

The properties of organisms are not tunable parameters selected because they create maximum entropy production on the biosphere scale: A by-product framework in response to Kleidon

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Abstract Axel Kleidon (Clim Change 66:271–319, 2004) proposed that the organisms that constitute Earth's biota have free parameters that can be selected to create states of maximum entropy production (MEP) on various scales, from the biota to the planetary radiation balance of the Earth system. I show that Kleidon's concept, here called the biotic-MEP hypothesis, is fundamentally mistaken. A thought experiment with a life form that would be selected against even though it would generate a higher degree of entropy demonstrates my case: A hypothetical tree that puts forth a non-productive but high-entropy producing black carpet of tissue clearly separates out entropy production from other biological processes and shows that entropy production is not a functional adaptation and therefore it cannot be selected for. A real world example comes from dimethyl sulfide-emitting plankton, which, by increasing cloud albedo, do not raise but rather lower the entropy flux of the Earth system. I provide a number of other examples of biotic processes that individually either decrease or increase the environmental entropy production. It is argued that biological effects on environmental entropy production can be expected to include both positive and negative examples, because these effects are merely by-products of the actual processes that are selected for by evolution. Given my framework of entropy production as a by-product of the true processes that are being selected for, the concept of MEP on environmental scales has no great relevance for discussions of biological evolution or the time history of the effects of life on the global system.

1 How Kleidon sees the role of the biota in maximum entropy production

I focus on Kleidon's application of the hypothesis of maximum entropy production (MEP) to the Earth's biota (Kleidon 2004, sections 3 and 4, pages 285–315). The hypothesis, in his more general formulation that is not restricted to the biota, is that energy-transforming processes in the Earth system, such as the planetary radiation balance, atmospheric dynamics, and the active biota (the sum of all living things) will shift the Earth system

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toward states of MEP. I will examine Kleidon's inclusion of the biota as an active process that might contribute to this hypothetical shift.

Kleidon justified including the biota in the general hypothesis of MEP because the biota "introduce additional degrees of freedom to Earth system processes." To show how crucial this concept is within his overall framework, I will quote him, choosing one example from numerous similar ones in his paper.

The biota add degrees of freedom to Earth systems processes. Through the addition of degrees of freedom to Earth system processes, states of higher entropy production can be selected for, eventually leading to a state of MEP. (Kleidon 2004, p. 302)

Kleidon said that biotic activity not only itself goes to a state of MEP but creates environmental changes that then enhance entropy production toward MEP. The boldest part of his hypothesis is that biotic processes will evolve to create states of MEP for the total Earth system, for example, by affecting the global radiation balance. I will use the term "biotic-MEP hypothesis" for Kleidon's application of the general MEP hypothesis to the constituents of Earth's biota and to their effects on the entropy production of their local and global environments.

Kleidon's strategy to support the biotic-MEP hypothesis was to offer examples. In the first (section 3.2), a "conceptual model of biogeochemical cycling," Kleidon pointed out that because nutrients are recycled in the biosphere, photosynthesis is much higher than it would be, were the photosynthesizers to depend exclusively on new nutrient fluxes from volcanoes and rock weathering. Indeed, in his equation (21), the entropy production by the biota, under certain cases and assuming constant conversion efficiency, can be nearly proportional to rate of photosynthesis, because photosynthetic productivity entails a certain amount of conversion of low-entropy shortwave radiation into several forms of high-entropy waste heat.

First of all, we all will grant that by the mere act of living, photosynthesizers – indeed, all organisms – will degrade free energy and therefore create a positive entropy production. This fact has been recognized since the days of Schrödinger. So what is the potential news?

Given Kleidon's assumptions, one being that the ratio between entropy production and photosynthesis is a constant, then if you double the photosynthesis you also double the entropy production. No debate there. And were this all that Kleidon were claiming, the claim would be trivial, as noted above. But Kleidon used this fact as a pillar of support for his biotic-MEP hypothesis by professing something much stronger. Recall that his quoted words pointed to selection being for "states of higher entropy production." So according to the biotic-MEP hypothesis, ecosystem recycling from the evolution of photosynthesizers and other organisms has come into being *because* the increased biological absorption of sunlight raises the entropy production to levels greater than would exist without life (or with less life). Kleidon seems to claim (in particular, see pages 302–303) that the diversity of life forms with different physiological parameters help achieve the MEP state (or as near to it as possible, given constraints) because the biological parameters can be differentially selected and therefore tuned to create the general trend toward an MEP state. I dispute this entire line of reasoning, as will be detailed below.

Kleidon's second example (section 3.3) showed that the global entropy flux of today's world is just slightly higher than that computed for both a Desert World (by 0.6%) and a Green Planet (by 0.2%). The calculations included a number of radiative and heat fluxes, some of which, in terms of entropy contributions, even stay the same or decrease, but Kleidon says the global totals, are "primarily driven by the increased absorption of solar radiation" (page 291), which is affected by clouds, which are affected by transpiration. Note

the slim differences in entropy production. Indeed, a reviewer of this current paper, James Kirchner, doubted that “even the MEP enthusiasts claim that systems self-organize on the basis of <1% differences in entropy production.” Even more problematic is Kleidon’s use of this example as a pillar of support. The way I read his hypothesis, the particular parameters of the biota are what they are because they help create a global state of MEP. That he does endorse this reasoning is clear in his next example.

Kleidon’s third and final example (section 3.4) was a “simple coupled climate-carbon cycle model.” Across geological time, during which the sun’s output increased by about 30%, he computed carbon dioxide and global temperature, assuming that a physiological parameter of the global biota (in this case, global respiration) is tuned by evolution and population dynamics at each point in time to create the MEP state. The model linked respiration to the greenhouse effect and thus clouds, and in the results, global temperature was relatively stable. According to Kleidon, this MEP model is a novel way to generate the phenomenon that in Lovelock’s Gaia hypothesis was termed global homeostasis.

But is global homeostasis a fact that needs accounting for? The issue is not clear. For example, in a different model, which focused on the geological carbonate-silicate cycle (a cycle which Kleidon, in a caveat, admittedly ignored and yet is absolutely essential to calculating CO₂ levels over geological time scales), Schwartzman and Volk (1991) showed that evolutionary changes in the land biota and their impact on soils, as factors that increased the biological enhancement of chemical weathering, would have lowered global temperature over geological time. In this model, evolutionary changes created climatic change, not stability. Kleidon’s third example should be regarded as “what if” model and should not carry any weight of support for the biotic-MEP hypothesis.

But Kleidon’s model does help us in one crucial point. It helps us see exactly how he thinks his hypothesis operates. His model contains two rate coefficients, one for carbon burial and another for global respiration. Over evolutionary time, with the rising solar flux, he arbitrarily set the first as constant and varied the second to whatever value yielded MEP. Thus he explicitly assumed that global respiration coefficient is a free parameter that can change. Nothing wrong there: the physiology of organisms does evolve, and populations do shift. But Kleidon thinks these changes will be channeled – that the respiration rate adjusts over earth history – specifically to create the MEP state. So must ecosystem recycling, transpiration rates, and other characteristics of life: in the biotic-MEP hypothesis they have been selected to shift the Earth toward MEP.

2 A thought experiment disproves the biotic-MEP hypothesis

Here is the crux of the matter. Evolution in the standard sense refers to the fact that alterable properties of creatures can be selected for adaptive improvements. For the biotic-MEP hypothesis to be true, entropy production must be selectable as an adaptive improvement to the reproductive success of the organisms and not a mere by-product of something else (say photosynthetic efficiency) that is being selected for. If entropy production is a by-product, as I will submit, then one would expect to find cases in which a decrease (not an increase) in entropy production leads to enhanced reproductive success. But we need a logically crisp means to separate out entropy production from other factors that might really be the ones that are being selected for.

Consider a hypothetical tree, which, in addition to its normal, life-supporting green leaves, can also grow a gigantic black leaf—say a carpet of tissue that emerges from the trunk and spreads out upon the ground for perhaps a hundred square meters. Assume that this black

carpet – a mutation in pigment production and tissue growth – performs no photosynthesis but does absorb sun over a wide area not captured by the productive green leaves.

This non-productive black carpet will increase the tree's biological contribution to entropy production because it transforms low-entropy, shortwave solar radiation into high-entropy, longwave infrared radiation and other waste heat, which contributes to Earth's entropy production, according to Kleidon's equation (1). So a planet full of trees with big black carpets that do not photosynthesize but are nonetheless effective at absorbing sunlight can have a large entropy production. Will trees like this evolve? Will their mutant black carpets get ever larger over evolutionary time *because* they help push the planet toward MEP?

Not a chance! These mutant trees would be out-competed by ordinary trees that only put forth tissues that create useful photosynthetic products. The black carpets might increase entropy production but they are biologically detrimental because they are costly for the trees to grow and maintain. It is therefore obvious that entropy production itself cannot be the driver for guiding the biota along an evolutionary route of tuned biological variables.

3 The case of dimethyl sulfide also disproves the biotic-MEP hypothesis

If increasing the rate of entropy production, both locally and globally, drives biological evolution, we should not be able to find cases in which biological adaptations decrease the rate of entropy production. But we do. An additional disproof of the biotic-MEP hypothesis involves marine plankton and dimethyl sulfide (DMS).

In a classic paper, Charlson et al. (1987) assembled evidence that DMS gas cools the Earth. Many species of phytoplankton produce a precursor molecule that functions as an osmoregulator inside their cell bodies. When the precursor is released from the cells, primarily via predation, it changes into DMS, which enters the atmosphere where it oxidizes to a sulfate aerosol that acts as cloud condensation nuclei, increasing the brightness of marine clouds and thus Earth's overall albedo. Caldeira (1989) inquired into whether plankton could be selected to produce DMS specifically because of its climatic effects, but found that metabolic costs outweigh generously assumed climatic benefits by a factor of a billion or more. Thus phytoplankton synthesize the DMS precursor solely because it benefits their internal metabolisms, not because of a dilute influence on the atmosphere or Earth's radiation budget.

The problem with searching for instances in which organisms are selected specifically to alter the large-scale environments of air or ocean goes much deeper than calculating costs versus benefits. Assume that the presumed benefits in terms of reproductive success, from brightening the clouds, did happen to outweigh the metabolic costs of making the DMS precursor. Sounds pretty good, right? But then consider the evolution of cheater plankton, who live alongside the producers and derive all the benefits from the altered clouds but pay zero costs because they do not even make the DMS precursor. That is an even better game. The cheaters will out-compete the DMS producers and drive the producers to extinction. At that point there is no DMS and the cheaters no longer derive the benefits, but they have won the game of evolution.

The cheater problem comes in for any cases in which organisms might have to pay metabolic costs to produce large-scale beneficial effects. I have argued that large-scale effects occur only if they are for free, as by-products (Volk 2002, 2003). For example, it doesn't matter to the evolution of the cellular, osmoregulatory DMS precursor whether the effects of DMS are considered detrimental or beneficial to communities on larger scales; as long as the precursor enhances the reproductive success of the cells that possess it, the

precursor will be selected for. The planetary effects of DMS are only by-products (Volk 1998). The same logic applies to the biotic-MEP hypothesis. For states of higher environmental entropy production to be “selected for” (in Kleidon’s terminology) and for organisms to be “degrees of freedom” in that selection, the increase in entropy production must create an improvement for the organisms. And then the cheater problem would arise. Hence, increased entropy production can only be a free by-product. And the effects of by-products can go in both directions.

Does DMS decrease (rather than increase) global entropy production? Using Kleidon’s calculations, entropy effects from albedo changes will come from both the solar absorption and Earth’s effective radiating temperature. In Kleidon’s equation (2), the radiative entropy production (E) of the earth system on a unit area basis can be calculated by knowing the absorbed solar flux by the earth (Q_{in}), the infrared radiative flux to space (Q_{out}), the effective radiating temperature of the Earth (T_e), and the radiating temperature of the sun (T_{sun}).

$$E = Q_{out}/T_e - Q_{in}/T_{sun}$$

In addition, $Q_{in} = (S/4)(1-A)$, in which S is the solar constant, A the planetary albedo, and $(1-A)$ the planetary absorptivity.

In steady state, $Q_{out} = Q_{in}$, and since $T_{sun} \gg T_e$, the second term to a first approximation can be neglected, and the entropy production of the earth system is $E = Q_{out}/T_e$. Or, $E = (S/4)(1-A)(1/T_e)$, using $Q_{out} = (S/4)(1-A)$.

Now, T_e can be calculated knowing the Stefan–Boltzman constant (B), by substituting the expression for Q_{out} into the blackbody radiation balance of $T_e = (Q_{out}/B)^{0.25}$:

$$T_e = [S(1-A)/(4B)]^{0.25}$$

Substituting, we arrive at

$$E = C(1-A)^{0.75}, \text{ where } C \text{ is a constant equal to } (S/4)^{0.75}(B)^{0.25}$$

In words, the entropy production is proportional to the absorptivity $(1-A)$ to the 3/4 power. Watson and Liss (1998) computed that DMS, globally, raises planetary albedo by about 7%, from what would be 0.28 without DMS to 0.3 today. Since DMS raises the albedo (A), it decreases the absorptivity, and therefore decreases the planetary entropy production. DMS production is a real-world example of a biological process that acts to decrease the entropy production of the Earth system, counter to the biotic-MEP theory.

4 Entropy production can be either increased or decreased by specific constituents of the biota because it is only a by-product

As this analysis shows, any biological process that increases albedo, like the generation of DMS, lowers entropy production. We can observe the same phenomenon on the local scale, whenever a photosynthesizer has a higher albedo than the surrounding substrate. Figure 1 shows such an example: a lichen with a higher albedo than the rock. Less solar energy is absorbed than if the lichen were not there; with this particular biotic process the entropy production is lower. But the lichen does not “care” what it is doing to environmental entropy production, because it is absorbing and utilizing enough solar energy to live, as it has been selected to do.

We can also look at biotic processes that change the entropy production as a by-product either up or down by affecting atmospheric CO_2 and temperature. Here I will use Kleidon’s

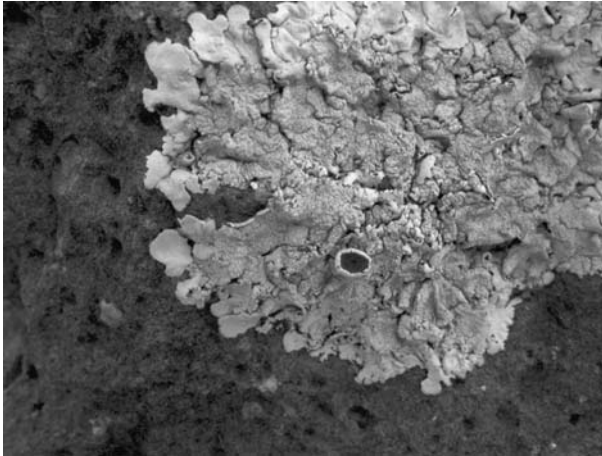


Fig. 1 This light-colored lichen reflects more solar radiation than does the rock's surface. Here the environmental entropy production is decreased by the biotic process. (Photo: the author)

own calculations for the relationship between planetary radiative entropy production, temperature, and atmospheric carbon dioxide levels. From Kleidon's climate model calculation (see his Figure 4), for values of atmospheric CO_2 and temperature higher than a cold "white Earth" threshold, Kleidon shows that $dE/d(\text{CO}_2) < 0$ and $dE/dT < 0$. Therefore, when the earth is above his critical values for CO_2 and T , which it presumably has been for cases discussed below, biological processes that increase CO_2 and T will decrease the global entropy production. Are there such processes?

One occurred in the evolution of calcareous plankton (Volk 1989). These plankton shifted a substantial fraction of ocean carbonate burial from shallow water to deep water, increasing the carbonate sediments that enter subduction zones, and almost certainly increasing the flux of CO_2 released at plate boundary zones up into the atmosphere. This biological process, which has the by-product effect of warming the planet, has been incorporated as a climate-affecting factor into models of the Phanerozoic (Berner 1994). Accordingly, the contribution to greenhouse warming from the evolution of calcareous plankton would have decreased (not increased) the global entropy production. Of course, the plankton "knew" nothing about their effects of global radiative entropy production. They evolved their tiny shells for individual reasons having to do with propagation of the species. Indeed, the calcareous lifestyle was independently evolved many times. Their effect on net global entropy production (negative in this case) just happened to be what it was (and is, presumably).

Another counter-example to the biotic-MEP hypothesis comes from the suggestion by Jennifer Robinson (1990) that the evolution of lignin-degrading fungi during the Phanerozoic occurred substantially later than the evolution of lignin itself, as a molecule that functioned to help support the earliest trees. The lack of lignin-degrading organisms might have created the drop in temperatures near the end of the Permian, an effect on atmospheric CO_2 modeled by Berner (1994). So, first, the evolutionary invention of lignin would have increased entropy production (by lowering CO_2 and temperature) and then, second, the eventual evolution of lignin-degrading fungi, in Robinson's scenario, by decreasing carbon burial, increased both the steady state CO_2 and global temperature, and therefore decreased the global entropy production. Of course, neither the lignin-producing trees or lignin-degrading fungi were selected for their effects on global entropy production. They evolved their new physiological

parameters because these new inventions gave them biological advantages. The impacts on entropy production are only by-products that can (and did) go in either direction.

Also relevant is the biotic enhancement of weathering, briefly noted above. Nutrient-obtaining mechanisms that have evolved in terrestrial ecosystems had the effect of lowering earth's CO₂ levels and temperatures over long evolutionary time scales (Schwartzman and Volk 1989, 1991). Thus the biotic enhancement of weathering would have increased the rate of global entropy production. But this example of increase does not support the biotic-MEP hypothesis. The point, in support of my by-product framework, is that we can find examples that go in both directions. Indeed, David Schwartzman pointed out (personal communication) that the bright lichen on the dark rock would not only increase albedo but increase chemical weathering, and thus, create by-product effects that both decrease and increase entropy production.

One final intriguing example of a biotic process that decreases, rather than increases, the entropy production is anthropogenic global warming. The emission of carbon dioxide from the combustion of fossil fuels is warming the planet, which decreases the planetary radiative entropy production (using the results from Kleidon's model again). Are we emitting CO₂ because we are fulfilling the role of a free parameter being selected in the inexorable move toward a global MEP state? In fact, we are causing the Earth to shift away from the MEP state and therefore, according to the biotic-MEP hypothesis, we should not exist.

In evaluating the biotic-MEP hypothesis, should we tabulate all the examples that we can find of increasers and decreasers, then add up both "sides" and see which one "wins"? No. Mere examples without a theoretical explanatory framework are worth nothing. I have tried, using an analysis that argues for entropy production as a by-product, to show why we should expect examples on both sides. That is what we have found. The single thought experiment of the black-carpet tree is really enough to falsify the biotic-MEP hypothesis. My alternative framework says that the biological processes forged by evolution will affect environmental entropy production in both directions, and that seems to be true.

5 Discussion and conclusion

Admittedly, organisms as local "control volumes" decrease free energy and create net positive entropy. They must do so to live. This is not news. And this is not the biotic-MEP hypothesis. The biotic-MEP hypothesis says that higher states of entropy production will be selected for, and claims that this selection is aided by the degrees of freedom in biological variables subject to evolution. But if a plant could live just as well with fewer light-absorbing chlorophyll molecules, perhaps by being more efficient in photosynthesis, it would do so and, as a lower entropy producer, would soon out compete the higher entropy producers. The thought experiment with the tree and its wasteful but high-entropy producing black carpet of tissue clearly separates out entropy production from other biological processes and shows that entropy production is not a functional adaptation and therefore cannot be selected for.

Kleidon noted that the MEP state might not be reached because of biological limitations and constraints. I agree that in the real world the biota are clearly subject to constraints such as nutrients. It is upon those constraints that evolution works, to create new variants of metabolic processes. As organisms draw in nutrients and put forth wastes, and are constrained by their abilities to do so, they affect the environment in ways that just happen to either increase the entropy production or decrease it.

I have offered five real world examples of planetary entropy production decreasers, namely, the DMS-plankton, the lignin-degrading fungi, the calcareous plankton, the light-

colored lichen on a dark rock, and anthropogenic global warming. I have also provided examples of entropy increasers that can be added to Kleidon's own list: the lignin manufacturing trees and the biotic enhancement of weathering. All these biological processes evolved because the reproductive success of certain organisms was enhanced by particular metabolic inventions. In some cases these inventions increased the global entropy production, in other cases they decreased the global entropy production. Although all organisms create an increase in entropy around the immediate boundary of the bodies by their individual metabolisms, their effects on the surrounding environment are by-products that can push the dynamics of the environment in any number of ways, constrained only by the second law. I can only conclude that the concept of MEP on environmental scales has no relevance for discussions of biological evolution or the time history of the effects of life on the global system.

Clearly, the biotic-MEP hypothesis is mistaken. Because the biosphere's air and waters are dispersed and shared among many creatures, any changes to these fluid environments that might constitute improvements would also give rise to the virtual certainty of cheater organisms who would benefit from the improved biosphere but not pay the metabolic costs involved in making it so. The cheats would win. This is the problem with much of "Gaia" theorizing about the creation of better large-scale habitability, as pointed out in this journal by Kirschner (2002) and Volk (2002, 2003). Despite claiming in his paper's title to go "beyond Gaia" by extending the discussion to thermodynamics, Kleidon has fallen into basically the same conceptual error.

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