is different, whereas 'white' represent a high albedo and 'black' represent a low albedo. A 'black' daisy hardly (or not at all) reflects incoming sunlight, keeping the local temperature relatively warm. It can be seen as an adaptation towards colder weather. The exact opposite is true for a 'white' daisy. Notice that, compared to planet Earth, it's a very simplified environment: daisyworld functions without an atmosphere and there are no clouds to block the sunlight or greenhouse gas formations causing heat because they absorb and emit radiant energy. Climate on our imaginary planet is simply represented by temperature as a result of the radiation balance between the *received* shortwave solar energy and the *outgoing* energy. The received energy depends on the albedo of the surface. With lower albedo the heat is retained, leading to a warmer planet surface, with higher albedo the energy is bounced back thereby cooling the planet.

Note that the unit of time cannot be explicitly derived, since our planet is an imaginary one. Daisyworld is however, as stated before, originally presented as defence of the Gaia theory, where Lovelock states that Earth began its existence about 4,5 billion years from today, and the earliest traces of life where found in sediment rocks formed more than 3 billion years ago (Lovelock, 1979). In these early stages, fluctuations in radiation from the sun occurred. In daisyworld, the solar radiation fluctuates as well, thus for now we will assume that one time unit stands for one million years on our imaginary planet. We will run our extended daisyworld model 3000 time units, thereby hypothetically simulating a period of 3 billion years, so almost like the beginning of life on planet Earth.

The growth rates of the daisy populations depend on the temperature. White daisies have a higher optimum local temperature for thriving than black daisies, but the albedo of white daisies is higher too, meaning they reflect more incoming energy from the sun, thereby cooling the planet. That will eventually trigger the growth of black daisies. The back daisies on the other hand absorb all incoming energy, leading to a higher global temperature once again, thereby unintentionally stimulating the growth of white daisies. This balancing feedback loop stabilises the global temperature. We expect that this 'rivalry' between two plants will result in a global temperature homeostasis of our imaginary planet, within the limits of their ability to grow, that is to say, when the surface is not poisoned. When the daisies die, the surface becomes bare (fertile) ground that can be occupied by new plants again, but in our extended model this bare ground can get poisoned, leaving less fertile space on the planet for the vegetation to grow upon. So, the extension of the original model is implemented by introducing a fraction of the surface as poisoned. This fraction has its own albedo. The surface of the planet can thus contain four different states: white daisies, black daisies, bare (fertile) ground or poisoned soil. Furthermore, the surface occupation by poison can be enlarged by adding more poison, but it can also be limited by a cleaning up mechanism (several cleaning events can be implemented). This will lead to regaining fertile ground upon which the white and/or black daisies might be able to flourish once again.

3. Mathematical model

The model presented is similar to the original daisyworld model of Watson and Lovelock (1983), with a modification to the equation describing the balance between incoming solar radiation and outgoing longwave radiation.

Incoming (solar) energy = outgoing (planet surface) energy

$$SL(1- A)= sT^4$$

or

$$SL(1 - (Awhite*Frwhite + Ablack*Frblack + Abare*Frbare+ Apoisoned*FrPoisoned)) = 5.6703\ 10^{-8}T^4$$

where S is the constant flux of solar radiation, L (unitless) is a dimensionless measure of the luminosity of the sun, and A is Albedo of the planet, calculated by the sum of all albedo's from all four surface (Fr) states: white daisies, black daisies, bare ground and poisoned. The constant s represents the Stefan Bolzman law stating that the total radiant heat power emitted from a surface is proportional to the fourth power of its absolute temperature. T is the temperature at which the planet radiates like a black body.

The growth of the daisies depend on the present population, the natural birth and mortality, the available space and the temperature. The calculation is based on daisies in real life. Both black and white daisies can grow according to the following differential equation:

dP/dt = P*Frbare*b-P*d

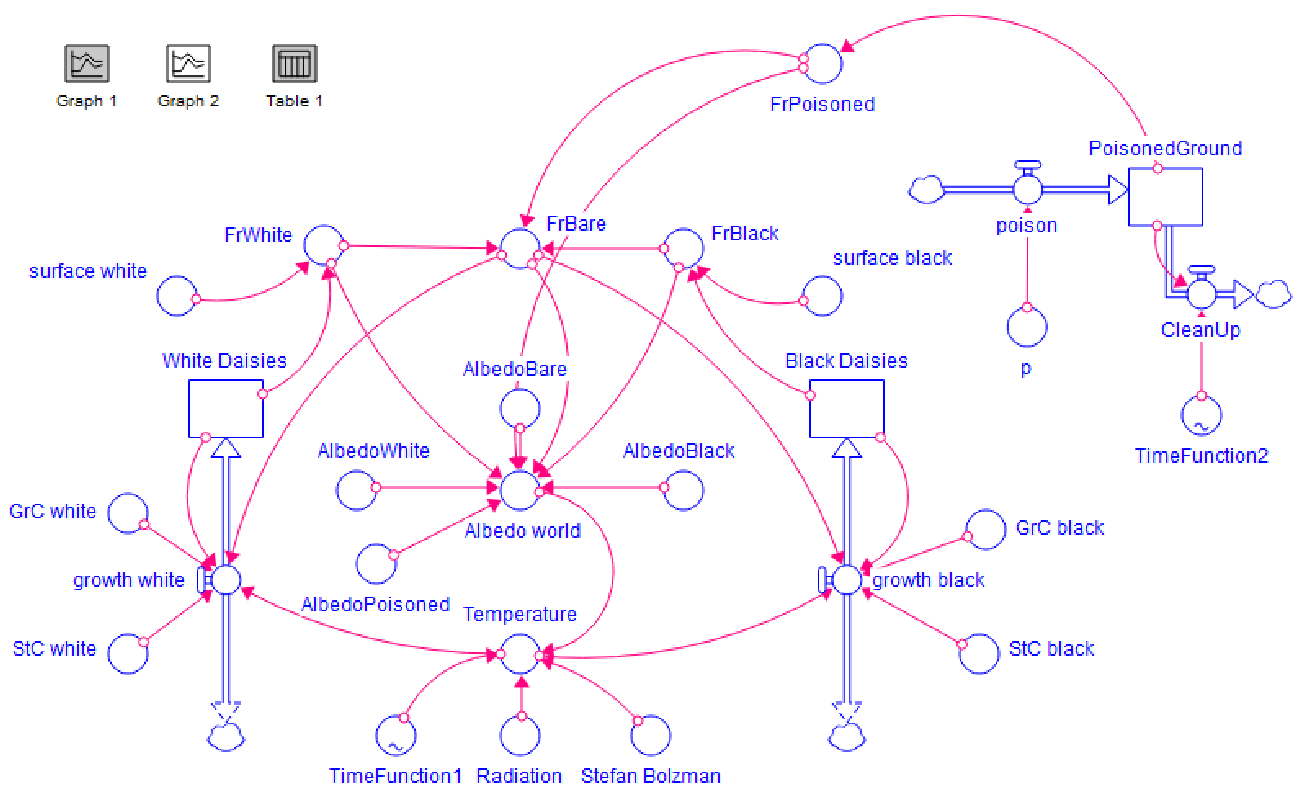
where b stands for the birth of the plant and d for the death of the plant. The bare surface available will be occupied if plant growth is possible. The value b however severely depends on the current temperature of the planet, with a substantial difference between the white and black daisies:

For white daisies the formula is extended like this: dP/dt = P*Frbare*b*(T-10)-d*P

For black daisies the formula is extended like this: dP/dt = P*Frbare*b*(T-30)-d*P

4. Stella model

Our stella model contains the simple extension of the basic model at the right side, where the possible increase of poisoned ground for conquering fertile soil fractions of the planet and its possible clean-up mechanism is placed.



5. The model-parameter(values)

	Description	Initial value
State variables		
White daisies	% of planet surface occupied by white plants	1
Black daisies	% of planet surface occupied by black plants	1
Poisoned ground	% of planet surface occupied by poisoned ground	0
Fluxes		
Growth white	White daisies*FrBare*GrCWhite*(Temperature-10)-StCWhite*White dasies	*Calculation*
Growth black	Black daisies*FrBare*GrCBlack*(Temperature-30)-StCBlack*White dasies	*Calculation*
Poison	Rate of poison added to the soil: p/100	*Calculation*
CleanUp	Rate of cleaning up the poison: TimeFunction2*PoisonedGround	*Calculation*
Converters		
Surface white	Multiplier of fraction occupied by white plants	1
Surface black	Multiplier of fraction occupied by black pants	1
FrWhite	Fraction of planet surface occupied by white plants: (WhiteD.*Surface white)/100	*Calculation*
FrBlack	Fraction of planet surface occupied by black plants: (BlackD.*Surface black)/100	*Calculation*
FrPoisoned	Fraction of planet surface occupied by poison: =Poisoned ground	*Calculation*
FrBare	1 – FrWhite – FrBlack – FrPoisoned (the bare ground left for possible growth of new plants)	*Calculation*
GrC white	Birth parameter of white daisies	0,01
GrC black	Birth parameter of black daisies	-0,02
StC white	Death parameter of white daisies	0,005
StC black	Death parameter of black daisies	0,03
AlbedoWhite	% of reflected incoming solar energy of the white daisies	0,9
AlbedoBlack	% of reflected incoming solar energy of the black daisies	0
AlbedoBare	% of reflected incoming solar energy of the bare ground	0,35
AlbedoPoisoned	% of reflected incoming solar energy of the poisoned ground	0,15
Albedo world	% of reflected incoming solar energy of the planet: FrWh*AlbedoWh+FrBl*AlbedoBl*FrBare*AlbedoBare+FrPois.*AlbedoPois.	*Calculation*
Radiation	Incoming Energy of the sun (Solar flux constant)	1000 W/m2
Stefan Botzman	$\sigma = 5.6703\ 10^{-8}\ W{\cdot}m^2{\cdot}K^4$	Constant
TimeFunction1	A unitless value of luminosity over time: between 0 and 2	1
Temperature in Celcius	The planet temperature: (Radiation*TimeFunction1*(1-AlbedoWorld)/ Stefan Botzman)^0,25-273	*Calculation*
p	% of poison added	0
TimeFunction2	A dynamic value of the clean-up over time: between 0 and 1	0

The two type of plants have a parameter for birth and death, a parameter for albedo and an optimum temperature for thriving. Please notice that the influence of temperature on growth deviates from the original model of Watson and Lovelock(1983). Within the original model the growth of the daisies is a parabola that has a peak value of 1 -- the maximum growth factor possible at an optimum temperature of 22.5°C -- and drops to zero at local temperatures of 5°C and 40°C. Thus, growth of the daisies can only occur within this temperature range, where the albedo difference influences the local temperature. Within our simplified model, the temperature range is not limited; there is only the direct difference between the black and white daisies growth rate at certain temperatures. The white daisies grow relatively better at higher temperature levels, the black daisies grow relatively better at lower temperature levels.

Cleaning up can be implemented with TimeFunction 2, as shown below in an example:

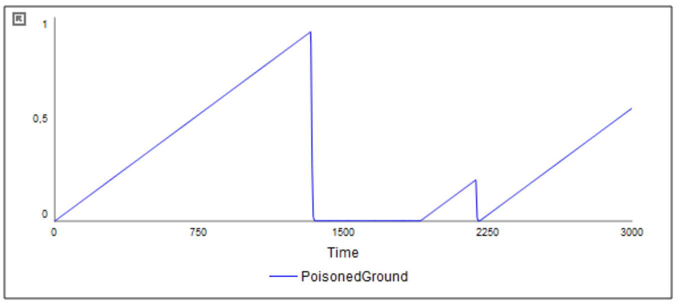


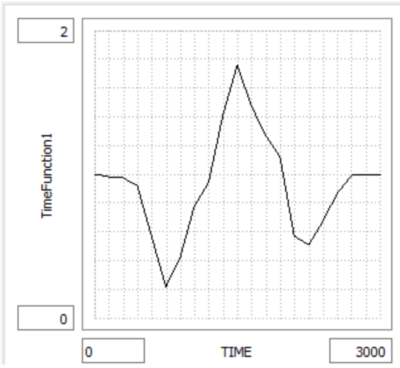
Figure 1. Clean-up can be done fully or partially, it can last for a given amount of time and it can be done on a number of occasions In this sample, clean-up is done twice, but only at first instance its lasting for quite a while. The poisoning of the surface is executed by a steady increase in time, until a rather sudden clean up occurs.

6. Simulation results: sensitivity analyses

Before we start, it's important to realize that the p value is set to zero, meaning no ground will be poisoned yet during the 3 billion years of our simulation. Furthermore, the graph of TimeFunction1 must be mentioned, since this determines the fluctuation of the radiation of the sun, heating up our planet.

6.1 With or without daisies

Now let's first look how our planet temperature behaves when we start with no daisies, so with only bare ground since there is no vegetation possible somehow (plants are extinct or haven't come into existence yet).



During the first period, solar luminosity decreases. Then it increases for a long period before it starts to decrease again, after which it returns to its starting point.

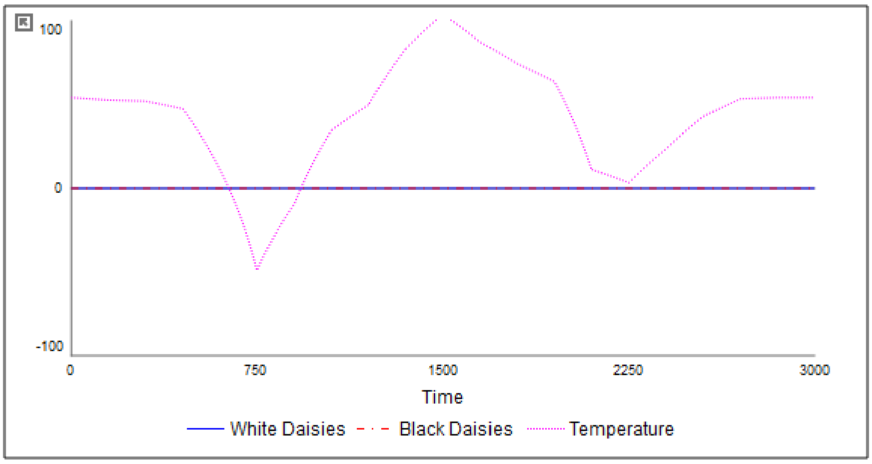


Figure 2. We can see that the planets temperature then follows the fluctuation of the solar luminosity as shown in the first graph.

But what happens when the two plant species come alive? We start with let's say 0,001% of white daisies occupying the land and with 0,001% black daisies occupying the surface on our imaginary planet by changing their initial values. Then we will run our simulation of 3 billion years again:

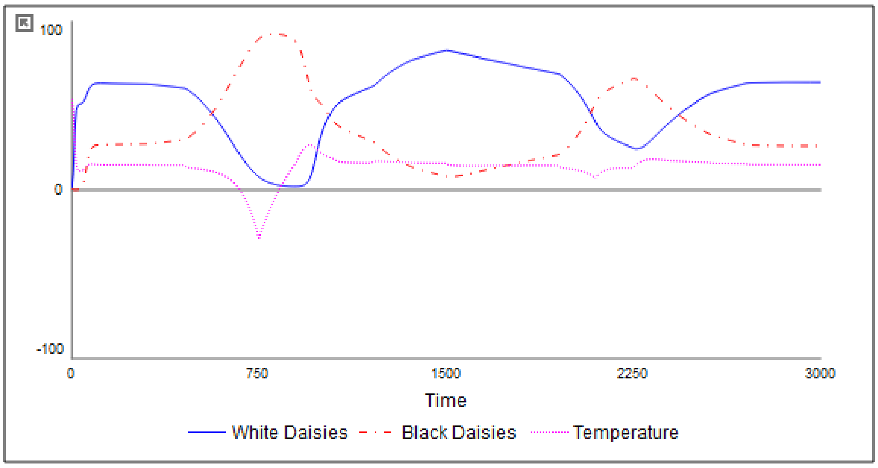


Figure 3. Comparing this result with figure 2 clearly shows that the thriving flower population stabilises the planet's temperature. When the incoming energy of the sun drops (with a lowest point at 750 million years), the population of the black daisies grow and warm up their surrounding and thereby the planet temperature. During the period of higher solar energy, our white daisy population increases, causing the planet temperature to drop again, since they are cooling down the environment.

This oscillations of the two plant species induce a homeostasis of the temperature on our imaginary planet.

6.2 Climate change

With this second sensitivity analyse we will act as if we investigate the consequences of climate change from the outside using a different luminosity. Two possible outcomes of the current climate change problems are: a steady increase in temperature over time or bigger oscillations between warm and cold periods. How will these different patterns influence the population of our flower species? Let's change the behaviour of TimeFunction1 to see what happens. Since our model is nonzero dynamic, we can simply consider one time unit not as one million years but as one year for this purpose, making it more realistic and easier to comprehend.

The first result:

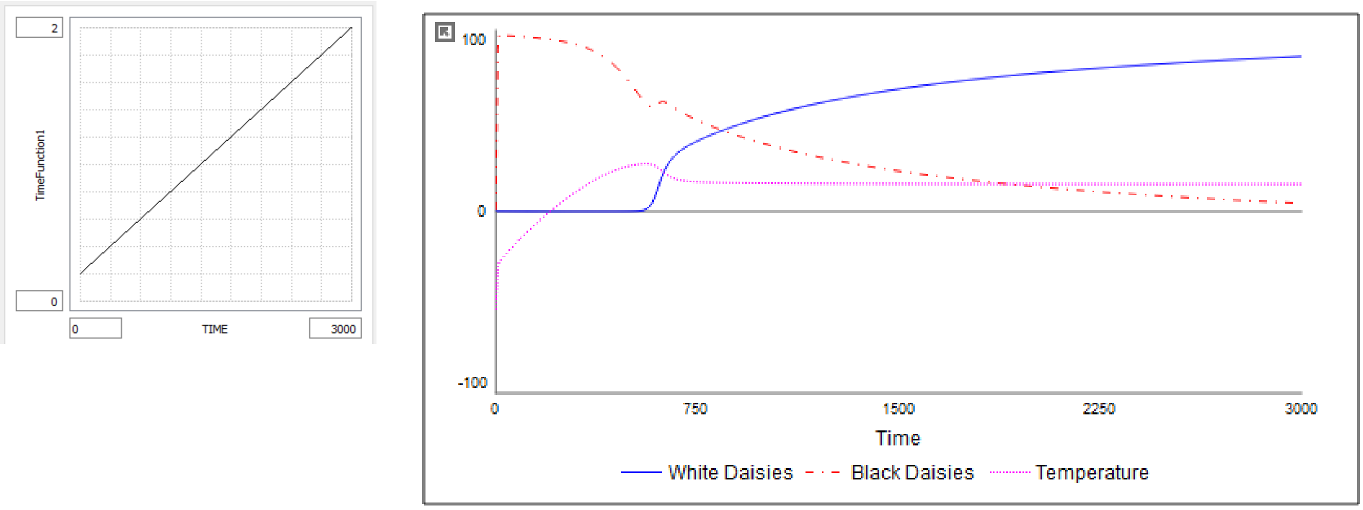


Figure 4. We can see above that with a fairly steady rising of solar energy, as a metaphor for climate change over this period of 3000 years, the populations of plants adapt in such manner that the homeostasis can be maintained. The white daisies grow steadily and expand on the surface of the planet, thereby, of course unintentionally, cooling down local temperature and keeping the equilibrium intact, with a planet's temperature around 15℃.

The second result:

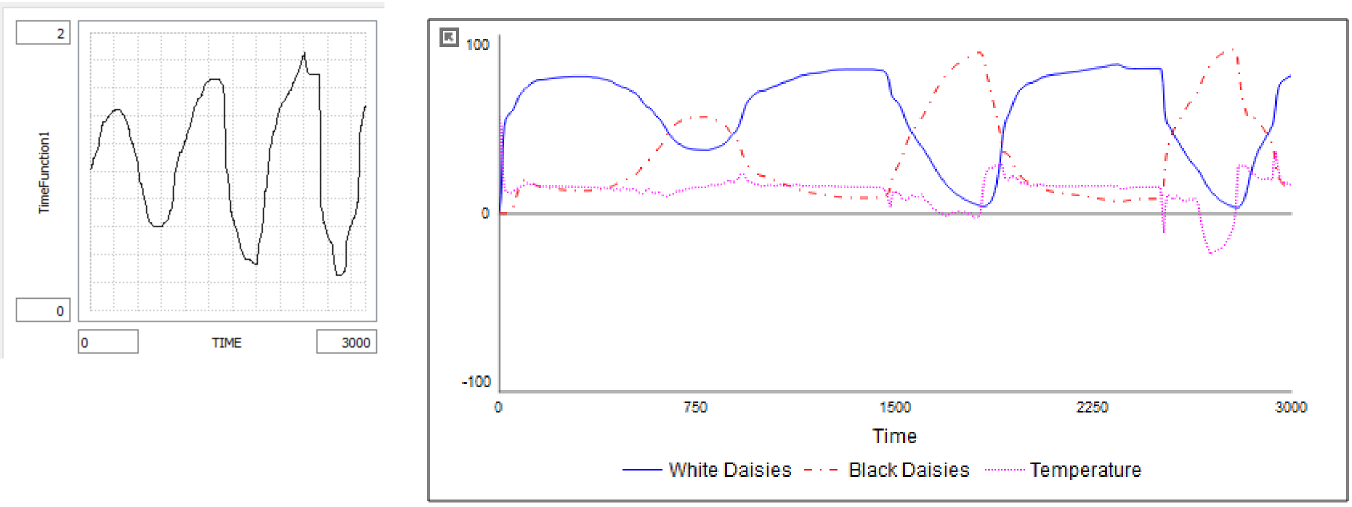
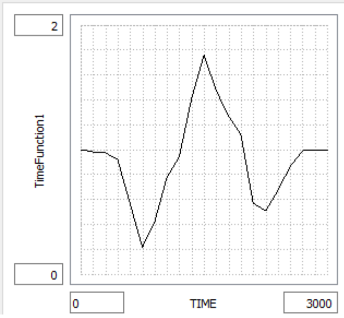


Figure 5. Within the second simulation we witness what happens when oscillation of warm and cold periods enlarge. The plant populations increasingly occupy more surface or die off in oscillation too, thereby 'trying' (unintentionally) to stabilise the planet temperature. The colder it gets, the larger the black population grows at cost of white daisies. The warmer it gets, the larger the white population grows at cost of black daisies occupying the surface. We could broadly speaking state that it becomes increasingly harder for the plants to maintain the homeostasis. Note: this result broadly shows some similarity with the research by Nevison et all (1999) *Self-sustained temperature oscillations on daisyworld*, showing oscillations that look quite a bit like predator-pray combinations.

7. Simulation results: scenario analyses

Before we start our different scenario investigations, we will first return to our starting point with the following TimeFunction1 representation of solar energy:



Furthermore, both black and white daisies start at the initial value of 1.

7.1 Poisoning of the soil

When we change the initial value of p (poison) with an empty TimeFunction2, so without CleanUp occurring for the time being, the result is the following for p=0,02 and p=0,03:

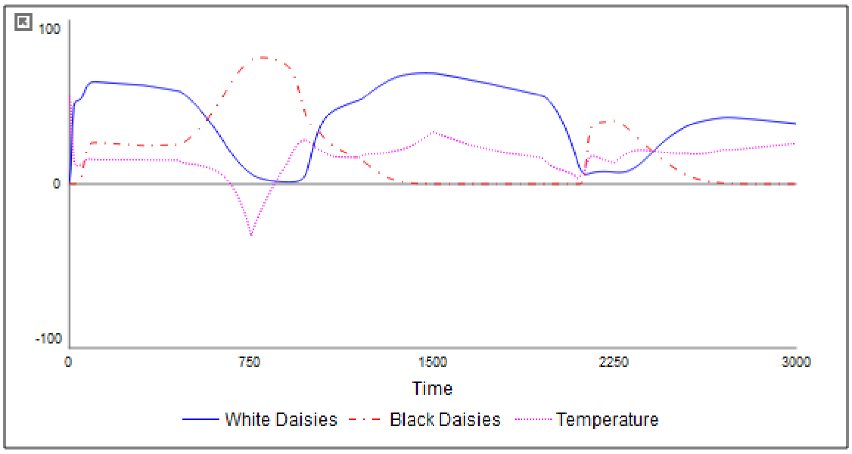
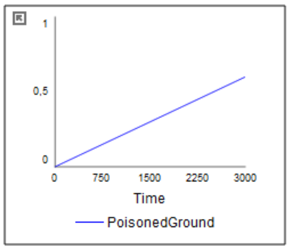


Figure 6.

p=0,02



Temperature is still fairly stable.

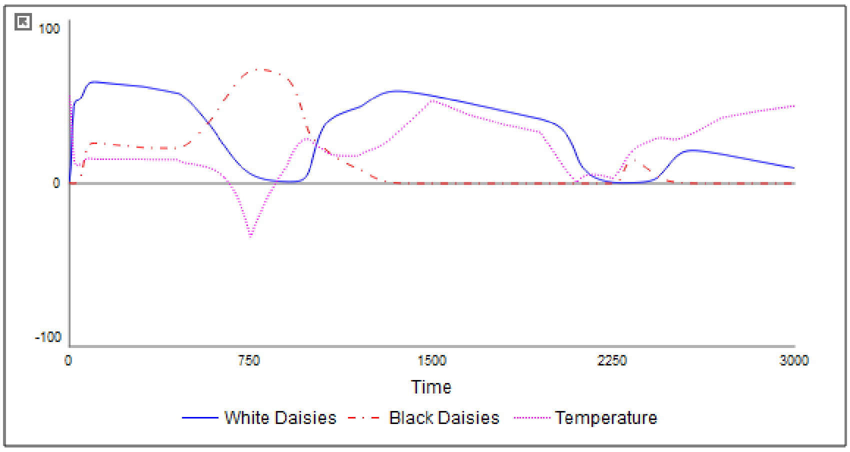
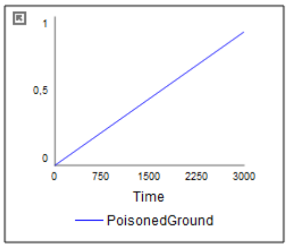


Figure 7.

p=0,03



Temperature can hardly be balanced by the plants populations anymore.

An increasing occupation of the fertile soil by poison leads to an increasing inability to maintain the temperature balance through the feedback loop. Note how in this situation the black daisies are the first species that cannot sustain, but when the land is fully poisoned, eventually also the white daisies will become nearly extinct.

When we run a sensitivity analyse of five ad-hoc stages p=0,01 p=0,02 p=0,03 p=0,04 p=0,05, we can see how the planet temperature changes:

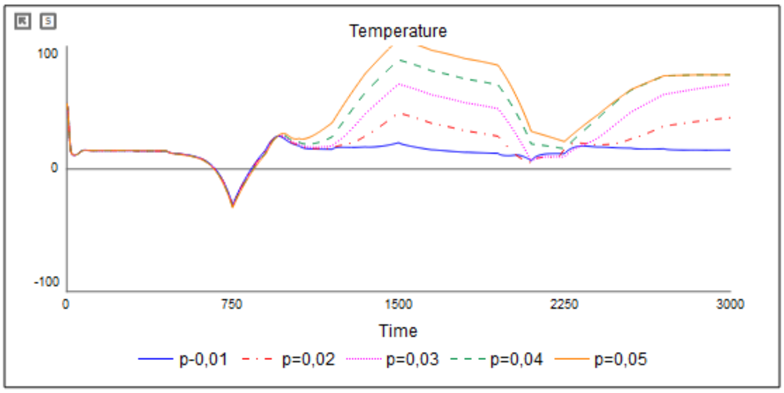
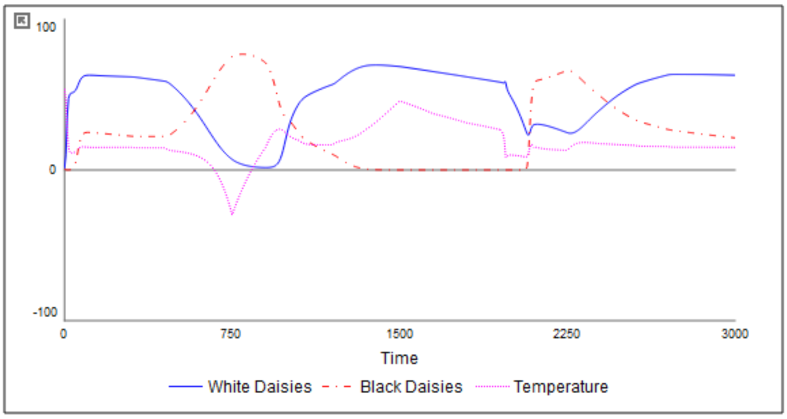


Figure 8. A wider spreading of the poison across the planet shows a decreasing self-regulation ability of planet's temperature by the two plant species, since they have increasingly less ground to grow on and 'do their job' of balancing their environment

7.2 Cleaning up the poison

We can now clean-up the poison and discover that, on our imaginary planet this is at least the case(!), there will always be a few plants left. So, if we clean-up the soil at any time, both species will find a way to thrive once again.



p=0,03 with a clean-up period implemented as shown below

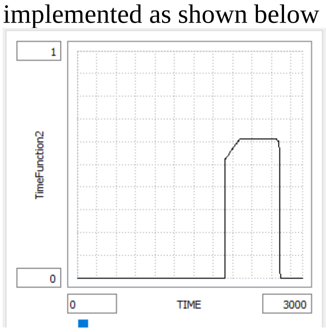
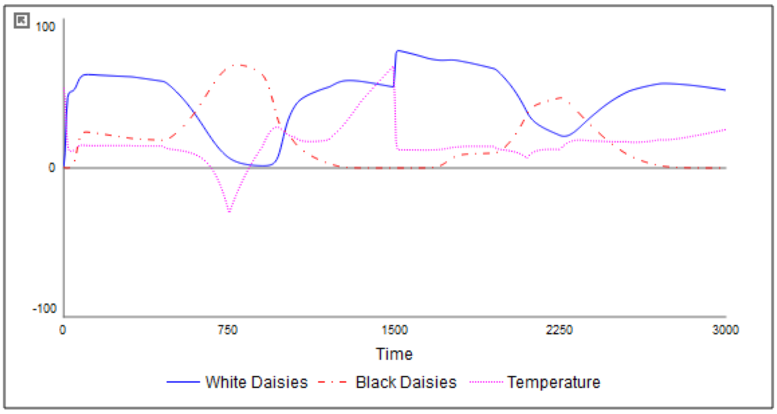


Figure 9. Relatively soon after clean-up starts (around 1950 million years), the black and white daisy populations recovers fully, thereby balancing the planets temperature once more like before.



p=0,03 with a relatively short clean-up executed around 1500 million years

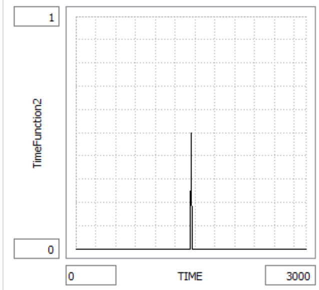


Figure 10. Almost 'immediately' (within this timeframe of three billion years) after clean-up the population of white daisies expands cooling down the planet. Then a more stable self-regulation period develops again, although slowly but surely the soil starts to be poisoned again from then on. On our imaginary planet, one thorough clean-up can do the job for a long period of time, so it seems. And when we compare the two samples of cleaning up the environment, it looks like it's better to start as soon as possible.

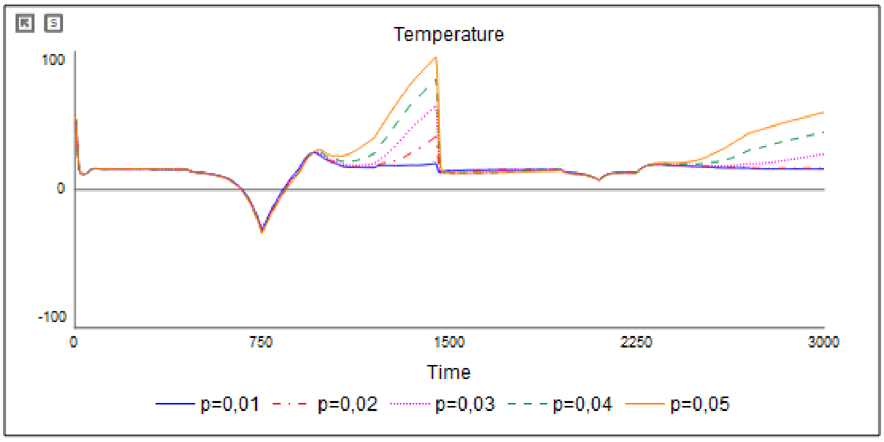


Figure 11.
If we execute another sensitivity analyse of five ad-hoc stages p=0,01 p=0,02 p=0,03 p=0,04 p=0,05 with clean-up around 1500 million years, we view how it affects planet temperature: after clean-up temperature is balanced again to normal levels for all poison states, and only after a long time of poisoning it deviates again

7.3 Climate oscillation scenario: Milankovitch cycles

Milankovitch (1941) hypothesized long-term, collective effects of changes in Earth's position relative to the Sun as strong drivers of Earth's long-term climate, and responsible for triggering the beginning and end of glaciation periods (Ice Ages). Three characteristics of Earth's orbital motion change slightly over long periods of time. These cyclical changes cause differences in the amount of sunlight the Northern and Southern Hemispheres receive. Analysis of deep-sea sediments has shown that these changes are closely associated with climate change.

To simulate this, we take 800.000 years from the past and put this oscillation within TimeFunction1, where every time unit is 100 years, leaving us a simulation of 8000 runs. First we will multiply the insolation representing the Milankovitch cycles by two, thereby situating the oscillation roughly within the range of TimeFunction1 between 1 and 2, so much like how we used it beforehand.

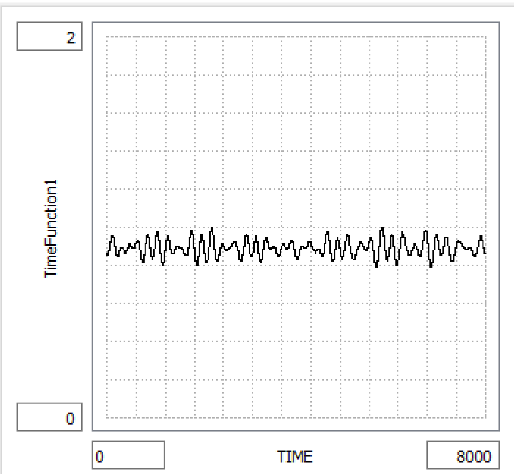


Figure 12.
Variation in insolation at 65° N in July. It is generally considered that the insolation received during July at a latitude of 65°N is the most sensitive indicator. The measured insolation ranged from 400 to 500 W/m^2 but is multiplied by 2

Imported from the following source:
http://www.climatedata.info/forcing/milankovitch-cycles/.

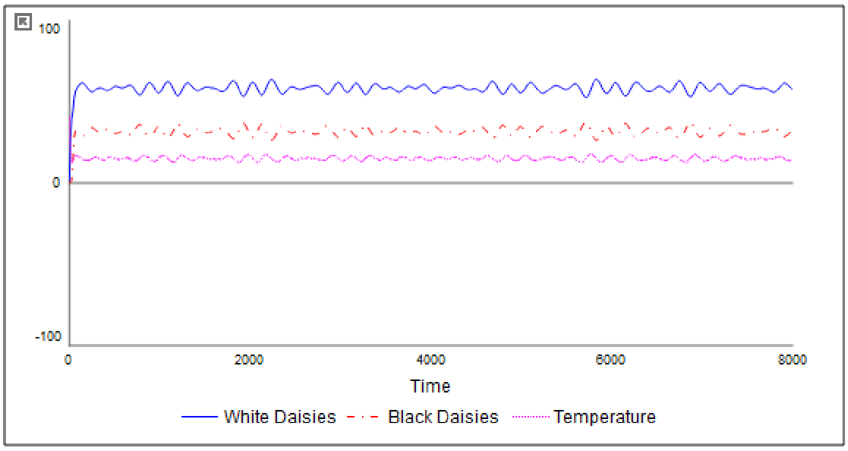
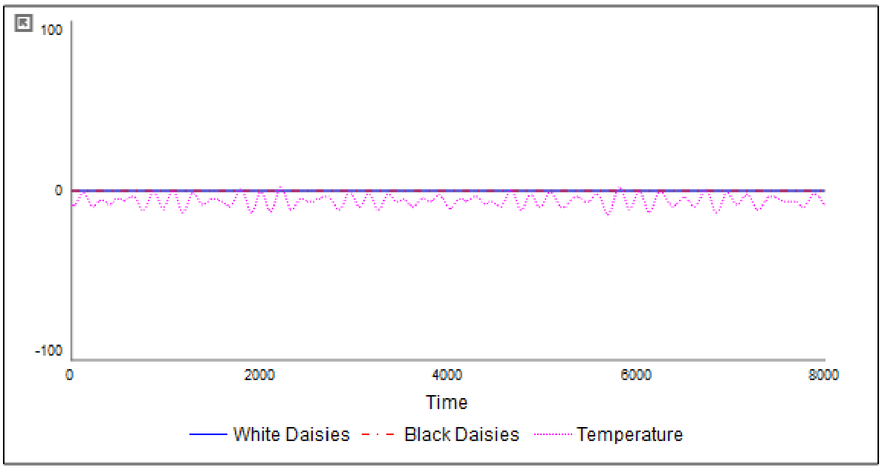
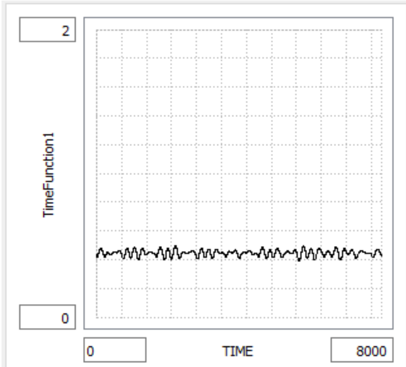


Figure 13.
The population of white and black daisies during this 800.000 years and the planet’s temperature.

Note that without plant species the planet temperature would be between 37 and 51℃. The white daisies however grow most severely and occupy the land of daisyworld, thereby cooling down the temperature to around 12℃. Then black daisies can grow as well. After that both plants can thrive, keeping a balance for a relatively stable temperature around 12 to 17℃.

Now we will simulate by using the real insolation measured: between 400 to 500 W/m^2. We will at first set the flowers species on our imaginary planet on extinction.





Insolation between 400 and 500 W/m^2 and with no daisies alive on our planet (black- and white daisies initial value =0)

Figure 14. Above we view how the temperature stays low during a long period of time, mainly below zero.

Then we start with the initial values of daisies set to 1 and zoom in at the first part of our simulation process, to see what happened just there.

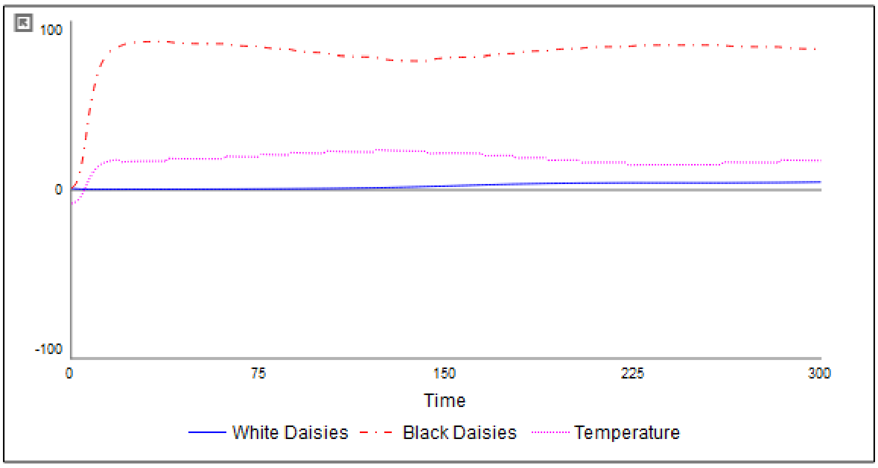


Figure 15.
Zooming in at the first 30.000 years, we see that the black daisies bring the temperature to acceptable level for both flowers to thrive, so around 15℃.

The planet temperature increased from basically below zero to well above, and the balance is then roughly maintained over a long period. White daisies have very little of the surface of daisyworld occupied, since it's to cold for them to thrive.

When we however replace the oscillation of Milankovitch simply by a steady low insolation over time, we get the following, basically similar, result: see figure 18.

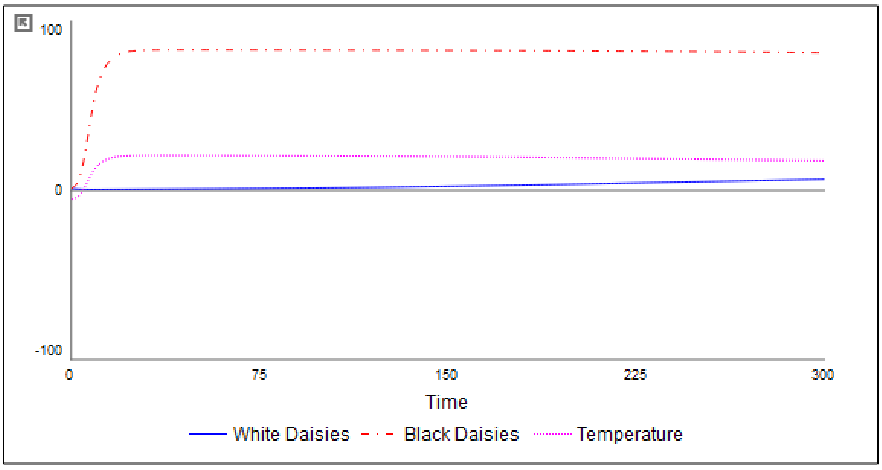
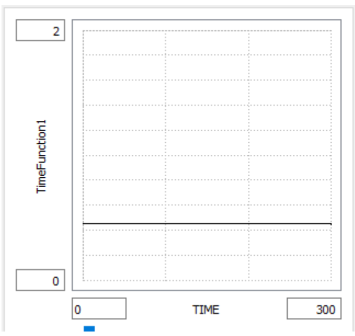


Figure 16.



A steady low insolation, so without the oscillation measured by Milankovitch

Summarising these results, we see that vegetation (the two daisies species) indeed balance the planet's temperature as expected. Furthermore, we can conclude that vegetation on our daisyworld planet can always recover after the first plants came into existence, even when the soil was poisoned severely, as long as we clean-up this poison. The more poison there still is however, the harder it becomes for the remaining vegetation to balance the temperature, and the sooner the poison will be removed (thus fertile ground is regained), the better the homeostasis can be maintained. Furthermore we see that the relatively small changes within the Milankovitch cycles, as well as a steady rising solar radiation (as a first metaphor for outside temperature rising by climate change), doesn't have much impact on the ability to balance the temperature within our daisyworld model, but increasing oscillations of warm and cold periods (as a second metaphor for outside temperature rising by climate change) do indeed have a significant impact on the homeostasis.

8. Discussion

Climate change sensitivity
The sensitivity analyses show a severe difference between the steady heating up versus the warm- and cold period oscillations. We can wonder why this is happening. The reason can be that the population of the flower species need too much time to grow and occupy the land in combination with the relative impact the albedo difference has upon temperature. Before the feedback mechanism starts to work, another climate period already starts. It's clear from our simulations that the bigger the temperature difference in smaller amount of time, the more difficult it is to self-regulate temperature.

Milankovitch cycles
The hypothesis of Milankovitch is about fluctuations in the Sun's radiation from the outside of our system boundaries, like our TimeFunction1. When we read from Nasa that Milankovitch combined the cycles to create a model for calculating differences in solar radiation at various Earth latitudes along with corresponding surface temperatures, it becomes clear that it is difficult to put such influence of orbital movements into the value within our TimeFunction1 because of regional differences. Our simple daisyworld can be viewed as a sphere without local differences from the outside, so to do this properly, we would need to build in temperature differences at regions within daisyworld, much like Biton & Gildor (2012) did. Taking this constraint into account, we can look at our simulation of Milankovitch and discuss the results. What makes these cycles so interesting is that while the change in global radiation was so small, the change at 65 ºN was enough to take us out of the ice age and into our current warm interglacial. Whilst it is generally accepted that Milankovitch cycles explain the sequences of warm and ice ages, there is no agreement on the mechanism by which this happens. Looking at the results of our simplified model, it becomes quite clear why it's rather hard to grasp how small temperature changes like this can indeed trigger ice ages, since within daisyworld they do not have influence on planets temperature regulation. The reason for this is that the difference in insolation by the Milankovitch cycles is simply not enough to trigger the daisies growth or death rate, at least not enough to make a difference; that is to say, before the difference start to be significant, the value within the oscillation wave changes direction already. One possible explanation might be that at these latitudes there is a higher proportion of land - which heats up more rapidly than sea - than elsewhere. When we think of balancing or reinforcing feedback loops over time, we come to realize that when the loop is active, and when it can stay active over a long period, this can trigger other feedback loops, causing possibly some kind of chain of reactions. Within this frame of system thinking, a tipping point in climate can be a threshold that, when exceeded, can lead to large changes in the state of the system as a whole. Potential tipping points have been identified in the physical climate system, in impacted ecosystems and sometimes in both. Politicians, economists and some natural scientists have tended to assume that such tipping points in the Earth system — such as the loss of the Amazon rainforest or the West Antarctic ice sheet — are of low probability and little understood. Yet evidence is mounting that these events could be more likely than was thought have actually high impacts and are interconnected across different biophysical systems, potentially committing the world to long-term irreversible changes (Lenton, T.M., et al., 2019).

Poisoning the soil
Looking at our model, representation of daisyworld as a parable for our own 'Gaia' world is extended with the idea of poison. This can be taken literally, but it can also be seen as a metaphor for humans polluting Earth with manufactured chemicals and occupying more and more surface of the planet at the expense of the natural world. In a very simple sense we can view our poison model as leading to loss of biodiversity and loss of the richness of vegetation, and therefore as a treat to the equilibrium state, causing climate change. That is to say, within our simple model the loss of vegetation leads clearly to a decrease of balance in temperature, but this of course doesn't mean that our model can function as prove that loss of biodiversity on Earth will lead to climate change as well. Research of Pires et all (2018) however demonstrate that effects of climate change and biodiversity loss on ecosystems cannot be understood in isolation: interaction between these stressors can be multifaceted. And within the *environmental science and sustainable development* curriculum of the Open University it is stated that: in geological history mass distinction of species led in several occasions to large-scale disruption of bio-geochemical cycles. This all represents the very idea behind the Gaia hypothesis, in my opinion, with the warning that the natural living world might survive, but our own species might not necessarily be one of the survivors.

How realistic is the parable Daisyworld?

The word parable means: a simple story used to illustrate a moral lesson. So, it is a type of metaphorical analogy. This analogy of the imaginary planet in our model with the Earth is by no means adequate, but it never was intended to be that way in the first place (Lovelock, 1983). A key point about daisyworld is for example that the daisies alter the same environmental variable temperature in the same direction at local and global level. Hence, what is selected for at the individual level is directly linked to its global effects. This makes the original model one that is not prevalent in the real world (Wood et al, 2008). Still, research have shown that in our real world on planet Earth, the (extra) greenhouse gas CO2 cause global temperature rising, while more vegetation can reduce the global amount of CO2. This lowering extra greenhouse effect will have a decrease (or less higher rising) of global temperature as a result. Another sample of indirect feedback in the real world we know of is winter snow-cover causing temperature decrease through a higher albedo (similar to white daisies), while melting of this snow can be seen as a positive feedback on temperature, since the lower albedo caused by less snow will increase temperature to an even higher level: global warming is melting the ice, thus reinforcing global warming, which amplifies ice loss. More in detail on vegetation, we see that modelling experiments with biogeochemical, physiological and structural feedbacks on atmospheric CO2, but with no changes in precipitation, ocean activity or sea ice formation, have shown that a consequence of the CO2 fertilization effect on vegetation will be a reduction of atmospheric CO2 concentration, in the order of 12% by the year 2100 and a reduced global warming by 0.7 °C, in a total greenhouse warming of 3.9 °C (Woodward et all, 1998).

The Gaia hypothesis served as one of the foundations of the modern Earth system science. We have to realize that the idea that the Earth is alive can be found in philosophy and religion, but the first scientific discussion about it has been started by the Scottish scientist James Hutton. In 1785 he stated that the Earth was a superorganism and that its proper study should be physiology. Interestingly enough, Hutton is considered the father of geology, but his idea of a living Earth was forgotten in the intense reductionism of the 19th century. As stated in the introduction, environmental science is by nature multi-disciplinary, interdisciplinary and, arguably, holistic. Reductionism doesn't get us very far in investigating environmental problems we face. And when we read the book The Donut Economy (Raworth, 2017) for example, we come to realise that the so-called foundations of economic science hide certain assumptions that were taken for granted, but actually contain moral grounds. Their claim of objectivity and being apolitical is simply false. The moral compass and alternative perspective that The Donut Economy provides was inspired by the Gaia hypothesis but goes a few steps further. Like proposed by Lenton & Latour (2018) we may better call this Gaia 2.0. Furthermore, the definition of life is still debated, but the interconnection of life with its environment is widely accepted and what's more, highly important in this lifetime. As stated within Gaia 2.0, a central goal for this century is to achieve a flourishing future for all life on this planet, including a projected 9 to 11 billion people. Human flourishing is not possible without a biodiverse, life-sustaining Earth system. This is recognized in the United Nations' 17 Sustainable Development Goals. It seems evident that we as humans need to create more self-awareness about The Earth's self-regulation mechanisms (Morton, 2015), since the whole system might be a lot rougher and cruder than our species can endure.

Can we extrapolate our results onto planet Earth?

Not without restraint and nuancing as mentioned above. This model doesn't represent the real world of the Earth enough to use it for this purpose. The model cannot be tested with real data from our living environment, since it's all about an imaginary planet. We cannot measure if predictions became true, nor can we adjust our model using data from the past. Hopefully though, reading this paper can make one wonder about the strength and weakness of self-regulation within our own living environment: planet Earth.

Recommendations

Within our model, we did not only use an imaginary planet, but also imaginary daisies that can grow at any temperature. It is better to simplify a model if possible, since the challenge in dynamic modelling is to discover underlying principles that explain the observed complexity of natural systems, but in this case some reality seems lost without gain. Subsequent versions of daisyworld for example show that evolution can broaden the self-regulation mechanism, while adaptively plausible alterations of optimum growth temperature can narrow the range of environmental regulation (Lenton & Lovelock, 2000). And Ackland et al. entitled their paper 'Catastrophic desert formation in Daisyworld' because they found that, when solar luminosity increased to a critical value, a desert formed across a wide band of the planet. Their model illustrates a potentially decisive difference: strongly coupled (Gaian) systems will normally be stable but can collapse at crucial points, so that the system can show dramatic changes in response to small changes in external forcing. If this is a realistic way in which to view the natural world, then it has important implications for how our human species have influence on life on Earth. Daisyworld models, although simple, can thus provide a starting point for models that couple ecology with other aspects of the Earth system (Wilkinson, 2003). However, it all depends on our purpose of our modelling: if we want to use the model for educational means, then our current model simplification can be useful. But if we want to use the model to get a better resemblance of planet Earth and how it is functioning as a single system, then we better use the original growth rate calculation or an improved one, along with other improvements, like for example the one Ackland et al (2003) made.

Further investigation of useful extensions within daisyworld modelling is recommended to create a model that contains, as much as possible, all of these extensions, and to expand them with new insights taken from recent real world, planet Earth scientific knowledge from climate research. We can then use this sophisticated new model to provide a higher level of self-awareness of Earth's self-regulation, thereby making it one of the tools to support Gaia 2.0 as proposed by Lenton & Latour (2018).

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