nonlinear dynamics lab (110231)

daisyworld: biological homeostasis in an idealised world

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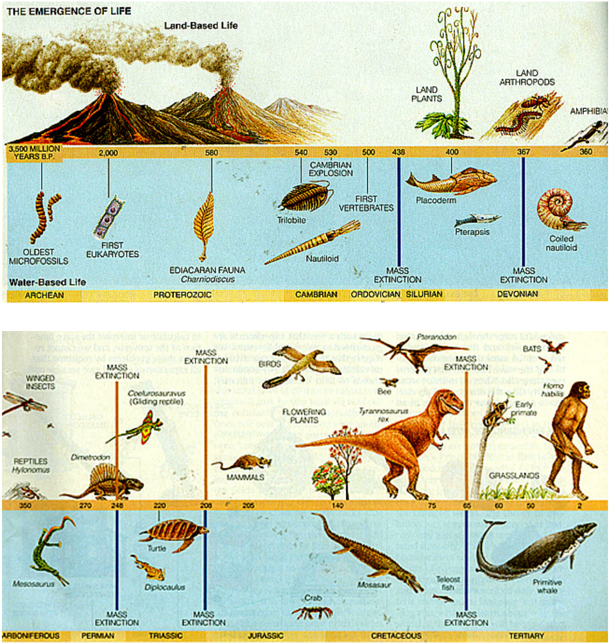
Spring 2016

Monday & Tuesday (9–10 May) 14:15 – 18:15

Location: **RLH seminar room & West Hall 8**



Weinberg's "Life in the Universe", *Scientific American*, October 1994

upper–temperature limits for growth

life is not so tollerant to extreme conditions...

taxon	**temperature (°C)**
archea	113
cyanobacteria	75
single-cell eukaryotes	60
metazoa	50
vascular plant	48

and it could be exterminated by less extreme events than those occurred in the past...

the Gaia hypothesis

ecology has traditionally considered the abiotic environment as an unchanging stage on which organisms interact

but another possibility could be that:

feedbacks between the organisms and their environment have helped to mantain habitable conditions on Earth

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the "original" Gaia hypothesis

Atmospheric homeostasis by and for the biosphere: the gaia hypothesis

By JAMES E. LOVELOCK, *Bowerchalke, Nr. Salisbury, Wilts. England* and
LYNN MARGULIS, *Department of Biology, Boston University, 2, Cummington Street, Boston, Mass. USA*

(Manuscript received May 8; revised version August 20, 1973)

ABSTRACT

During the time, 3.2×10^9 years, that life has been present on Earth, the physical and chemical conditions of most of the planetary surface have never varied from those most favourable for life. The geological record reads that liquid water was always present and that the pH was never far from neutral. During this same period, however, the Earth's radiation environment underwent large changes. As the sun moved along the course set by the main sequence of stars its output will have increased at least 30 % and possibly 100 %. It may also have fluctuated in brightness over periods of a few million years. At the same time hydrogen was escaping to space from the Earth and so causing progressive changes in the chemical environment. This in turn through atmospheric compositional changes could have affected the Earth's radiation balance. It may have been that these physical and chemical changes always by blind chance followed the path whose bounds are the conditions favouring the continued existence of life. This paper offers an alternative explanation that, early after life began it acquired control of the planetary environment and that this homeostasis by and for the biosphere has persisted ever since. Historic and contemporary evidence and arguments for this hypothesis will be presented.

[Lovelock & Margulis, 1974]

the "modern" Gaia hypothesis

"organisms and their environment evolve as a single coupled system, from which emerges the sustained self-regulation of climate and chemistry at a habitable state for whatever is the current biota"

[Lovelock, 2003]

homeostasis

is the property of a system that regulates its internal environment and tends to maintain a stable, constant condition of properties (e.g.: temperature).

daisyworld

daisyworld model: a simple model that illustrates the potential for life to influence planetary ecologies; the purpose of the model is to demonstrate that feedback mechanisms can evolve from the actions of "self-interested" organisms, rather than through classic group selection mechanisms.

daisyworld is a hypothetic world seeded with two varieties of daisies as its only life forms: black daisies and white daisies.

daisyworld

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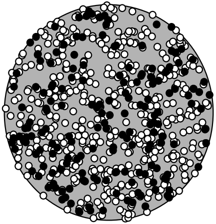
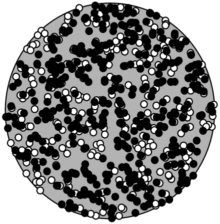


daisyworld with dominant white daisies



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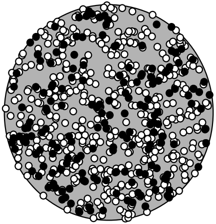

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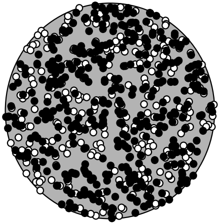

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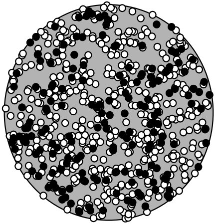

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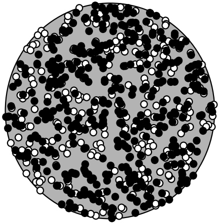

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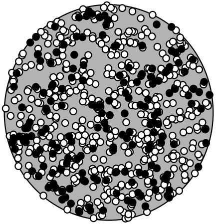
the temperature of the planet daisyworld is governed by the input of stellar and the albedo of the planet, thus life and the physical environment are coupled in the model.



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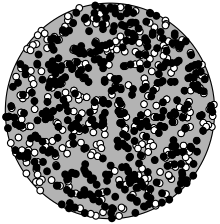

daisyworld with dominant black daisies

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the equations are:

$$\begin{aligned}\frac{d\alpha_w}{dt} &= \alpha_w\,(x\,\beta_w - \gamma)\\ \frac{d\alpha_b}{dt} &= \alpha_b\,(x\,\beta_b - \gamma)\end{aligned}$$

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$$\frac{d\alpha_w}{dt} = \alpha_w\,(x\,\beta_w - \gamma)\ ; \qquad \frac{d\alpha_b}{dt} = \alpha_b\,(x\,\beta_b - \gamma)$$

α_w	fraction of planet covered by white daisies
α_b	fraction of planet covered by black daisies
β_w	growth rate of white daisies
β_b	growth rate of black daisies
γ	death rate for all daisies
x	fraction of planet not covered by daisies ($x = 1 - \alpha_w - \alpha_b$)

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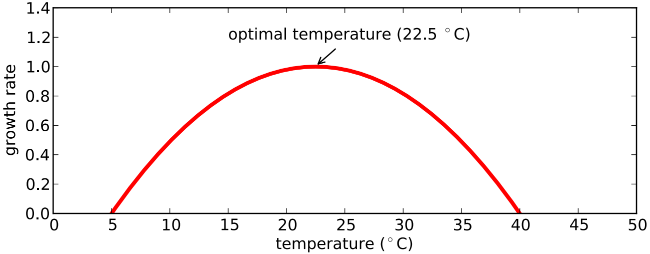
the growth rate (β) of each daisy type is a parabolic function of their local temperature T, for white daisies for example:

$$\beta_w = \max\left[0\ ,\ \ 1 - \left(\frac{T_{opt} - T_w}{17.5}\right)^2\right]$$



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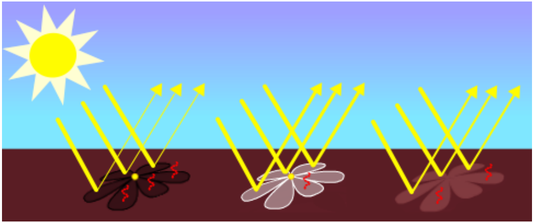

Sunlight reflects off different color daisies. Black daisies absorb most light, turning it into heat. White daisies reflect most light, and stay cooler. Barren spot has intermediate albedo.

see also: `http://gingerbooth.com/flash/daisyball/`

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where $q = 2.06425 \times 10^9\,\mathrm{K}^4$ is a constant indicating the degree of insulation between regions of the planet's surface.

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(it follows that $T_b > T_x > T_w$)

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the effective temperature of daisyworld (T_e) is then contrasted with the temperature of the planet without daisies (in which $A_p = A_x$).

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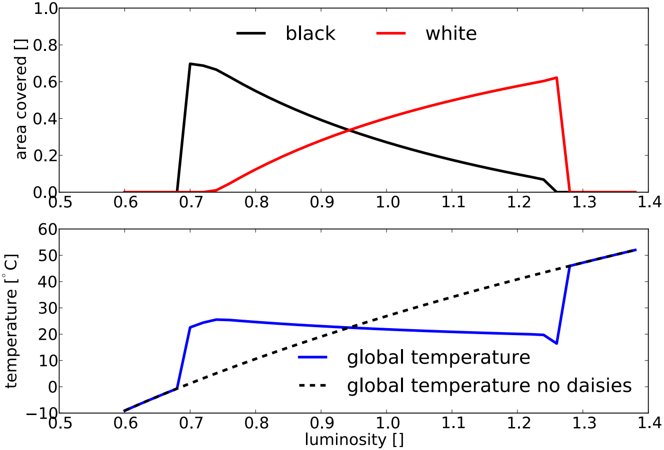
daisyworld exhibit self-regulation...



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daisyworld illustrates the potential for biology to regulate conditions on a planet but only if life covers much of the planet's surface.

the mathematics of daisyworld – summary

the black daisies work with the Sun to warm the planet: positive feedback;

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the white daisies work against the Sun to cool the planet: negative feedback;

black and white daisies together regulate planet's temperature producing a stable environment despite the increase in solar radiation.

role of life in planetary physiology - examples

is there anything operating like the black and white daisies on Earth?

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Aspen Snowmass, western Colorado (USA)

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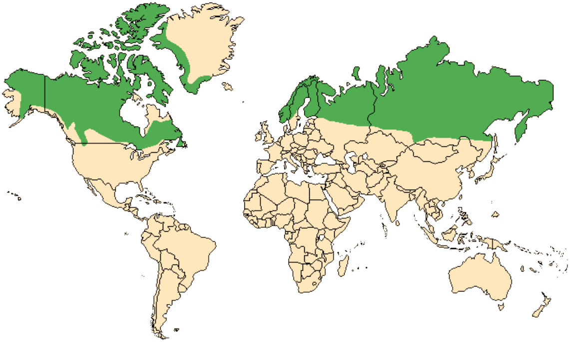

Boral forest biomes on Earth

role of life in planetary physiology - examples

boreal forests (covering 15.8 million km^2) and coniferous forests in temperate mountain areas (covering 3.3 million km^2) represents a great expanse of trees with lower albedo than a snow-covered ground;

role of life in planetary physiology - examples

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clearly boreal forests can potentially act like black daisy !

Bibliography

Lovelock, J.E. & Margulis, L.
Atmospheric homeostasis by and for the biosphere:
the gaia hypothesis.
Tellus, 26(1-2):2–10, 1974.

Watson, A.J. & Lovelock, J.E.
Biological homeostasis of the global environment: the parable of Daisyworld.
Tellus, 35B:284–289, 1983.

Lenton, T.M. & Lovelock, J.E.
Daisyworld revisited: quantifying biological effects on planetary self-regulation.
Tellus, 53B:288–305, 2001.

Lovelock, J.E.
Gaia: The living Earth.
Nature, 426:769–770, 2003.

Carter, R.N. & Prince, S.D.
Epidemic models used to explain biogeographical distribution limits.
Nature, 293:644–645, 1981.