

Appendix E: Modeling exercises and the OGT

Modelling Gaia through our theory is not easy because it is ultimately an attempt to mathematically model an enormous organism, and the process we describe assumes emergent properties and the capacity for “open-endedness” (Adams et al. 2024; Peng et al. 2020; Moreno and Ofria 2019) based on the closure of the trinomial and its serial couplings like “Matryohska dolls” (de Castro and McShea 2022). That is, if the emergent property is not modelled directly, it is very difficult (Adams et al. 2024), not to say impossible, to do so from only bottom-up models in which the “atoms” are genes, bacteria, or populations. Artificial Life (AL) models are relatively simple and seek to answer concrete questions. When these models try to make a leap in individuality (as in the MTEs) - which would be most comparable with what we argue in the OGT -, such as DYSTHINY (Moreno and Ofria 2019), they have computing time problems as soon as they move to a diversity and number of individuals closer to reality.

Also, since Gaia is in some ways analogous to the emergence of life itself from chemical autocatalytic ecological networks (Peng et al. 2020), but from a larger, more capable aggregate (with finalistic properties), i.e. bacteria, it is not expected that a bottom-up model would generate the emergencies that we postulate here and that can be observed (MTEs, the behavior of life as a whole, etc.).

In Rubin and de Castro (2021), it was already discussed that the modelling approach proposed by Lovelock for Gaia, the Daisyworld models, in which only bottom-up parameters typical of the Darwinian paradigm are added, tend to worsen regulation. However, if emergent features are assumed in Daisy-like models that better fit the OGT, such as the altruistic predisposition of daisies regulation occurs and is better than in classical Daisyworld models (see Appendix C and the discussion in Rubin and de Castro, 2021).

More elaborate but spatially and temporally more specific models have also been developed, for example in relation to biogeochemical cycles, where the “life” component is treated at an ecosystem or at global scale (e.g., a good part of the articles in this journal and those referenced in this article). If the introduction of a few wolves into Yellowstone park (Ripple 2012) has rapidly changed the ecosystem and even the landscape through their direct or indirect interactions with dozens of other species and the physical environment, how can we model the interaction of millions of species, genes, and vast populations like the “atoms” of biology? There is no choice but to create partial models, as has been done with the Daisyworld models initially and other models later, or to assume certain emergent aggregates, even beyond bacterial populations, as proposed here.

Thus, a potential Gaian model would begin with the first steps of the process described in section 3 of the main text:

Step 1: Exponential growth in population (e.g., total biomass), productivity (e.g., NPP), etc.

Let P represent population or productivity. “P begets P”.

The differential equation is $dP/dt = c \cdot P$, ($P=P_1$ at $t=t_0$) where c is a positive constant, the “natural” growth rate of P.

This equation gives rise to an exponentially increasing function. This creates a problem: No dynamic can grow permanently in an exponential way in the universe because the accessible universe is finite. Therefore, limiting factors arise for P (which

Darwin, Malthus, etc., also base their arguments on, as we noted in the process of Gaia's emergence in section 3).

Step 2: Approximation to a "local" limit = K_1

We find the logistic equation, in population dynamics studied by Verhulst (which would later provide the basis for the Lotka-Volterra equations when one population—e.g., predator—depends on the population of another—e.g., prey—which in turn is the limiting factor for the prey).

The logistic equation is:

$$dP/dt = c \cdot P \cdot (1 - P/K_1) \quad \text{eq.1.}$$

Where growth slows down because as P grows, the P/K_1 value grows and, by the time P reaches the K_1 value, P stops growing.

The problem is that in the following steps (3, 4 and 5) it is assumed that they generate a new structure (postulate 2) that, by processing more energy potentially stabilizing it (postulate 1), and through the formation by means of symbiosis in our biological case of ecological networks, allows a leap and a rupture of the local limits thanks to these networks. For example, recycling networks could do that in the case where the limiting factors come from the flow of input materials ("food") and/or output (potentially "poisonous" waste). In the case of the formation of Bénard cells, the structure allows to break the limit of energy flow that was being dispersed, increasing its dispersion (see appendix A).

Steps 3, 4, and 5 lead to step 6, the breaking of local limits. The way to model this mathematically would be to change the value of K_1 to a larger one, K_2 , at some point after $t=0$. One way to visualize this is with the example of generating a structure that causes the recycling rate to increase, as we see in Appendix C, where without recycling, the external material flow can result in a maximum population, K_1 , due to the external "food" supply limit, and by recycling the food input at a rate of 50% the food is used twice (although coordination is required, which will otherwise require energy), potentially taking the total population to a double K . This could be done, for example, by more or less discrete jumps as growth hits the previous limit K_1 and by reaching the limit, this "stimulates exploration" of new structures that end up pushing the limit further away to K_2 . In MTEs, de Castro and McShea 2022 reasoned that each level of individuality encounters some limit to its own complexity, for example, and this was resolved by allowing a jump in greater complexity and individuality (also in size) through a trinomial (i.e., our postulates 1 and 2), with the symbiotic cooperation of the elements (postulate 3). There it was shown that classical theories were unable to predict what had been observed in the fossil record on Earth, that MTEs were accelerating, fitting with a global exponential function, although each level could behave like a logistic curve (the behavior of logistics on logistics giving rise to a global exponential was already reflected intuitively in de Castro 2020[2008], fig 2.13).

Step 7 generates a return to steps 1 and 2, that is, a potentially positive feedback loop. Step 8 assumes the possibility of MTEs and ecosystems becoming physiologies (leaps to biofilms as tissues and to Gaia as an organism (postulate 3)).

Step 9 assumes teleological characteristics of anticipation and learning, so that once Gaia is formed (step 10), it allows its internal processes to accelerate. This would imply an acceleration in the acquisition of the following, increasingly higher K s, until some absolute limit restraints Gaia's possibilities.

Without going into each step in detail, ultimately, we expect Gaia and its P to change exponentially.

One prediction that follows from the OGT is that Gaia's P will follow an exponential trend because the organization it carries out with trinomials and coupled trinomials rapidly breaks the limits—which tend to generate logistic curves—unless we are relatively close to some absolute limit for Gaia. If we assume a close absolute limiting factor, we would again find ourselves with Verhulst's equation, but if the "learning" toward the absolute limit is rapid (as our theory suggests) and proportional to the size of P itself, then a preliminary "toy" model of organic Gaia could follow these equations:

$$dP/dt = c \cdot P \cdot (1 - P/K) \quad (\text{eq. 2.}) \quad (\text{eq. 1, but in this case with a variable K})$$

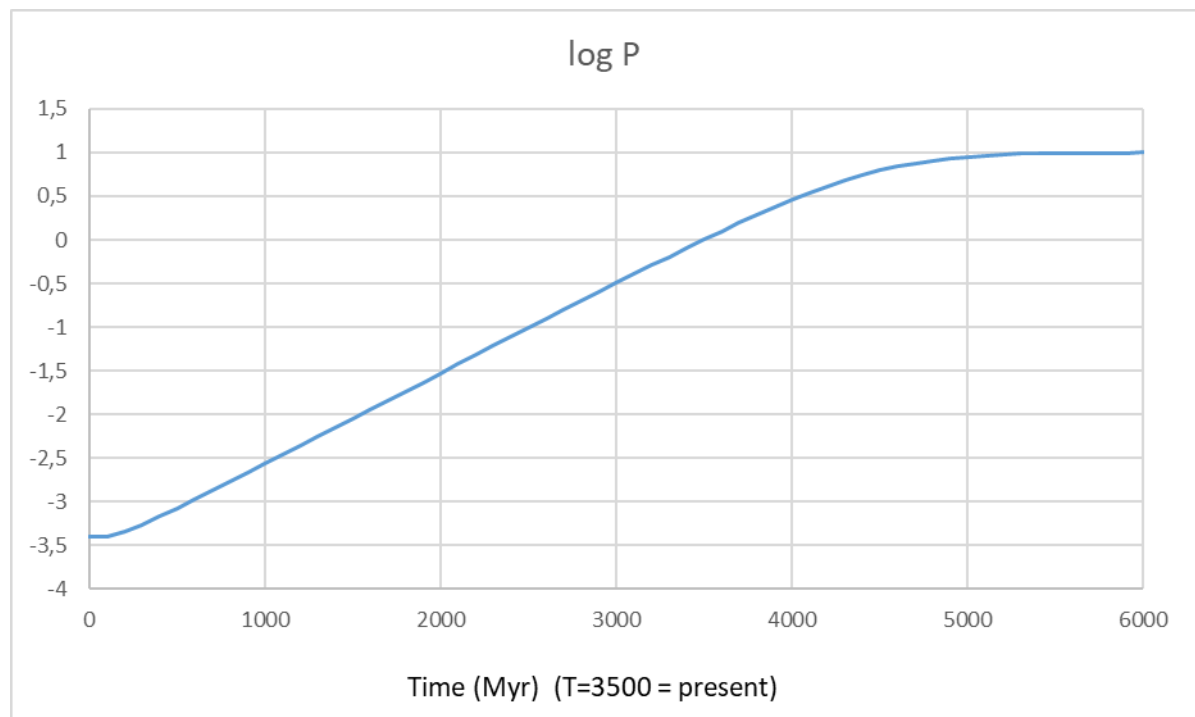
Being K, the integral of:

$$dK/dt = b \cdot P \cdot (1 - K/P_{\max}) \quad (\text{eq. 3.})$$

The growth limit of P has a maximum at K that changes in proportion to P (eq. 2), which in turn has an absolute maximum at P_{\max} (eq. 3). Equation 3 would describe how the evolution of K (the departure from the local limits) tends to be proportional to P but with an absolute limiting factor at P_{\max} . That is, we would have a kind of logistic function (K) within another logistic function (P).

These equations can be modelled by choosing the parameters so that $P(t=0) = 4E-4$, $P(t=3500 \text{ Gyr}) = 1$ and $P_{\max}=10$. We assume that the limit encountered by the first Gaia populations occurred 3500 Gyr ago (Guerrero and Berlanga 2006) and that the population size that could be sustained was $4E-4$ times lower than the current one (the numbers are derived by taking the average value of the case 2 of the model of Kharecha et al. 2005). We assume also that P_{\max} is 10 times the present (assuming 5 to 100 does not give qualitatively different results).

The figure represents Log (P) as function of time (in million years).



From 500 to 4000 Myr, LogP has a very good linear correlation, i.e. an exponential-like increase of P.

A priori, based on the fossil record or with the help of complex partial models of the limits Gaia may have encountered over time (for example, the oxygenation of the atmosphere and oceans removed limiting factors by increasing the energy acquisition possibilities of metabolisms based on oxygen respiration), our simple model that makes the above prediction could be tested or contrasted. If, for example, Gaia's top-down learning and causation are "slow" or non-existent, what we would predict would be a slower function than an exponential one. In the case of MTEs, the reasoning would be similar and what is expected is again an exponential function of the rate of appearance of MTEs (de Castro and McShea, 2022), since Gaia "takes control of its internal evolution", as an agent of "natural selection" of its cells (Margulis 2008) (while neo-Darwinism predicted an increasing function that slows down over time, especially if one assumes that the speed of exploration of the "state space" of individuality decreases with complexity, since more complex organisms reproduce more slowly and are less numerous).

In short, if Gaia has not yet encountered absolute limits, it is expected (and testable as a prediction of the OGT) that parameters such as living biomass or GPP/NPP have been growing exponentially for billions of years up to the present, and into a future that would ultimately depend on the absolute limits encountered. It is also expected that the cycling capacity of elements and, in general, the RAMO properties we have described have also grown strongly and rapidly over geological time. In the last 400 million years alone, there has been a leap in Gaia's productivity that has at least doubled its NPP value (the conquest of land by plants is relatively recent in geological terms, and today terrestrial NPP is similar to oceanic NPP; in addition, the latter has been able to increase thanks to the conquest of soils through increased leaching and other feedbacks that would "feed" the oceans with nutrients). Therefore, we expect that Gaia is still in the exponential phase and not at its absolute growth limits. And even if we were to observe a slowdown in its growth function, this also has very interesting implications for the future of Gaia and its "cells."

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