BEYOND GAIA: THERMODYNAMICS OF LIFE AND EARTH SYSTEM FUNCTIONING

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Abstract. Are there any general principles that govern the way in which life affects Earth system functioning? Most prominently, the Gaia hypothesis addresses this question by proposing that near-homeostatic conditions on Earth have been maintained "by and for the biosphere." Here the role of the biota in the Earth system is described from a viewpoint of nonequilibrium thermodynamics, particularly with respect to the hypothesis of maximum entropy production (*MEP*). It is argued that the biota introduce additional degrees of freedom to Earth system processes. Therefore, we should expect biotic activity, and Earth system processes affected by the biota, to evolve to states of *MEP*. The consistent effects of the biota on entropy production are demonstrated with a conceptual model of biogeochemical cycling, by using extreme climate model simulations of a "Desert World" and a "Green Planet", and by a simple coupled climate-carbon cycle model. It is shown that homeostatic behavior can emerge from a state of *MEP* associated with the planetary albedo. This thermodynamic perspective is then discussed in the context of the original Gaia hypothesis and in light of a recent discussion in *Climatic Change*. Potential implications of the MEP hypothesis for global change research are also discussed. It is concluded that the resulting behavior of a biotic Earth at a state of *MEP* may well lead to near-homeostatic behavior of the Earth system on long time scales, as stated by the Gaia hypothesis. However, here homeostasis is a result of the application of the *MEP* hypothesis to biotically influenced processes rather than a postulate. Besides providing a fundamental perspective on homeostasis, the *MEP* hypothesis also provides a framework to understand why photosynthetic life would be a highly probable emergent characteristic of the Earth system and why the diversity of life is an important characteristic of Earth system functioning.

1. Gaia and Beyond

Life affects Earth system functioning in various ways. For instance, biotic carbon uptake affects the global carbon cycle, which in turn is intimately linked to atmospheric carbon dioxide concentrations and the strength of the atmospheric greenhouse effect. But is there a general direction in which biotic effects act? The Gaia hypothesis of James Lovelock (1972a,b) has been central to the debate of whether there are any general governing principles by which life affects Earth at the planetary scale. Motivated by the observation that the atmospheric chemical composition is far from chemical equilibrium (Lovelock, 1965; Hitchcock and Lovelock, 1967), the original version of the Gaia hypothesis stated "homeostasis by and for the biosphere" (Lovelock and Margulis, 1974). Since then, the hypothesis has been intensively debated, has stimulated various research (e.g. Lovelock and Whitfield, 1982; Watson and Lovelock, 1983; Charlson et al., 1987; Lovelock,

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1989; Schwartzman and Volk, 1989; Schneider and Boston, 1991; Lenton, 1998) and has received substantial criticisms (e.g. Schneider, 1986; Kirchner, 1989, 2002; Caldeira, 1989). Among the most cogent criticisms are that (a) no clear definitions are used so that the Gaia hypothesis is difficult to test, and (b) that it would contradict established evolutionary biological theory, in particular, the process of natural selection which acts on individuals and not at the global scale.

1.1. RECENT DISCUSSION ON THE GAIA HYPOTHESIS

Recently, I attempted to provide a precise definition of terms for the Gaia hypothesis in order to formulate null hypotheses for testing (Kleidon, 2002). In Kleidon (2002) I used the global gross uptake of carbon by the biota (gross primary production, *GPP*) to describe biotic activity and used it as a measure of how beneficial environmental conditions are for life. With this definition, a series of hypotheses were formulated, all of which focused on how *GPP* for an environment including biotic effects compared to the hypothetical value of *GPP* for an environment without biotic effects. This approach does not focus on whether particular biotic feedbacks are positive or negative, but on the *sum* of all biotic effects. It would be difficult to construct the environmental conditions without biotic effects in the real world, but numerical simulation models provide a means to do so. I used climate model simulations of extreme vegetation conditions (Fraedrich et al., 1999; Kleidon et al., 2000), a “Desert World” and a “Green Planet”, to show that the overall climatic effects of terrestrial vegetation generally lead to a climate which is more favorable for carbon uptake. Therefore, I concluded in Kleidon (2002) that “life has a strong tendency to affect Earth in a way which enhances the overall benefit (that is, carbon uptake)”.

Kirchner (2002) raised three major criticisms to Kleidon (2002): (1) biotic feedbacks do not necessarily lead to environmental homeostasis; (2) biotic effects do not necessarily lead to a more suitable environment; and (3) both, beneficial and destructive feedbacks, can evolve by natural selection. Lenton (2002) extended the idea of setting up null hypotheses and focussed on the role of biotic effects regarding the response of the Earth system to external perturbations. While these hypotheses are difficult to test, Lenton (2002) argued that the Earth system is more resistant and resilient to many perturbations with life than without, and that life has not survived for 3.8 billion years purely by chance. Volk (2002) summarizes the proposed definitions and null hypotheses by Kleidon (2002) and Lenton (2002), and the criticisms by Kirchner (2002) points out weaknesses and offers his own conclusion. Specifically, Volk promotes the notion that “life is built from free byproducts,” and sees the general role of the biota in Earth system functioning progressing towards a “Wasteworld” interpretation. The debate is certainly not at an end (Lovelock, 2003; Volk, 2003a; Lenton and Wilkinson, 2003; Kirchner, 2003; Volk, 2003b). The motivation for this paper is to move the discussion ahead by applying thermodynamic considerations of nonequilibrium systems to biotic functioning in an Earth system perspective.

At the center of the debate on the Gaia hypothesis is the question of whether life on Earth is a coincidence, or whether life and the associated biotic effects on the climate system are a predictable outcome. To start at the microscopic, individual level, life, in the words of Schrödinger (1944), depletes free energy and produces high entropy waste that maintains internal order. Since free energy is a general requirement for any chemical reaction to take place and therefore applies to the processing of chemical compounds by all lifeforms, this perspective suggests that biotic effects are not random, but that biotic activity is directed towards depleting free energy. Practically all metabolisms are intimately connected to important chemical compounds that profoundly affect atmospheric radiative properties, for instance, carbon dioxide, methane (both greenhouse gases), and sulphur compounds (which can produce highly reflective clouds). At the planetary scale, the biota consist of a vast number of diverse individual organisms, and the question arises whether we can predict the outcome of individual-based dynamics and the evolution of the biota as a whole from a fundamental basis which can then be used to understand biotic effects on Earth system processes.

1.2. THE HYPOTHESIS OF MAXIMUM ENTROPY PRODUCTION (*MEP*)

It has been suggested that physical, dissipative processes within the climate system, with many degrees of freedom, evolve to states at which the production of entropy is maximized (hypothesis of *MEP*). Several studies indicate that the atmospheric circulation operates at a state which is close to a state of maximum intensity (approximately the same as *MEP*). Such a state would be associated with the largest generation of available potential energy, maximum conversion to kinetic energy, and maximum dissipation by friction (e.g. Lorenz, 1960; Paltridge, 1975, 1978, 1979; Grassl, 1981). It has also been shown that the radiative–convective equilibrium in the atmosphere can be understood in terms of such a state (Ozawa and Ohmura, 1997), as well as the atmospheric circulation on other planetary bodies (Lorenz et al., 2001). The existence of *MEP* states associated with the atmospheric circulation has also recently been confirmed by model simulations with an atmospheric General Circulation Model (Kleidon et al., 2003).

A theoretical explanation for *MEP* has recently been derived from information theory (Dewar, 2003, also highlighted by Lorenz, 2003). Dewar applied Jaynes' information theory formalism of statistical mechanics (Jaynes, 1957) to nonequilibrium systems. He showed that out of all possible macroscopic stationary states compatible with the imposed constraints (e.g. external forcing, local conservation of mass and energy, global steady-state mass and energy balance), the state of MEP is selected because it is statistically the most probable, i.e. it is characteristic of the overwhelming majority of microscopic paths allowed by the constraints. That it is entropy production which is the quantity maximized emerges from his analysis as a direct consequence of the constraint of local conservation of energy and mass. This general derivation from information theory shows that *MEP* should be the outcome not only for turbulent motion, but any nonequilibrium thermodynamic process with sufficient degrees of freedom. Note that the *MEP* hypothesis discussed here is different from the Maximum Entropy Principle which is commonly used in the statistical description of equilibrium systems. It is here referred to as a 'hypothesis', since it is not (yet) accepted as a general description of thermodynamic processes in nonequilibrium systems with many degrees of freedom, such as poleward heat transport by the atmospheric circulation.

The *MEP* hypothesis introduces an important additional criteria to describe the steady state of nonequilibrium systems. In the case of polar heat transport by the atmospheric circulation, both extreme cases of no heat transport, and infinite heat transport would seem to be feasible from a standpoint that only considers the energy balance. While energetically feasible, any state between these extremes differs in the amount of entropy being produced. The two extreme cases of atmospheric heat transport can be used to demonstrate the existence of a maximum in entropy production: with no heat transport, the equator–pole temperature gradient is at a maximum, but since no heat is transported, no entropy is produced by poleward heat transport. At the other extreme of very large heat transport, the temperature difference becomes very small, so that the conversion of heat occurs at roughly the same temperatures and again no entropy is produced. Consequently, there is a maximum in entropy production for an intermediate value of heat transport, resulting in an intermediate temperature gradient between the tropics and the poles. Given that the turbulent processes associated with atmospheric motion introduce many degrees of freedom, the *MEP* hypothesis then states that the atmospheric circulation would evolve to states associated with an intermediate value of polar heat transport, leading to *MEP* (this is further demonstrated below in Section 2.2).

1.3. *MEP* AND BIOTIC ACTIVITY

The *MEP* hypothesis should also apply to the activity of the Earth's biota, here taken as the global aggregate of all living individuals. Biotic activity derives its free energy primarily from utilization of low entropy solar radiation by photosynthesis, which is subsequently converted into heat by respiration at roughly the surface temperature of Earth. The Earth's biota is inherently diverse, with individual species differing in their strategy to grow and reproduce thereby affecting rates of carbon uptake and release. Therefore, overall biotic carbon exchange can be viewed as an entropy-producing, thermodynamic process with many degrees of freedom, which may evolve to a state of *MEP* in steady state given external constraints imposed, e.g. by solar radiation, water and nutrient availability. Since biotic activity is intimately linked to carbon cycling and surface energy exchange, it would also seem that the diversity of the biota introduces many additional degrees of freedom to other Earth system processes that it affects, and thereby impacts the overall rate of entropy production by the Earth system. This is illustrated by the following two examples.

- *Surface energy balance.* Over land, the partitioning of energy at the surface is strongly affected by the presence of vegetation, in terms of the surface albedo, the aerodynamic roughness, and the capacity to transpire soil moisture with respect to rooting characteristics and stomatal function. Both, the extreme states of a bare land surface and one covered by a tropical rainforest are both energetically feasible (given sufficient availability of light, water and nutrients in the latter case). These states, however, differ by the amount of entropy produced (Ulanowicz and Hannon, 1987, also Section 3.3). The type and composition of terrestrial ecosystems, composed of a large number of individuals of a range of functionally distinct plant species, should add many degrees of freedom to land surface functioning, which would then allow for a state of *MEP* to emerge from the system dynamics. As a result, we would expect land surface processes to evolve to a state of *MEP* under given energy and water constraints.
- *Carbon cycle.* Photosynthesis utilizes solar radiation and provides the main source of energy for biotic activity. Through this biotic activity is intimately linked with the global carbon cycle and the atmospheric concentration of carbon dioxide (CO_2). Atmospheric CO_2 affects the strength of the atmospheric greenhouse effect, and therefore surface temperature. Its concentration has probably changed substantially during the Earth's history, at least in part due to biotic activity (e.g. Kasting and Ackerman, 1986; Kasting, 1993; Berner, 1993, 1997). Surface temperature in turn is connected to the presence of snow, and to the value of the equilibrium Bowen ratio (i.e. the ratio of sensible to latent heat for a wet surface and a saturated atmosphere), which in turn is likely to affect the stability of the planetary boundary layer and the development of convective clouds. It would therefore seem reasonable to assume that the overall planetary albedo, that is, the combined effects of convective clouds and the extent of snow cover, would partly depend on surface temperature. The planetary albedo in turn affects the amount of absorbed solar radiation and therefore directly the overall production of entropy, but also the amount of solar radiation available for photosynthesis and therefore biotic activity. What this amounts to is a connection between biotic activity, planetary albedo, the amount of entropy production and the strength of the atmospheric greenhouse effect, which is strongly affected by the concentration of atmospheric carbon dioxide. An Earth in a weak greenhouse, "Snowball Earth" state (Evans et al., 1997; Hoffman et al., 1998) or a strong greenhouse state are both energetically feasible, but are likely to have very different values of planetary albedo and entropy production. The Earth's biota introduce additional degrees of freedom to the functioning of the carbon cycle, for instance by different rates of

carbon uptake, different strategies to grow and reproduce, and different rates of respiring organic carbon back into the atmosphere. We may therefore ask whether we could expect a state of *MEP* as an outcome of the biotically moderated carbon cycle and what the emergent behavior of the coupled carbon cycle–climate system would be at a state of *MEP*.

1.4 OUTLINE OF THIS PAPER

The purpose of this paper is to apply the hypothesis of *MEP* to the evolution of biotic effects and how the biota modify Earth system functioning. Three central questions are considered in this paper.

1. Does biotic activity, as a diverse Earth system process with many degrees of freedom, evolve towards a state of *MEP*?
2. Do biotic effects lead to states of *MEP* for associated Earth system processes, such as absorption of solar radiation, carbon cycling and evapotranspiration?
3. Would the overall emergent behavior of the Earth system at a state of *MEP* share characteristics suggested by the Gaia hypothesis?

To address these questions, I first briefly review the foundations of the thermodynamics of nonequilibrium systems, and how the *MEP* hypothesis has been applied to processes within the physical climate system (Section 2). In Section 3, I apply entropy production considerations to biotic activity as an Earth system process, in terms of its effects on biogeochemical cycling, biogeophysical effects on land surface functioning, and the evolution of the carbon cycle. Section 4 contains a discussion of the limitations and broader implications of the application of the *MEP* hypothesis to biotic activity. It also includes a comparison of the emergent behavior at *MEP* with the predictions of the original Gaia hypothesis and the arguments raised in the recent discussion on the Gaia hypothesis by Kirchner (2002, 2003), Lenton (2002), Volk (2002, 2003a,b), Lovelock (2003), and Lenton and Wilkinson (2003). The practical implications of the *MEP* hypothesis for global change research is discussed in Section 4 as well. This paper closes with a brief summary and conclusion in Section 5.

2. Thermodynamics of Climate System Processes

2.1. NONEQUILIBRIUM THERMODYNAMIC SYSTEMS AND EARTH'S ENTROPY PRODUCTION BUDGET

At the foundation of classical thermodynamics are the first and second laws, stating that the total energy of a system is conserved and that the entropy of an isolated system can only increase. The second law implies that the free energy of an isolated system is successively degraded over time by diabatic processes, resulting in an equilibrium state with zero free energy and maximum entropy. In its statistical interpretation, the direction towards higher entropy can be interpreted as a transition to more probable states.

Prigogine (1962) showed that the formulations from classical thermodynamics can also be applied to nonequilibrium systems which are not isolated. By exchanging energy of different entropy (or mass) across the system boundary, these systems maintain states which do not represent thermodynamic equilibrium. For these systems, the second law then takes the form of a continuity equation, in which the overall change of entropy of the whole system dS/dt is the sum of the entropy increase within the system dS_I/dt (due to diabatic processes) and the entropy flux convergence dS_E/dt (i.e. the net flux of entropy across the system boundary):

$$\frac{dS}{dt} = \frac{dS_E}{dt} + \frac{dS_I}{dt} \tag{1}$$

In steady state, with no change of the internal entropy S of the system, the production of entropy by diabatic processes within the system σ that leads to the increase dS_I/dt balances the net flux of entropy across the system boundary dS_E/dt. The second law in this form then states that $\sigma = dS_I/dt \geq 0$. A nonequilibrium system can maintain a state of low entropy by "discarding" high entropy fluxes out of the system.

Equation (1) can be used to determine the overall production of entropy by the Earth system. At the planetary scale in steady state, the absorption of solar radiation by the Earth Q_{IN} is balanced by the emission of terrestrial radiation Q_{OUT}. The two radiative fluxes represent radiation of different entropies (Essex, 1984; Lesins, 1990). Solar radiation, emitted at a high radiative temperature of the Sun (of about $T_{SUN} = 5760$ K), represents a flux of low entropy. It consists of a flux of photons of high energy, that is, the emitted energy is concentrated on relatively few photons, each carrying a large amount of energy. When the absorbed solar radiation is reemitted from the Earth at an effective radiative temperature of $T_E = 255$ K, the same amount of energy is spread over many photons of relatively low energy, therefore corresponding to a flux of high entropy. In steady state (i.e. $Q_{OUT} = Q_{IN}$), the total production of entropy σ_{TOT} by diabatic processes of the climate system can therefore approximated by the fluxes across the Earth–space boundary:

$$\begin{aligned}\sigma_{TOT} &= \frac{Q_{OUT}}{T_E} - \frac{Q_{IN}}{T_{SUN}} \\ &= S_0 \cdot (1 - a_P) \cdot \left(\frac{1}{T_E} - \frac{1}{T_{SUN}}\right) \approx 900 \text{ mW m}^{-2}\,\text{K}^{-1}\end{aligned} \tag{2}$$

using values of incoming solar radiation $S_0 = 342$ W m^{-2} and a planetary albedo $\alpha_P = 0.3$.

By using the energy fluxes of the global energy balance and estimates for the respective temperatures at which the transformations of energy occur, one can derive

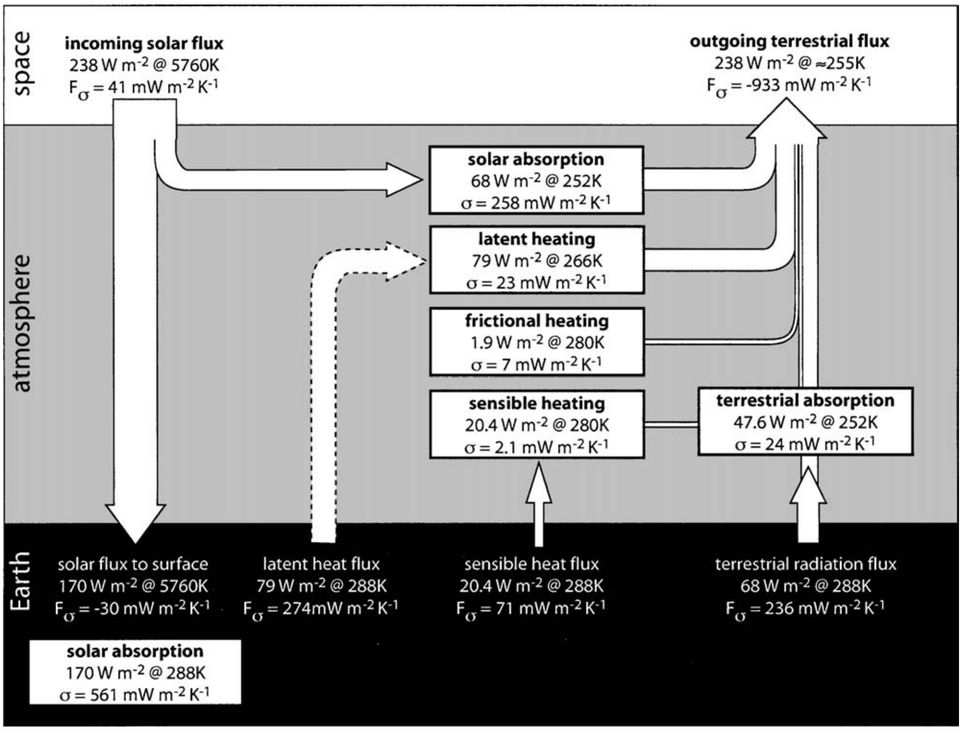


Figure 1. An estimate of the global entropy production budget of the Earth after Peixoto et al. (1991). The entropy production of the latent heat flux differs from Peixoto et al.'s value and has been calculated as 79 W m^{-2} (1/266K–1/288K).

the contribution of various diabatic processes of the climate system to the overall production of entropy. Figure 1 shows a global estimate of entropy production by different, climate-related processes, based on the analysis of Peixoto et al. (1991). From Figure 1 it is evident that the greatest amount of entropy is generated by the absorption of solar radiation in the atmosphere and at the surface. The entropy production associated with the absorption of longwave radiation in the atmosphere and by the transfer of latent heat from the surface to the atmosphere associated with the global hydrological cycle is an order of magnitude less. The contributions that originate from the sensible heat flux and the frictional dissipation associated with the atmospheric circulation are seemingly small. What Equation (2) tells us is that entropy production can be most strongly affected by changes in the Earth's planetary albedo. To a lesser extent, overall entropy production is affected by the partitioning of energy at the surface into radiative and turbulent fluxes, which includes entropy production by the absorption of terrestrial radiation, and the latent and sensible heat flux. Since the radiative temperature of the Earth T_E is primarily determined by the planetary energy balance, T_E plays a relatively minor role (although it can be lowered by more effective heat redistribution, e.g. by poleward heat transport, see below).

2.2. ENTROPY PRODUCTION BY POLAR HEAT TRANSPORT

I will first illustrate the *MEP* hypothesis by using the commonly used example of polar heat transport, following earlier work by Lorenz (1960), Paltridge (1975) and others. A simple two-box model of the climate system is used to calculate the entropy production associated with heat transport from the tropics to the polar regions. The only processes considered are the absorption of solar radiation in the tropics $Q_{\mathrm{IN,T}}$ and in the polar regions $Q_{\mathrm{IN,P}}$, the emission of terrestrial radiation Q_{OUT}, taken as σT^4, (with σ being the Stefan-Boltzmann constant $\sigma = 5.67\ 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$) and the transport of heat between the boxes Q_{HT}. With these simplifications, we can write the energy balances for the two boxes as:

$$Q_{\mathrm{IN,T}} - Q_{\mathrm{OUT,T}} - Q_{\mathrm{HT}} = 0 \tag{3}$$

$$Q_{\mathrm{IN,P}} - Q_{\mathrm{OUT,P}} + Q_{\mathrm{HT}} = 0 \tag{4}$$

The total production of entropy σ_{TOT} of this two-box system in steady state can then be written as the difference in entropy fluxes across the Earth–space boundary:

$$\begin{aligned} Q_{\mathrm{TOT}} &= \left(\frac{Q_{\mathrm{OUT,T}}}{T_{\mathrm{T}}} - \frac{Q_{\mathrm{IN,T}}}{T_{\mathrm{SUN}}}\right) + \left(\frac{Q_{\mathrm{OUT,P}}}{T_{\mathrm{P}}} - \frac{Q_{\mathrm{IN,P}}}{T_{\mathrm{SUN}}}\right) \\ &= Q_{\mathrm{IN,T}} \cdot \left(\frac{1}{T_{\mathrm{T}}} - \frac{1}{T_{\mathrm{SUN}}}\right) + Q_{\mathrm{IN,P}} \cdot \left(\frac{1}{T_{\mathrm{P}}} - \frac{1}{T_{\mathrm{SUN}}}\right) + Q_{\mathrm{HT}} \cdot \left(\frac{1}{T_{\mathrm{P}}} - \frac{1}{T_{\mathrm{T}}}\right) \\ &\equiv \sigma_{\mathrm{RAD}} + \sigma_{\mathrm{HT}} \end{aligned} \tag{5}$$

In the last line of Equation (5), the total production of entropy is grouped into two terms: one term which describes the production of entropy by the absorption of solar radiation (σ_{RAD}) at the tropical and polar temperatures T_{T} and T_{P}, respectively, and by the heat transport (σ_{HT}) which is caused by radiative heating in the tropics and cooling at the poles, resulting in the transport of heat by the atmospheric circulation. This separation has been made to reflect the very different physical natures of the two processes. While σ_{RAD} reflects solely contributions to entropy production by absorption of solar radiation, the σ_{HT} implicitly describes the diabatic heating of the atmosphere and the resulting production of entropy by the atmospheric circulation. Both of these terms nevertheless depend on the temperatures T_{T} and T_{P}, and are therefore both affected by the magnitude of polar heat transport. Note that the calculation of entropy production as presented here differs slightly from previous studies which focused on the heat transport term only (e.g. Paltridge, 1975, 1979, 2001; Lorenz et al., 2001).

In contrast to the absorption process, the transport of heat by mid-latitude eddies in the atmosphere can be achieved in many different ways, therefore representing many degrees of freedom (e.g., Kleidon et al., 2003). The *MEP* hypothesis then states that the atmospheric circulation evolves to one of many states for which the production of entropy σ_{HT} is maximized. We can express the heat transport term

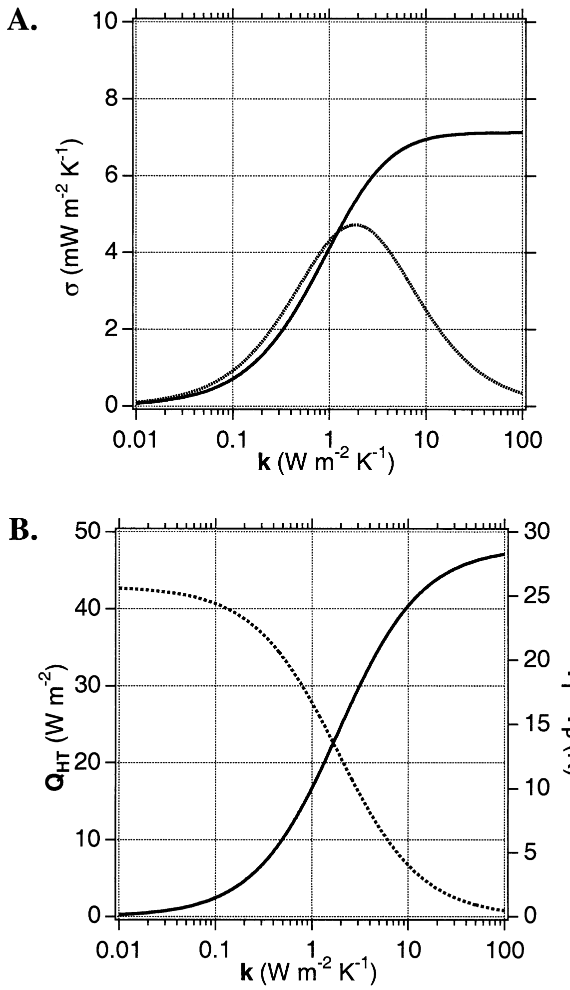


Figure 2. Polar heat transport as an example for a process close to a state of maximum entropy production (*MEP*). (a) Entropy production associated with polar heat transport σ_{HT} (dotted line) and total entropy production σ_{TOT} (solid line) as a function of heat conductivity k as simulated by the two box model described in the text. (b) Polar heat transport Q_{HT} (solid line) and equator-pole temperature difference $T_{\mathrm{T}} - T_{\mathrm{P}}$ (dotted line) as a function of heat conductivity k. The plots were obtained by using $Q_{\mathrm{IN,T}} = 288$ W m^{-2} and $Q_{\mathrm{IN,P}} = 192$ W m^{-2}.

σ_{HT} effectively as a diffusive flux as:

$$Q_{\mathrm{HT}} = k \cdot (T_{\mathrm{T}} - T_{\mathrm{P}}) \tag{6}$$

with k being an effective conductivity. While the value of k is kept to a fixed value in the traditional application of energy balance models (Budyko, 1969; Sellers, 1969), the *MEP* hypothesis states that σ_{HT} is maximized with respect to k. Figure 2a shows σ_{HT} and σ_{TOT} as a function of k, and clearly shows a maximum value for σ_{HT} at a value of k around 2 W m^{-2} K. The maximum is the result of the competing effects of enhanced heat transport Q_{HT} and reduced temperature gradient $T_{\mathrm{T}} - T_{\mathrm{P}}$ on σ_{HT} with increasing values of k (Figure 2b). Note that the total entropy production σ_{TOT} also increases with increasing k, since enhanced heat transport leads to a more uniform distribution of temperature, resulting in a reduction of the overall net radiative temperature.

What Lorenz (1960), Paltridge (1975) and others showed with more detailed model simulations is that several observed features of the climate system, such as the intensity of the atmospheric circulation, the equator–pole temperature difference in surface temperature, and the meridional distribution of cloud cover reflect a state of the climate system which is close to a state of *MEP*. Lorenz et al. (2001) showed that the equator–pole temperature gradients of Mars and Titan can also be understood in terms of the *MEP* hypothesis.

2.3. ENTROPY PRODUCTION BY TURBULENT HEAT FLUXES

A state of *MEP* can also be found for the turbulent fluxes of sensible and latent heat between the surface and the atmosphere (similar to the maximum convection hypothesis of Paltridge (1975) and related to the temperature profile in radiative–convective equilibrium, Ozawa and Ohmura (1997)). Another conceptual box model illustrates this state of *MEP*. This model consists of two boxes, representing the surface and the atmosphere. It is assumed that all solar radiation Q_{IN} is absorbed at the surface, and that the atmosphere absorbs terrestrial radiation with an absorptivity of ε. The surface and the atmosphere exchange energy by emission and absorption of terrestrial radiation and by turbulent heat fluxes Q_{TF} (that is, the sensible and latent heat fluxes combined) as described by the energy balance for the surface and the atmosphere respectively:

$$Q_{\mathrm{IN}} + \varepsilon \cdot \sigma \cdot T_{\mathrm{A}}^4 - \sigma \cdot T_{\mathrm{S}}^4 - Q_{\mathrm{TF}} = 0 \tag{7}$$

$$\varepsilon \cdot \sigma \cdot T_{\mathrm{S}}^4 - 2\varepsilon \cdot \sigma \cdot T_{\mathrm{A}}^4 + Q_{\mathrm{TF}} = 0 \tag{8}$$

For given values of Q_{IN}, ε, and Q_{TF} the following expressions for the temperature of the surface T_{S} and the atmosphere T_{A} can be derived from Equations (7) and (8):

$$\sigma \cdot T_{\mathrm{S}}^4 = \frac{2 \cdot Q_{\mathrm{IN}} - Q_{\mathrm{TF}}}{(2-\varepsilon)} \tag{9}$$

$$\sigma \cdot T_{\mathrm{A}}^4 = \frac{\varepsilon \cdot Q_{\mathrm{IN}} + (1-\varepsilon) \cdot Q_{\mathrm{TF}}}{\varepsilon \cdot (2-\varepsilon)} \tag{10}$$

The total net production of entropy by the Earth system σ_{TOT} is given by the fluxes of outgoing longwave radiation at the top of the atmosphere, which is composed as a mixture of the emission from the surface $Q_{\mathrm{OUT,S}}$ and from the atmosphere $Q_{\mathrm{OUT,A}}$, minus the flux associated with incoming solar radiation Q_{IN}:

$$\sigma_{\mathrm{TOT}} = \frac{Q_{\mathrm{OUT,S}}}{T_{\mathrm{S}}} + \frac{Q_{\mathrm{OUT,A}}}{T_{\mathrm{A}}} - \frac{Q_{\mathrm{IN}}}{T_{\mathrm{SUN}}} \tag{11}$$

which, by using Equations (9) and (10), yields:

$$\begin{aligned}\sigma_{\mathrm{TOT}} &= Q_{\mathrm{IN}} \cdot \left(\frac{1-\varepsilon}{2-\varepsilon}\frac{2}{T_{\mathrm{S}}} + \frac{\varepsilon}{2-\varepsilon}\frac{1}{T_{\mathrm{A}}} - \frac{1}{T_{\mathrm{SUN}}}\right) + Q_{\mathrm{TF}} \cdot \frac{1-\varepsilon}{2-\varepsilon} \cdot \left(\frac{1}{T_{\mathrm{A}}} - \frac{1}{T_{\mathrm{S}}}\right) \\ &\equiv \sigma_{\mathrm{RAD}} + \sigma_{\mathrm{TF}}\end{aligned} \tag{12}$$

In the last line of Equation (12), σ_{TOT} is written as the sum of two terms, representing the contribution to the total by the entropy production by absorption of radiation σ_{RAD} and by turbulent fluxes σ_{TF}.

In contrast to the absorption process, the turbulent transfer of heat from the surface to the atmosphere can be viewed as a process that introduces many degrees of freedom. The *MEP* hypothesis then states that the turbulent motion in the boundary layer would evolve to one of many states for which the production of entropy σ_{TF} is maximized. We can write the overall turbulent flux Q_{TF} as a diffusive flux as:

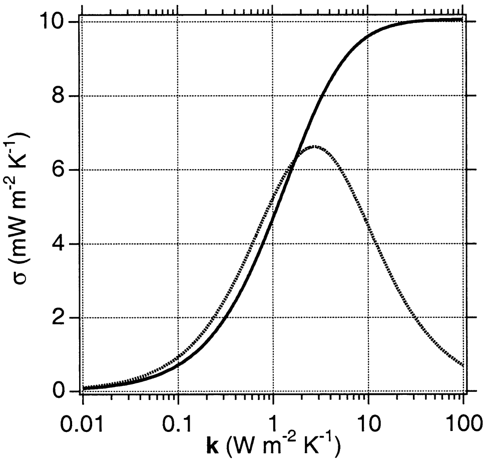
$$Q_{\mathrm{TF}} = k \cdot (T_{\mathrm{S}} - T_{\mathrm{A}}) \tag{13}$$

with k being a conductivity. Note that writing the turbulent heat flux in this form does not account for the fact that the latent heat flux depends primarily on atmospheric humidity, which in turn depends on temperature in a nonlinear way.

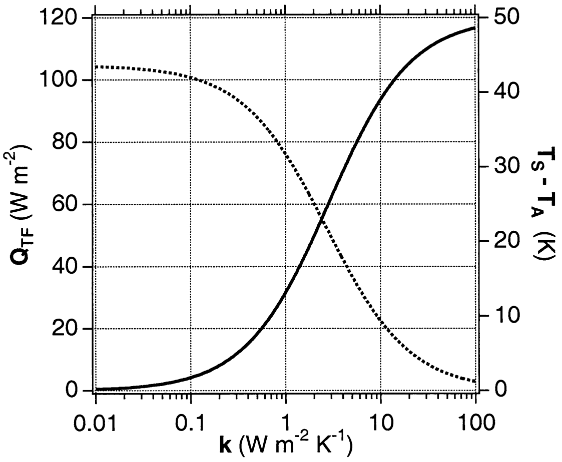
With this formulation and a fixed, intermediate value for atmospheric emissivity ε, we find a maximum of entropy production σ_{TF} associated with turbulent heat fluxes with respect to k (Figure 3a), and a general increase of overall total entropy production σ_{TOT} with increasing values of k. The maximum in σ_{TF} is the result of the contrasting effects of increasing values of Q_{TF} versus decreasing values of $T_{\mathrm{S}} - T_{\mathrm{A}}$ on σ_{TF} with increasing values of k (Figure 3b). The general increase in σ_{TOT} with k is the result of a lower effective radiative temperature. In the absence of turbulent fluxes, the highest rate of entropy production takes place for the extreme cases of a white, nonabsorbing atmosphere ($\varepsilon = 0$), and a black, fully absorbing atmosphere ($\varepsilon = 1$). In a gray atmosphere, the outgoing longwave radiation (*OLR*) is composed of a mixture of terrestrial radiation emitted from a warmer surface

Figure 3. Turbulent heat fluxes (i.e. sensible and latent heat flux) between the Earth's surface and the atmosphere as an example for a process close to a state of *MEP*. (a) Entropy production associated with turbulent heat fluxes σ_{TF} (dotted line) and total entropy production σ_{TOT} (solid line) as a function of heat conductivity k as simulated by the two box model described in the text. (b) Turbulent heat transport Q_{TF} (solid line) and surface–atmosphere temperature difference $T_{\mathrm{S}} - T_{\mathrm{A}}$ (dotted line) as a function of heat conductivity k. (c) Entropy production σ_{TF} a function of the ratio of turbulent heat fluxes to the net longwave radiative flux for three different values of atmospheric absorptivity ε (dotted: $\varepsilon = 0.25$; dashed: $\varepsilon = 0.5$; solid: $\varepsilon = 0.75$). The plots were obtained by using $Q_{\mathrm{IN}} = 240$ W m^{-2} and $\varepsilon = 0.5$ for plots (a) and (b).

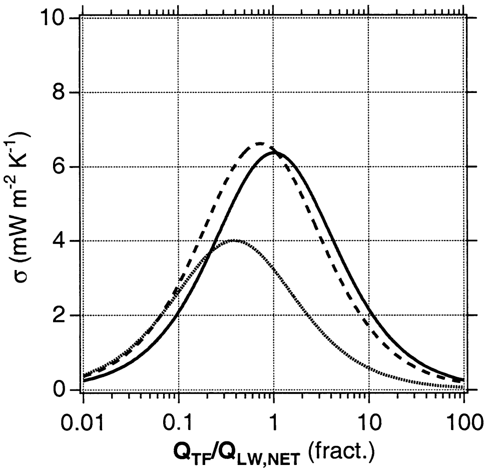
A.


σ (mW m^{-2} K^{-1})
0
2
4
6
8
10
0.01
0.1
1
10
100
k (W m^{-2} K^{-1})

B.


Q_{TF} (W m^{-2})
0
20
40
60
80
100
120
$T_S - T_A$ (K)
0
10
20
30
40
50
0.01
0.1
1
10
100
k (W m^{-2} K^{-1})

C.


σ (mW m^{-2} K^{-1})
0
2
4
6
8
10
0.01
0.1
1
10
100
$Q_{TF}/Q_{LW,NET}$ (fract.)

and a colder atmosphere. Consequently, the overall radiative temperature of *OLR* is increased, which leads to a lower associated entropy flux. At the limit of a white atmosphere, all *OLR* originates from the surface. Since there is no greenhouse effect, terrestrial emission is solely determined from Q_{IN}, leading to a minimum radiative temperature and a maximum of entropy production. At the other limit of a black atmosphere, all *OLR* originates from the fully absorbing atmosphere, again leading to the lowest radiative temperature and a maximum of entropy production. For the case of a gray atmosphere entropy production can be increased when turbulent fluxes are allowed to transfer heat from the surface to the atmosphere. The transfer of heat in the vertical reduces the temperature difference between the surface and the atmosphere, thereby resulting in a lower overall radiative temperature. The maximum is attained when both temperatures are equal $T_{\mathrm{S}} = T_{\mathrm{A}}$, which, as for the case of polar heat transport, is thermodynamically impossible.

When we look at the partitioning of energy at the surface associated with the state of *MEP*, in particular, the ratio of turbulent fluxes to the net emission of terrestrial radiation, we see that both fluxes are roughly of same magnitude (Figure 3c), and this characteristic is fairly independent of ε (with some tendency to a higher ratio for higher values of ε). This characteristic is remarkably close in magnitude to the observed value of this ratio of about $Q_{\mathrm{TF}}/Q_{\mathrm{RAD}} = (79 + 20)/68 \approx 1.5$ (cf. Figure 1). Obviously, many processes and details regarding the spatial variations are omitted in this simple model. For instance, the diffusion constant k would need to include other factors, such as wind speed, surface roughness, and atmospheric stability, which may limit the exchange of heat fluxes between the surface and the lower atmosphere. Also, Q_{TF} is not solely driven by the temperature difference (this would apply to the sensible heat flux only), but the latent heat flux is primarily driven by the gradient in specific humidity. Since saturation-specific humidity depends approximately exponentially on temperature, the latent heat part of Q_{TF} would lead to a more effective heat exchange given the same value of k. Also not included are, for instance, cloud feedbacks, which would seem to be intimately connected with increases in the latent heat flux. It is nevertheless surprising that this simple model provides an accurate magnitude of energy partitioning at the surface.

2.4. SUMMARY

The two examples demonstrate how the *MEP* hypothesis applies to physical processes associated with the turbulent motion in the atmosphere. In addition to the common example of polar heat transport, a simple energy balance model of the surface–atmosphere system demonstrates the existence of a state in which entropy production is maximized for turbulent heat fluxes. The resulting state of *MEP* shows characteristics similar to the observed state of the surface energy balance. In addition to the maximization of entropy production associated with the process, these examples also show that the entropy production of the whole system is also increased (that is, while σ_{HT} is at a maximum, σ_{TOT} is increased: $\sigma_{\mathrm{TOT}}(Q_{\mathrm{HT}} > 0) > \sigma_{\mathrm{TOT}}\ (Q_{\mathrm{HT}} = 0)$). However, by considering the overall entropy production budget of Earth we note that the planetary rate of entropy production can most profoundly be changed by changes in the planetary albedo. The emergence of *MEP* associated with solar absorption and the planetary albedo is discussed in the context of biotic effects in the following section.

3. Thermodynamic Consequences of Biotic Effects

3.1. ENTROPY PRODUCTION BY BIOTIC ACTIVITY: CONCEPTS AND HYPOTHESES

The concepts of nonequilibrium thermodynamics have long been applied to biotic systems. At the individual level, life maintains order by utilizing free energy and producing high entropy waste (Boltzmann, 1886; Schrödinger, 1944). This corresponds to an energy flux of low entropy ("food") into the organism and a flux of high entropy ("waste") out of the organism, resulting in the depletion of free energy and dissipation into heat. The same degradation of free energy, that is, the conversion of energy to successively higher entropy, has been used to describe energy transformations in food webs and the development of ecosystems, and forms the foundation of systems ecology (e.g. Odum, 1969, 1988; Odum and Odum, 1981). Thermodynamic considerations have also been used to describe the biosphere as a whole (Vernadsky, 1926; Lovelock and Margulis, 1974; Lesins, 1991; Schwartzman, 1999) and in the context of defining life (Ulanowicz and Hannon, 1987; Schneider and Kay, 1994). All of these nonequilibrium thermodynamic systems, from individual organisms to planet Earth do not act independently, but should be viewed as a tightly coupled thermodynamic system (Lotka, 1922a,b, 1925).

Any depletion of free energy by life has inherent consequences for the surrounding environment, and therefore also for Earth system function. While early life forms predominantly depleted chemical compounds released from the geosphere, e.g. around hyperthermal vents (Nisbet and Sleep, 2001), present-day life has much wider effects. The use of solar energy by photosynthesis and subsequent respiration affects atmospheric carbon dioxide concentrations and therefore the strength of the CO_2 greenhouse effect. Methanogenic bacteria affect atmospheric concentrations of methane, another important greenhouse gas. Early, anoxic photosynthesizing bacteria converted $CO_2 + H_2S \rightarrow CH_2O + S$ (Kaplan and Bartley, 2000) thereby affecting sulfur chemistry in the atmosphere (Kasting, 2001). Sulfur-related compounds are known to cause highly reflective clouds in the atmosphere of the Earth, for example leading to uncertainties in prediction of anthropogenic climatic change (IPCC, 2001), and on Venus, thereby affecting planetary albedo. Land surface functions are strongly affected by vegetation characteristics, influencing the absorption of solar radiation at the surface and its partitioning among radiative and turbulent fluxes. All of these processes affect physical properties of the climate system (planetary albedo, greenhouse strength, partitioning of surface fluxes) that affect the entropy production budget of Earth. In order to evaluate the role of biotic effects on biotic entropy production and overall Earth system entropy production, I will first define biotic entropy production and then set up hypotheses for testing.

3.1.1. *Biotic Entropy Production*

The production of entropy by biotic activity σ_{BIO} associated with carbon exchange can be described in terms of the energy flux associated with photosynthetic carbon uptake, Q_{P} and its dissipiation into heat by respiration Q_{R} (composed of both autotrophic and heterotrophic respiration). The energy flux associated with photosynthesis Q_{P} forms the input of solar energy into the biota, leading to the production of organic carbon compounds. Ultimately, these compounds are respired (i.e. converted back to CO_2, leading to the release of heat) at a temperature close to surface temperature T_{S}, or buried into the geologic carbon pool. I take respiration Q_{R} and the burial flux Q_{B} (i.e. the loss of biotic carbon to the geologic carbon pool) to be proportional to biomass C_{B}:

$$Q_{\mathrm{R}} = \rho \cdot C_{\mathrm{B}} \tag{14}$$

$$Q_{\mathrm{B}} = \beta \cdot C_{\mathrm{B}} \tag{15}$$

and then write biotic entropy production at steady state (i.e. $Q_{\mathrm{P}} = Q_{\mathrm{R}} + Q_{\mathrm{B}}$) as:

$$\begin{aligned}\sigma_{\mathrm{BIO}} &= \frac{Q_{\mathrm{R}}}{T_{\mathrm{S}}} - \frac{Q_{\mathrm{P}}}{T_{\mathrm{SUN}}}\\ &= Q_{\mathrm{P}} \cdot \left(\frac{\rho}{\rho+\beta}\frac{1}{T_{\mathrm{S}}} - \frac{1}{T_{\mathrm{SUN}}}\right)\end{aligned} \tag{16}$$

Note that this formulation estimates biotic entropy production by considering the energy fluxes across the boundary between the biota and the physical Earth system, similar to how it is done by Equation (2) for the whole Earth system. Estimating biotic entropy production in this way captures the various contributions to entropy production associated with mass fluxes across chemical gradients (including all biochemical reactions) which are not resolved in detail here.

Equation (16) states that entropy production by biotic activity is directly proportional to the rate of energy uptake by photosynthesis, and, to a lesser extent, to the partitioning of gross carbon uptake in respiration and burial to the geologic pool. The mean rate of photosynthesis in carbon units, *GPP*, can in turn be expressed in terms of the availability of photosynthetically active radiation Q_{PAR} and limiting factors associated with temperature T_{S}, soil water availability W and vapor pressure deficit *VPD* (over land), and nutrient availability N (Monsi and Saeki, 1953; Monteith, 1977):

$$GPP = \varepsilon \cdot f\big(T_{\mathrm{S}}, W, VPD, N\big) \cdot Q_{\mathrm{PAR}} \tag{17}$$

where ε is the light-use efficiency and f is some functional relationship of the effect of limiting factors on the rate of photosynthesis.

3.1.2. *Hypotheses*

With Equation (16) as a definition of biotic entropy production σ_{BIO}, two hypotheses can be formulated whether (a) biotic activity can be treated as a diabatic process with many degrees of freedom, with *MEP* emerging in a steady state; and (b) total entropy production σ_{TOT} of the Earth system is increased due to the effects of biotic activity. I use the notation of E to describe the cumulative environmental conditions of Earth without biotic effects, and ΔE to describe the modification of the Earth's environment by biotic effects. In this notation, all environmental conditions (temperature, radiative fluxes, concentration of chemical compounds etc.) are all idealized and lumped into one single variable E. With these notations, the two hypotheses are as follows.

Hypothesis A

Biotic activity can be treated as a diabatic process which assumes a *MEP* state in steady-state subject to energy and nutrient constraints. Since biotic activity is inherently linked to environmental changes, these changes are such that they enhance biotic entropy production:

$$\sigma_{\mathrm{BIO}}(E + \Delta E) > \sigma_{\mathrm{BIO}}(E)$$

Hypothesis B

Biotic effects increase the total entropy production of the Earth system, that is, the rate of total entropy production of a biotic Earth is greater than the total entropy production of an abiotic Earth:

$$\sigma_{\mathrm{TOT}}(E + \Delta E) > \sigma_{\mathrm{TOT}}(E)$$

3.1.3. *Testing of hypotheses*

In the following I provide three examples relating to biotic processes and show how entropy production is consistently affected. For these examples I assume that the biosphere is sufficiently diverse so that it introduces enough degrees of freedom to the associated processes which provides the conditions for the applicability of the *MEP* hypothesis. The following three examples refer to biotic productivity as formulated in Equation (17) and focus on a qualitative evaluation of the role of nutrients (variable N) in Section 3.2, the role of water and light for land productivity (variables W and Q_{PAR}) in Section 3.3, and the role of Q_{PAR} in relation to greenhouse strength and cloud cover in Section 3.4.

3.2. ENTROPY PRODUCTION BY BIOGEOCHEMICAL CYCLING

Photosynthesis is often constrained by the availability of nutrients. During ecosystem development, and presumably during the evolution of the biota, the cycling of nutrients increases (e.g. Odum, 1969; Ulanowicz and Hannon, 1987; Volk, 1998). Volk (1998) expressed this general tendency in terms of a cycling ratio, defined as the actual uptake flux of a nutrient in proportion to the flux associated solely with the abiotic source. For instance, the cycling ratio of carbon is roughly 200, meaning that out of 200 carbon dioxide molecules taken up by photosynthesis, one was released by volcanism (the major abiotic source) while 199 were released by biotic respiration. The same tendency can also be found for other nutrients, e.g. nitrogen (with a cycling ratio of 500–1300) and phosphorus (with a cycling ratio of 46) (Volk, 1998).

The effect of enhanced nutrient cycling on biotic entropy production is shown with a simple model. In this model, I express the photosynthetic rate associated with the abiotic nutrient influx as $Q_{\mathrm{P,A}}$ I take the internal cycling of nutrients proportional to Q_{R}, and a removal of nutrients from the biota proportional to Q_{B} (as in Equation (15)). In steady state, abiotic nutrient input is balanced by nutrient loss, i.e. $Q_{\mathrm{P,A}} = Q_{\mathrm{B}}$, leading to a nutrient-limited, steady-state biomass of:

$$C_{\mathrm{B,LIM}} = \frac{Q_{\mathrm{P,A}}}{\beta} \tag{18}$$

For this biomass, the overall carbon uptake by photosynthesis $Q_{\mathrm{P,LIM}}$ is given by:

$$\begin{aligned} Q_{\mathrm{P,LIM}} &= Q_{\mathrm{P,A}} + \rho \cdot C_{\mathrm{B,LIM}} \\ &= Q_{\mathrm{P,A}}\left(1 + \frac{\rho}{\beta}\right) \end{aligned} \tag{19}$$

Consequently, the biotic entropy production is given by:

$$\sigma_{\mathrm{BIO,LIM}} = Q_{\mathrm{P,A}} \cdot \left(\frac{\rho}{\beta}\frac{1}{T_{\mathrm{S}}} - (1 + \rho/\beta)\frac{1}{T_{\mathrm{SUN}}}\right) \tag{20}$$

Biotic entropy production $\sigma_{\mathrm{BIO,LIM}}$ increases approximately linearly with ρ for a small, fixed β, in contrast to the unconstrained case (Equation (16)) which approaches a limiting value of

$$\sigma_{\mathrm{BIO}} \approx Q_{\mathrm{P}} \cdot \left(\frac{1}{T_{\mathrm{S}}} - \frac{1}{T_{\mathrm{SUN}}}\right) \tag{21}$$

This means that biotic entropy production is enhanced by increasing respiration in the nutrient-constrained case. This is associated with a faster rate of nutrient cycling within the biosphere, identical to the concept of ‘cycling ratios’ of Volk (1998). A cycling ratio r_C for the example here is given by:

$$r_C = \frac{Q_{P,LIM}}{Q_{P,A}} = 1 + \frac{\rho}{\beta} \tag{22}$$

With this, biotic entropy production $\sigma_{BIO,LIM}$ (Equation (20)) can be expressed in terms of the cycling ratio as:

$$\sigma_{BIO,LIM} = Q_{P,A} \cdot \left((r_C - 1)\frac{1}{T_s} - r_C \frac{1}{T_{SUN}} \right) \tag{23}$$

In other words, biotic entropy production $\sigma_{BIO,LIM}$ increases roughly linearly with the value of cycling ratio r_C. Since reported values of $r_C \gg 1$ (Volk, 1998), this supports hypothesis A that biotic effects enhance biotic entropy production. However, what this example does not show is whether there would be a maximum cycling ratio, at which biotic entropy production would be maximized. Such a maximum may be expected as a consequence of energetic constraints on nutrient cycling, but is not considered here.

3.3. ENTROPY PRODUCTION AND BIOGEOPHYSICAL EFFECTS OF TERRESTRIAL VEGETATION

The activity of terrestrial vegetation is to a large extent constrained by the availability of light, water, nutrients and temperature. On the other hand, terrestrial vegetation also affects land surface characteristics, such as surface albedo, roughness length, and the ability to transpire water and therefore has some degrees of freedom to modify these constraints. The differences in land surface characteristics in turn have consequences for the absorption of solar radiation and the exchange fluxes of latent and sensible heat at the surface, and would therefore have consequences for the overall entropy production as well. Here I focus on the biogeophysical effects of vegetation as a specific subset of all biotic effects. I use the simulated climates of a “Desert World”, the present-day, and a “Green Planet” (Fraedrich et al., 1999; Kleidon et al., 2000) to estimate the biotic effect on biotic and total entropy production. Note that the case of the “Desert World” resembles an abiotic Earth to a limited extent, since it only considers the biogeophysical effects of terrestrial vegetation on climate. The biogeochemical effects on atmospheric composition are not considered in any of the three simulations.

In the “Desert World” simulation, land surface parameters were prescribed to resemble the characteristics of a desert, that is, a high surface reflectance with low aerodynamic roughness, low soil water holding capacity and low surface conductance. At the other extreme of a “Green Planet”, rainforest characteristics were prescribed to all nonglaciated land surfaces, i.e. a low surface reflectance and aerodynamically rough surface with a high capacity to access soil moisture and transpiration. Contrasting these two extremes allows us to estimate the overall biogeophysical effects of vegetation on the climate system, and entropy production.

Table I

Simulated components of the annual mean energy balance in W m^{-2} of a "Desert World", a "Present-Day" and a "Green Planet" climate (after Kleidon et al., 2000; Kleidon, 2002). Negative values denote fluxes removing energy from the surface

	"Desert World"		"Present-Day"		"Green Planet"	
Annual means	Land	Global	Land	Global	Land	Global
Atmospheric absorption (shortwave radiation)	83	88	86	89	88	90
Surface absorption (shortwave radiation)	124	147	130	147	129	147
Surface emission (longwave radiation)	−74	−57	−62	−52	−53	−49
Sensible heat flux	−22	−13	−17	−11	−8	−9
Latent heat flux	−18	−77	−44	−82	−60	−86

Note that strong effects were also found over the oceans, but since sea surface temperatures were prescribed in the simulations, oceanic feedbacks are not reflected in the outcomes. Consequently, there is some uncertainty in the reported results.

The climate of a "Green Planet", in contrast to a "Desert World", is substantially wetter. Land surface evapotranspiration roughly tripled as a consequence of the altered land surface parameters, leading to an enhanced global water cycle in which global precipitation increased by 10%. These changes in the water cycle have important consequences for the energy budget. Table I shows that the partitioning of energy at the surface consistently shifts from net emission of longwave radiation towards turbulent heat fluxes, in particular, the latent heat flux in the sequence of a "Desert World" climate to the "Present-Day" and "Green Planet" climates.

3.3.1. *Biotic Entropy Production*

Following Equation (17), *GPP* has been estimated for the simulated climates from the amount of absorbed solar radiation at the surface, reduced by the simulated water stress factor which is used for the calculation of evapotranspiration in the model (Kleidon, 2002). The estimated value of global *GPP* is substantially enhanced for the "Present-day" climate with about 250% of the "Desert World"'s value. The *GPP* for the "Green Planet" is only marginally increased in comparison to the "Present-day", with about 255% of the "Desert World"'s value. Since *GPP* is proportional to biotic entropy production σ_{BIO} as shown above, biotic entropy production would increase accordingly for these simulations.

3.3.2. *Total Entropy Production*

The total entropy production budget for these climate model simulations has been estimated by using the components of the energy balance (Table I) in conjunction with the estimated temperatures of the Peixoto et al. (1991) budget shown in Figure 1. The resulting entropy production budgets for the simulated "Desert World", the "Present-Day", and the "Green Planet" climates are shown in Table II.

Table II

Estimated entropy production in mW m^{-2} K^{-1} of a "Desert World", a "Present-Day" and a "Green Planet" climate (after Kleidon et al., 2000; Kleidon, 2002, using temperatures from Figure 1 for the calculation of entropy production rates)

	"Desert World"		"Present-Day"		"Green Planet"		Peixoto et al. (1991)
Annual means	Land	Global	Land	Global	Land	Global	Global
Atmospheric Absorption (shortwave radiation)	420	445	433	452	446	457	344
Surface absorption (shortwave radiation)	547	647	570	647	568	645	749
Surface emission (longwave radiation)	34	26	29	24	24	23	32
Sensible heat flux	2	1	2	1	1	1	2
Latent heat flux	5	22	13	24	17	25	23
Total	1037	1175	1075	1182	1086	1185	1150

Both, the total entropy production averaged over land areas and the global averages show a consistent trend towards increased entropy production from the "Desert World" simulation to the "Present-Day" and the "Green Planet" simulations. This increase is primarily driven by increased absorption of solar radiation, which has the largest impact on the entropy production budget (see also Figure 1). Even though the differences in total entropy production associated with different land surface settings seem relatively small at the global scale, the magnitude is comparable to the overall entropy production by the atmospheric circulation (cf. Figure 1).

This example suggests that both hypotheses, A and B, are supported, that is, that the biogeophysical effects of terrestrial vegetation enhance both biotic entropy production and overall entropy production of the Earth system. A crucial factor leading to this conclusion is associated with the role of clouds: total absorption of solar radiation at the land surface is less in the "Green Planet" case as in the "Present-Day" case (Table I), even though the prescribed surface albedo is considerably lower in the "Green Planet" simulation. This is the result of substantially enhanced cloud cover in the "Green Planet" simulation due to the enhanced evapotranspiration compared to the other simulations. Not considered here are carbon constraints which would limit the development of vegetation structure, and therefore biotically mediated land surface parameters, which would particularly apply to the case of the "Green Planet" simulation. Another aspect not considered in these simulations is an "optimal" way of stomatal functioning as, for instance, formulated by Cowan (1977) and Cowan and Farquhar (1977). By maximizing carbon gain under given water availability, stomates control the rate of transpiration and would likely to be important (taken over sufficiently large areas) in affecting atmospheric boundary layer growth and cloud development, and therefore absorption of solar radiation at the surface and biotic entropy production. The results presented here may therefore underestimate the effect of terrestrial vegetation on overall absorption of solar radiation and entropy production.

3.4. ENTROPY PRODUCTION AND A BIOTICALLY INFLUENCED CARBON CYCLE

Throughout Earth's history, it is believed that the atmospheric composition, in terms of atmospheric oxygen and the strength of the atmospheric greenhouse in particular, has substantially changed at least in part due to the biota (e.g. Sagan and Mullen, 1972; Owen et al., 1979; Kasting, 1993). Here I use a simple coupled climate–carbon cycle model to argue that these changes were directed towards higher entropy production through changes in the Earth's planetary albedo, as suggested in the introduction. The existence of a minimum planetary albedo, and therefore a maximum in absorption of solar radiation, representing a *MEP* state, is assumed to be the result of the competing effects of surface temperature on surface albedo (cooler temperatures eventually lead to increased snow cover) and on convective cloud cover (warmer temperatures are assumed to lead to more convective clouds).

Increased cloudiness as a negative feedback to surface warming (and leading to a higher planetary albedo) has been suggested previously (Henderson-Sellers, 1979; Rossow et al., 1982). Henderson-Sellers (1979) argued that a warmer surface would favor a steepened lapse rate, therefore increasing convection and cloud cover which would act as a negative feedback to the warming and lapse rate change. The spatial variation of warming is also important (Schneider, 1972; Schneider et al., 1978) and clouds in general are still a major uncertainty (IPCC, 2001), particularly regarding the sign of the overall cloud feedback on surface temperature change. However, the role of clouds as discussed here is limited to an increase of reflected solar radiation by the atmosphere with temperature as a result of increased convection, regardless of whether this would lead to a positive or negative feedback on surface temperature change. The linkage between cloud cover and surface latent heat flux has been demonstrated in the examples of a "Desert World" and a "Green Planet" above, so that we may be sufficiently confident that the connection suggested here between the partitioning of energy fluxes at the surface and convective cloud cover is reasonable (see Section 4 for further discussion).

If we accept the contrasting effects of surface temperature on planetary albedo through the effects of snow and convective clouds, then the planetary albedo has a unique minimum. At this minimum, overall absorption of solar radiation, and therefore overall entropy production (cf. Equation (2)) would have a maximum. Since planetary albedo depends on surface temperature in this formulation, it is also related to the strength of the atmospheric greenhouse, and therefore to the global carbon cycle. In the following I use a simple carbon cycle model to illustrate the effect that an evolving biosphere—through the parameter ρ associated with respiration—can have on entropy production and the overall evolution of the climate system. If the biosphere is sufficiently diverse, and therefore introduces sufficient degrees of freedom to biotic carbon exchange, the *MEP* hypothesis would suggest that those biotic states would be most probable at which the production of entropy σ_{BIO} would be a maximum.

3.4.1. *A Simple Greenhouse Climate Model*

The model consists of a planetary energy balance, a formulation of planetary albedo which depends on atmospheric albedo and surface albedo, and a calculation of radiative and surface temperatures, which depend on a parameterization of the atmospheric greenhouse effect. Overall absorption of solar radiation Q_{IN} is expressed in terms of the planetary albedo α_P and the solar luminosity L:

$$Q_{IN} = (1 - \alpha_P) \cdot L \tag{24}$$

Planetary albedo is calculated from atmospheric albedo α_A and surface albedo α_S by:

$$\alpha_P = 1 - (1 - \alpha_A) \cdot (1 - \alpha_S) \tag{25}$$

Atmospheric albedo α_A is written as a function increasing with surface temperature (to capture the effect of increased convective cloud cover as discussed above) as:

$$\alpha_A = \alpha_{A,PD} \cdot e^{k_A \cdot (T_S - T_{S,PD})} \tag{26}$$

with values of $\alpha_{A,PD} = 0.2$, $T_{S,PD} = 288$ K, and $k_A = 0.01$. These parameters have been arbitrarily chosen such that atmospheric albedo increases by 10% with a warming of $\Delta T_S = 10$ K. Surface albedo α_S is written as a function which decreases with surface temperature T_S in order to capture the effect of snow on surface albedo:

$$\alpha_S = \alpha_{S,SNOW} - (\alpha_{S,SNOW} - \alpha_{S,NOSNOW})\left(1 - e^{-k_s (T_S - T_{S,0})}\right) \tag{27}$$

with an albedo of a snow-covered surface of $\alpha_{S,SNOW} = 0.6$, an albedo of a snow-free surface of $\alpha_{S,NOSNOW} = 0.1$, and parameters $k_S = 0.14$, and $T_{S,0} = 263$ K. These parameters have been chosen such that the transition from a highly reflective surface to a highly absorbing surface occurs approximately at the freezing point of water (273 K).

Radiative temperature T_R is calculated from the planetary energy balance:

$$\sigma \cdot T_R^4 = Q_{IN} \tag{28}$$

The surface warming ΔT associated with the atmospheric greenhouse effect is parameterized as a function of atmospheric carbon dioxide concentrations $p\mathrm{CO}_2$:

$$\Delta T(p\mathrm{CO}_2) = \Delta T_{PD} + 3\mathrm{K} \cdot \log_2 \left(\frac{p\mathrm{CO}_2}{p\mathrm{CO}_{2,PD}} \right) \tag{29}$$

using present-day $p\mathrm{CO}_2$ and greenhouse strength as reference values ($p\mathrm{CO}_{2,PD} = 330$ ppm, $\Delta T_{PD} = 33$ K). This formulation uses a surface warming of 3 K as a result of doubling $p\mathrm{CO}_2$, a sensitivity commonly obtained from atmospheric general circulation models (IPCC, 2001). The resulting surface temperature T_S is then calculated as:

$$T_s = T_R + \Delta T(p\mathrm{CO}_2) \tag{30}$$

Total entropy production σ_{TOT} is approximated by Equation (2):

$$\sigma_{TOT} = \frac{L}{4} \cdot (1 - \alpha_P) \cdot \left(\frac{1}{T_R} - \frac{1}{T_{SUN}}\right) \tag{31}$$

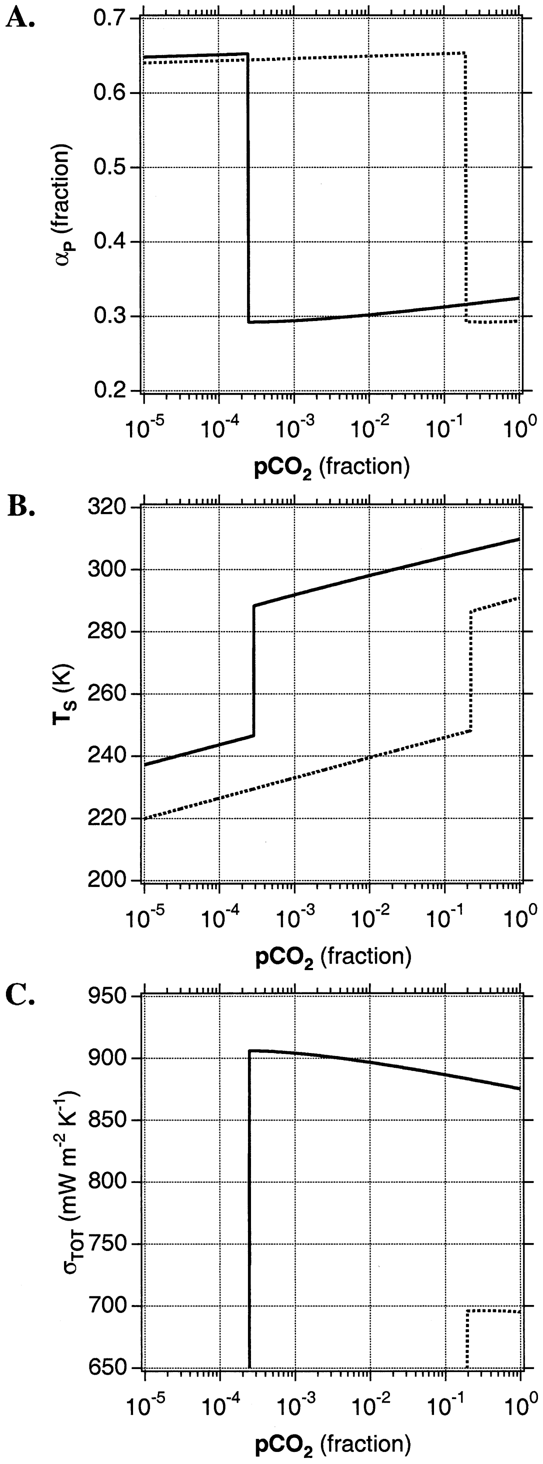
Figure 4 shows the simulated sensitivity of the model to atmospheric carbon dioxide concentrations $p\mathrm{CO}_2$. The parameters were chosen such that the model reproduces roughly the present-day conditions of $T_S = 289$ K and $\alpha_P \approx 0.3$ for $p\mathrm{CO}_2 = 330$ ppm (Figure 4a and b), as well as a reasonable sensitivity to doubled $p\mathrm{CO}_2$ concentrations. With the chosen parameter values, the model leads to a state close to *MEP* for current conditions (Figure 4c). This state of *MEP* is the result of the contrasting effects of surface temperature on surface albedo (i.e. snow) and atmospheric albedo (i.e. clouds) as discussed above. Note that the state of *MEP* is sensitive to solar luminosity (dotted line in Figure 4c).

3.4.2. *A Simple Biotic Carbon Cycle Model*

In order to simulate atmospheric carbon dioxide concentrations as a function of a biotically influenced carbon cycle, a simple three-box model of the global carbon cycle is used. This model consists of three carbon reservoirs, representing atmospheric carbon C_A, biotic carbon C_B, and geologic carbon C_G. The reservoirs exchange carbon by biotic carbon uptake F_{GPP} (flux from C_A to C_B), biotic respiration F_{RES} (flux from C_B to C_A), biotic carbon burial F_{BUR} (flux from C_B to C_G), and geologic release of carbon F_{GEO} (flux from C_G to C_A). In this simplifed view, the biotic effects on overall carbon exchange are only included through productivity and respiration. Indirect effects associated with biotic activity, for instance through the enhancement of rock weathering rates (Schwartzman and Volk, 1989), are not considered and neither are abiotic fluxes, such as those associated with the geochemical carbonate–silicate cycle (Walker et al., 1981). Even though the carbonate–silicate cycle leads to an important negative feedback to change, it is excluded here because it involves only one process, therefore representing one degree of freedom. It is argued here that for *MEP* to apply, we need to consider a sufficiently wide range of carbon exchange processes from which the most likely combinations will emerge in steady state. As argued in the introduction, the diversity of the biota add

⟶

Figure 4. Simulated climate of the simple climate model described in Section 3.4. (a) Planetary albedo α_P as a function of atmospheric carbon dioxide concentration $p\mathrm{CO}_2$ for current solar luminosity (solid line) and 70% of its value (dotted line). (b) same as (a), but surface temperature T_S (c) same as (a), but total entropy production σ_{TOT}. Present-day luminosity is taken as $L = 1370$ W m^{-2}.


A.
α_P (fraction)
0.7
0.6
0.5
0.4
0.3
0.2
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
pCO_2 (fraction)
B.
T_S (K)
320
300
280
260
240
220
200
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
pCO_2 (fraction)
C.
σ_{TOT} (mW m^{-2} K^{-1})
950
900
850
800
750
700
650
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
pCO_2 (fraction)

many degrees of freedom to carbon exchange. Therefore, the emergence of *MEP* states should be applicable primarily to a biologically influenced carbon cycle. The purpose of this simple carbon cycle model is to illustrate the emergence of this *MEP* state and to demonstrate the climatic consequences of the *MEP* state.

This simplified formulation of the carbon cycle leads to the following differential equations for the carbon pools:

$$\frac{dC_{\mathrm{A}}}{dt} = -F_{\mathrm{GPP}} + F_{\mathrm{RES}} + F_{\mathrm{GEO}} \tag{32}$$

$$\frac{dC_{\mathrm{B}}}{dt} = +F_{\mathrm{GPP}} - F_{\mathrm{RES}} - F_{\mathrm{BUR}} \tag{33}$$

$$\frac{dC_{\mathrm{G}}}{dt} = F_{\mathrm{BUR}} - F_{\mathrm{GEO}} \tag{34}$$

Using Equations (14) and (15), a factor ε to convert energy fluxes to carbon fluxes, and taking F_{GEO} being proportional to the geologic carbon pool C_{GEO} leads to the following expressions for C_{B}, C_{G}, and C_{A} in steady state:

$$C_{\mathrm{B}} = \varepsilon \cdot \frac{1}{(\beta + \rho)} \cdot Q_{\mathrm{IN}} \tag{35}$$

$$C_{\mathrm{G}} = \varepsilon \cdot \frac{1}{\gamma} \cdot \frac{\beta}{(\beta + \rho)} \cdot Q_{\mathrm{IN}} \tag{36}$$

$$\begin{aligned} C_{\mathrm{A}} &= C_{\mathrm{TOT}} - C_{\mathrm{B}} - C_{G} \\ &= C_{\mathrm{TOT}} - \varepsilon \cdot \frac{1}{\beta + \rho} \cdot \left(1 + \frac{\beta}{\gamma}\right) \cdot Q_{\mathrm{IN}} \end{aligned} \tag{37}$$

where C_{TOT} is the total amount of carbon in the Earth system, taken to be 40×10^6 GtC, the present-day size of the geologic carbon pool (Schlesinger, 1997). The geologic turnover time γ is calculated from the present-day geologic flux of 0.1 GtC yr^{-1} and a reservoir size of $C_{\mathrm{G}} = 40 \times 10^6$ GtC (Schlesinger, 1997) as $\gamma = 2.5\ 10^{-9}\ \mathrm{yr}^{-1}$. The conversion factor ε is taken to be $\varepsilon = 0.84$ (GtC yr^{-1})/(W m^{-2}) to yield an approximate global gross primary productivity of 200 GtC yr^{-1} for a mean absorption of solar radiation of $Q_{\mathrm{IN}} = 238$ W m^{-2}. Atmospheric $p\mathrm{CO}_2$ is calculated simply as:

$$p\mathrm{CO}_2 = \frac{C_{\mathrm{A}}}{C_{\mathrm{TOT}}} \tag{38}$$

Neglecting the effects of nutrient and water limitations for simplicity, Q_{P} is proportional to Q_{IN} (Equation (17)), and σ_{BIO} is then proportional to:

$$\sigma_{\mathrm{BIO}} \propto Q_{\mathrm{IN}} \cdot \left(\frac{\rho}{\rho + \beta} \frac{1}{T_{\mathrm{s}}} - \frac{1}{T_{\mathrm{SUN}}}\right) \tag{39}$$

3.4.3. MEP *and Homeostatic Behavior*

The coupled carbon–climate model is used to calculate the sensitivity of biotic entropy production σ_{BIO} and total entropy production σ_{TOT} to changes in solar luminosity L similar to the Daisyworld model setup (Watson and Lovelock, 1983) to demonstrate the emergence of homeostatic behavior due to biotic activity. The model parameter ρ is taken to reflect the degrees of freedom associated with the biota. Therefore, σ_{BIO} is maximized with respect to ρ in the following. This maximization is done numerically for different values of L using an arbitrarily chosen value of $\beta = 0.1\ \mathrm{yr}^{-1}$.

Figure 5a shows the value of ρ at which σ_{BIO} is maximized as a function of solar luminosity L. The resulting steady-state atmospheric $p\mathrm{CO}_2$ associated with the state of *MEP* decreases roughly exponentially with L (also shown in Figure 5a). Since σ_{BIO} is primarily determined by Q_{IN}, a state of maximum σ_{BIO} is close to a maximum in total entropy production σ_{TOT} (not shown). Figure 5b shows total entropy production σ_{TOT} as a function of L for the case in which σ_{BIO} is maximized and for the cases of a fixed strong greenhouse ($p\mathrm{CO}_2 = 1$) and a fixed weak greenhouse ($p\mathrm{CO}_2 = 10^{-6}$). These graphs show that a state of *MEP* can be maintained by changing the value of the respiration coefficient ρ. Figure 5c shows the simulated surface temperature T_{S} for these three cases. Surface temperature is almost constant (temperatures vary by 0.5 K over the range of solar luminosities simulated) in the case in which σ_{BIO} is maximized, in sharp contrast to a "constant" greenhouse scenario where temperatures vary by about 20 K. Figure 5c therefore shows how the maximization of biotic entropy production can result in homeostatic behavior. The simulated homeostatic behavior as a result of maximizing σ_{BIO} is, of course, the result of the model design in which the minimum planetary albedo depends on temperature only. Naturally, the particular, optimum value of ρ depends on the choice of β. Also, other limitations to biotic activity as discussed above have not been considered in this particular example. It nevertheless demonstrates that a state of *MEP* associated with the biotic effects on the global carbon cycle can lead to homeostatic behavior of the Earth system.

3.5. SUMMARY

In this Section I applied the *MEP* hypothesis to processes affected by the Earth's biota. The justification for this application is that the biota introduce additional degrees of freedom to Earth system processes, and therefore states of *MEP* should emerge as the most probable states from the system dynamics. The three examples provided here, which address fundamental biotic effects, support the hypotheses that biotic effects enhance entropy production of the biota (i.e. biotic activity) and of the Earth system as a whole, and possibly lead to a state of *MEP*. Entropy production can be increased most substantially by the biota through increasing the absorption of solar radiation at the surface, either directly through its effect on surface albedo, or indirectly through effects on planetary albedo, and secondarily through the partitioning of energy fluxes at the Earth's surface.

4. Discussion

4.1. LIMITATIONS AND FURTHER IMPLICATIONS

The application of the *MEP* hypothesis to biotic effects on Earth system functioning is obviously subject to limitations. Some of these limitations are discussed in the following, specifically regarding the applicability of the *MEP* hypothesis to biotic functioning, on the role of clouds and how they are affected by the biota, and on the consequences that a "Snowball Earth" state would have for the applicability of *MEP*. Further implications are drawn with respect to definitions of life that are based on entropy production.

4.1.1. MEP, *Diversity and Biotic Functioning*

When the *MEP* hypothesis is applied to processes that are affected by the biota, the inherent assumption for its applicability is that the biota add sufficient degrees of freedom to the process so that states of *MEP* can be selected for. This raises a series of questions: (a) what introduces degrees of freedom to biotic functioning? (b) how many degrees of freedom would be sufficient for a state of *MEP* associated with biotic activity to be selected for? and (c) which biotic parameters represent these degrees of freedom?

It is argued here that the diversity of how individuals grow and respond to environmental conditions would constitute one aspect that introduces degrees of freedom to biotic functioning. An ecosystem that is functionally diverse would constitute a wider range of options for functioning therefore permitting the system to evolve to a state of *MEP*. This interpretation in fact links directly to the general question of how biodiversity affects ecosystem functioning (e.g. Chapin et al., 2000; Loreau et al., 2001). Although no general consensus has been reached (Schwartz et al., 2000), it is nevertheless hypothesized that more diverse ecosystems would have a higher productivity, stability, and more resistance to perturbations (also shown in some experiments, e.g. Naeem et al. (1994), McGrady-Steed et al. (1997), and

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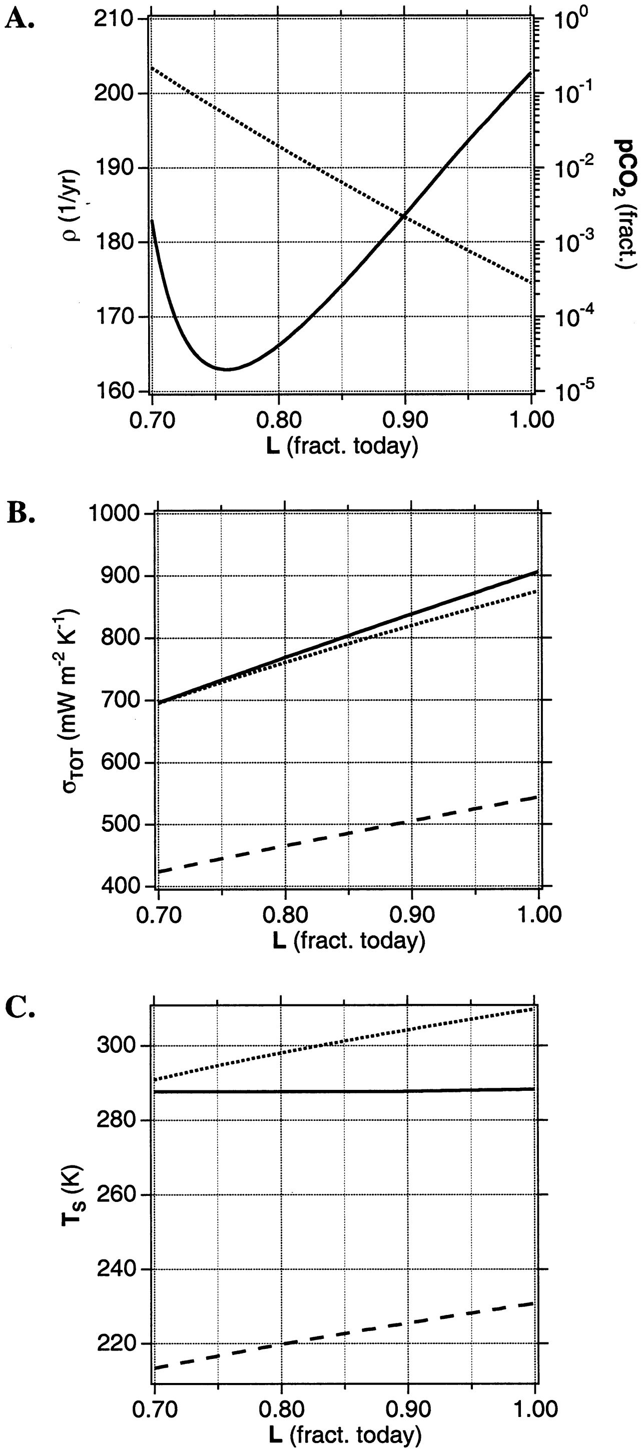
Figure 5. Homeostatic behavior emerging from a state of *MEP* associated with a biotically mediated carbon cycle. (a) Value of the respiration coefficient ρ (solid line) at which biotic entropy production is maximized and the associated atmospheric carbon dioxide concentration $p\mathrm{CO}_2$ (dotted line) as a function of solar luminosity L (expressed as a fraction of the present-day value). (b) Total entropy production σ_{TOT} associated with an optimally chosen value of ρ (solid line) and for the extreme cases of high $p\mathrm{CO}_2$ ($p\mathrm{CO}_2 = 1$, dotted line) and low $p\mathrm{CO}_2$ ($p\mathrm{CO}_2 = 10^{-6}$, dashed line). (c) Same as (b), but for surface temperature T_S. In the simulations, a prescribed value of $\beta = 0.1$ yr^{-1} and a present-day luminosity of $L = 1370$ W m^{-2} has been used.


A.
ρ (1/yr)
210
200
190
180
170
160
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
pCO_2 (fract.)
0.70
0.80
0.90
1.00
L (fract. today)
B.
σ_{TOT} (mW m^{-2} K^{-1})
1000
900
800
700
600
500
400
0.70
0.80
0.90
1.00
L (fract. today)
C.
T_S (K)
300
280
260
240
220
0.70
0.80
0.90
1.00
L (fract. today)

Tilman et al. (1996)). Taking productivity as a measure of the entropy production of the ecosystem, these hypotheses regarding biodiversity and ecosystem functioning are consistent with the thermodynamic interpretation proposed here. The level at which degrees of freedom are sufficient for an ecosystem to attain a state of *MEP* would likely relate to the climatic environment and its variability. On the other hand, climate affects geographic patterns of plant species richness, with drier and colder environments generally showing less diversity (e.g. Currie and Paquin, 1987). These patterns in turn can be interpreted as a reflection of climatic constraints on plant functional diversity (Kleidon and Mooney, 2000), and therefore as geographic variations of the biotic degrees of freedom as discussed here. Considering that climate constrains the 'biotic degrees of freedom', it would seem that not necessarily all ecosystems would exhibit sufficient degrees of freedom to attain states of *MEP*.

4.1.2. *Biotic Effects and Convective Clouds*

An important process discussed in Section 3 is the biotic influence on convective clouds. In terms of the entropy production budget, it would seem that convective clouds play a major role since they strongly affect solar absorption during periods of high solar radiation, rather than stratiform clouds which are generally associated with fronts in the mid-latitude winters (i.e. periods of low solar radiation). The development of convective clouds is linked to the conditions of the planetary boundary layer (particularly regarding its stability), which in turn is strongly affected by the partitioning of energy at the Earth's surface: while sensible heat flux contributes to the growth of the boundary layer, the latent heat flux moistens the boundary layer and makes it more unstable. Therefore, the partitioning of energy into sensible and latent heat can play an important part in determining the properties of the boundary layer in terms of depth and moisture content, and hence should affect the formation of convective clouds. This partitioning, as characterized by the Bowen ratio (i.e. the ratio of sensible to latent heat), is strongly affected by vegetation over land, as illustrated by the energy balances of a "Desert World" in Table I. So it would be without question that the land biota play a substantial role in convective cloud development. Even over the oceans a case can be made for a biotic role in determining the Bowen ratio: the equilibrium Bowen, which is roughly representative of ocean surfaces, decreases exponentially with temperature, that is, the partitioning of turbulent fluxes into sensible and latent heat shifts towards latent heat for warmer temperatures. At a global scale, temperature is affected by the strength of the greenhouse effect, so that the equilibrium Bowen ratio should decrease with increasing greenhouse gas concentrations. Since greenhouse gas concentrations are moderated by the biota, there would be an indirect connection between the value of the Bowen ratio and oceanic biotic activity through the carbon cycle. This connection would then justify the notion that convective clouds in general are affected by biotic activity. What has been suggested here, in the context of Section 3.4, is that the effects of the biota would not be arbitrary, but such that the overall absorption of solar radiation, and hence biotic activity, would be maximized under given external constraints. Such a particular connection between biotic activity and convective clouds, however, would need further evaluation.

The potentially important role that clouds play in regulating the Earth's climate has been suggested before (e.g. Henderson-Sellers, 1979; Rossow et al., 1982; Ou, 2001). For instance, Ou (2001) used an energy balance model which included parameterizations for low and high clouds and turbulent wind in conjunction with the *MEP* hypothesis to show how clouds could act to stabilize Earth's climate. Clouds as a stabilizing feedback have also been suggested in the context of the production of DMS by the marine biota and its effects on clouds through atmospheric sulfur (Charlson et al., 1987). The difference in which clouds are considered here within the context of the *MEP* hypothesis is that it is not necessarily attributed to one particular process, but rather that the biota introduces more degrees of freedom to any of these processes, that is, more ways in which clouds are affected, and that therefore the state of *MEP* would be the most likely state to emerge.

4.1.3. MEP *and Snowball Earth*

Some geologic reconstructions suggest abundant glaciations in the tropics for two time periods during the proterozoic, around 2.2 Gyr (Evans et al., 1997) and around 750–550 Myr (Hoffman et al., 1998) before present. The existence of such a "Snowball Earth" state is of relevance here because a fully glaciated Earth would likely have a high surface albedo. This, in turn, would lead to comparatively low absorption of solar radiation and therefore low total entropy production (Equation (2)). Even though a "Snowball Earth" state would be energetically stable for most time periods during the Earth's past (Budyko, 1969; Sellers, 1969), it would most likely not represent a state of *MEP*. This apparent violation of the *MEP* hypothesis may be resolved by the fact that the *MEP* hypothesis as derived by Dewar (2003) only applies to systems in steady state. Both suggested time periods of a "Snowball Earth" preceded major transitions in the atmospheric composition caused by the biota: a transition to an oxic atmosphere around 2.2 Gyr ago (Holland et al., 1986) and a 20-fold reduction of atmospheric CO_2, presumably caused by the colonization of land by life around 400 Myr before present (Schwartzman and Volk, 1989; Berner, 1997). Since both cases of "Snowball Earth" occurred at the beginning of major transitions in the Earth-life system, it would seem that these cases do not resemble a steady state and would therefore not satisfy the steady-state condition for the applicability of the *MEP* hypothesis. The "Snowball Earth" state was eventually terminated by an increase in atmospheric pCO_2 due to volcanic outgassing. Obviously, volcanic outgassing is not affected by biotic activity. However, atmospheric pCO_2 concentrations reflect the balance of carbon removal and addition to the atmospheric carbon reservoir, which includes carbon exchange due to biotic activity (or the lack of it). The overall phenomenon of a "Snowball Earth" state and its termination should therefore be viewed as an emergent outcome of atmosphere–biosphere interactions, with the termination of a "Snowball Earth" suggesting the lack of significant biotic carbon burial. The oscillation of planetary albedo associated with the initiation and termination of a “Snowball Earth” state could possibly be interpreted as a transition phase towards a state of higher entropy production of the Earth system. This would, however, require further investigations.

4.1.4. *Implications for Defining Life*

The role of energy degradation and the associated production of entropy has long been discussed as a driving force for life (Boltzmann, 1886; Lotka, 1922a,b; Schrödinger, 1944; Ulanowicz and Hannon, 1987; Schneider and Kay, 1994). Also the notion that biotically mediated processes are more efficient in degrading free energy than purely physical processes has been pointed out before (Ulanowicz and Hannon, 1987; Schneider and Kay, 1994). While in general agreement with these thermodynamic arguments, the interpretation provided here extends this perspective by adding two crucial aspects.

1. The biota add degrees of freedom to Earth system 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*. Note that this interpretation does not focus on one particular feedback, whether physical (e.g. clouds, Henderson-Sellers, 1979), geological (e.g. silicate rock weathering, Walker et al., 1981) or biological (e.g. DMS, Charlson et al., 1987) in nature. Rather, it views the sum of these feedbacks as a progression towards increasing degrees of freedom, which make states of *MEP* more likely as an outcome. In this context, the *MEP* hypothesis emphasizes the fundamental role that diversity plays for biotic effects and associated states of *MEP.*
2. The Earth’s environment is such that it “allows” for degrees of freedom to be added to Earth system processes, therefore making for photosynthetic life on Earth highly probable. In Section 3.4 the role of photosynthetic life was discussed in the context of the Earth’s planetary albedo which, as shown in Section 2.1, has the strongest effect on overall entropy production by the Earth system. A crucial aspect of a state of MEP associated with the planetary albedo is the fact that the Earth’s planetary albedo is not a fixed property, but flexible. It is not solely determined by the physical characteristics of the geology at the surface (like on Mars) or entirely by the planetary atmosphere (like on Venus). Instead, Earth’s planetary albedo depends to a large extent on the amount and location of clouds in the atmosphere and the extent of snow cover at the surface. An Earth without water may have a higher overall rate of entropy production. However, given the fact that water is abundant on Earth, its planetary albedo depends on the presence of snow and clouds. Both of these water-related aspects of the planetary albedo are affected by surface temperature and therefore by the strength of the atmospheric greenhouse. Because of this flexible nature of Earth’s planetary albedo and its relation to the atmospheric greenhouse effect, adding degrees of freedom can affect

planetary albedo and increase total entropy production substantially. As argued in Section 3.4, this may be achieved by increasing the diversity of processes in the global carbon cycle (e.g. by different rates of respiration), which then moderates the atmospheric carbon dioxide greenhouse, surface temperature, and therefore planetary albedo. It would seem that it is the flexible nature of the planetary albedo that allows for a wide range of degrees of freedom to be added to Earth system processes and therefore would make photosynthetic, abundant life on Earth a highly probable outcome. It also emphasizes the role of water and carbon (and the presence of an atmosphere) for abundant life on Earth in quite a different way than a microbiological perspective. If the presence of life on Earth is viewed from this perspective, then the fact that the planetary albedo is flexible, rather than static, adds a very important constraint to where abundant life is possible. This in turn leads to a different interpretation of which planetary environment is habitable compared to previous approaches (e.g. Lovelock and Whitfield, 1982; Caldeira and Kasting, 1992).

4.2. COMPARISON TO THE ORIGINAL GAIA HYPOTHESIS AND THE RECENT DISCUSSION

In the following I discuss the application of *MEP* to biotic effects and its implications in the context of the original Gaia hypothesis (Lovelock and Margulis, 1974) and the points and arguments raised in the recent discussion on the Gaia hypothesis in *Climatic Change* (Kleidon, 2002; Kirchner, 2002, 2003; Lenton, 2002; Volk, 2002, 2003a,b; Lovelock, 2003; Lenton and Wilkinson, 2003). In doing so, I assume that the application of *MEP* as done in Section 3 and the conclusions drawn from it are sufficiently justified and valid, that is, that (a) biotic effects enhance biotic entropy production, (b) biotic effects enhance total Earth system entropy production, and that (c) a state of *MEP* can result in homeostatic behavior.

4.2.1. *Original Gaia Hypothesis*

The Gaia hypothesis is originally described as "homeostasis for and by the biosphere" (Lovelock, 1972a,b; Lovelock and Margulis, 1974). The idea of the Gaia hypothesis derives from the comparison of the Earth's entropy budget and the associated state of the atmosphere far from chemical equilibrium with a living organism, which, in the words of Schrödinger (1944), maintains internal order by producing high entropy waste. From this comparison, the proposition was made that the Earth can be seen as a "superorganism" exhibiting homeostatic behavior maintained "for and by the biosphere".

The application of *MEP* to the examples in Section 3 leads to a similar interpretation to "homeostasis by and for the biosphere", but it removes the notion of teleology in Gaia, replacing it with a physically based hypothesis. Particularly the example of the Earth's planetary albedo and its relationship to the greenhouse effect and biotic activity in Section 3.4 shows a very similar outcome but with a very different interpretation: a homeostatic global mean temperature resulting from the maximization of biotic entropy production. The connection of planetary albedo with the atmospheric greenhouse and biotic activity also supports Lovelock and Margulis' (1974) argument to view the Earth–Space interface as the boundary for understanding the role of life in the Earth system. The results presented here are in support of what has been labeled the "Strong Gaia" hypothesis (Kirchner, 1989), rejecting the notion that "Strong Gaia" hypotheses 'may be useful as metaphors, but are unfalsifiable, and therefore misleading' (Kirchner, 1989, 2002). The example of Section 3.4 is certainly more than a metaphor, and it could be falsified by showing that the general reduction of the Earth's greenhouse effect throughout its history would in fact lead to a decrease (or no change) in the overall entropy production.

What is different here compared to the original Gaia hypothesis is that the latter was not formulated in terms of the *MEP* hypothesis. The *MEP* hypothesis provides a direction for how the system evolves and why biotically enhanced processes may result in homeostatic behavior. This perspective also puts an important emphasis on the environment in the sense that the environment "allows" for biotic degrees of freedom to be added to Earth system processes, as discussed at the end of Section 4.1. Life should therefore be seen as an emergent property of the Earth system by itself, and homeostasis should be viewed as an emergent system property rather than solely be attributed to the biota or teleologic arguments.

It is important to note that homeostasis may result from a *MEP* state, but it does not necessarily need to be the case. With respect to the Gaia hypothesis, Kirchner (2003) used the example of greenhouse gas fluctuations during the last 100,000s of years as an example that the Earth system is not homestatic, using this to refute the Gaia hypothesis. During glacial–interglacial cycles, the spatial and temporal patterns of solar radiation change due to orbital changes (in contrast to the general increase of solar luminosity discussed in Section 3.4, which does not resolve spatial details). Amplified by the ice-albedo feedback and by changes in the atmospheric greenhouse, these changes are likely to lead to a different state of *MEP* which may be associated with nonhomeostatic system behavior. Whether the observed changes in greenhouse gas concentrations during glacial periods reflect a different *MEP* state as a result of orbital forcing would clearly need further evaluation. Nevertheless, just because *MEP* may lead to homeostasis for long-term changes, nonhomeostatic behavior should not be used for outright rejection of the *MEP* hypothesis in general.

4.2.2. *Measuring and Testing Gaian Hypotheses*

For quantifying any particular directions of biotic effects we need a measure which quantifies how "good" an environment is for life and what constitute a "habitable" environment. The lack of clear measures and definitions for quantifying biotic effects and testing the Gaia hypothesis has been pointed out for a long time (e.g. Schneider, 1986), and initiated the recent discussion. It is interesting to note that a couple of measures which have been proposed, such as gross primary productivity *GPP* (Kleidon, 2002), cycling ratios (Volk, 2002), and biodiversity (Schneider, 1986) are linked to overall biotic entropy production in steady state: *GPP* is directly a measure of biotic entropy production in steady state (Equation (16)), enhanced cycling ratios emerge from an evolution towards a state of *MEP* associated with biotic productivity under nutrient constraints (Equation (23)), and biodiversity could be seen as a measure of the degrees of freedom added by the biota. Nevertheless, it is the production of entropy (and the associated degradation of free energy) that directly characterizes biotic activity and is central to the *MEP* hypothesis and the emergent, homeostatic behavior as shown in Section 3.4.

After defining a quantifiable measure for biotic activity, hypotheses for testing Gaia can be set up (Kleidon, 2002; Lenton, 2002, and as it is continued here at the beginning of Section 3). One of the main problems associated with testing these “Gaian” hypotheses is that Earth’s history only provides one sample, leading to criticisms by Kirchner (2002) and Volk (2002) regarding the generality of evaluating these hypotheses. This is, of course, an inherent problem that any general theory faces that intends to explain the general trends and emergent characteristics of the evolution of the whole Earth. It is interesting to note that the application of the *MEP* hypothesis to the poleward heat transport has faced similar criticism (e.g. Rodgers, 1976). But it is becoming increasingly clear that *MEP* holds for a wide variety of dissipative, nonequilibrium systems (see e.g. reviews by Lorenz (2002), and Ozawa et al. (2003)), such as Bérnard cells (Malkus, 1954), vertical temperature profile of the radiative–convective equilibrium (Ozawa and Ohmura, 1997), poleward heat transport on other planetary bodies of Mars and Titan (Lorenz et al., 2001), and the examples of determining biotic functioning or properties by optimizing biotic productivity as discussed here. This wide range of applicability clearly points out the advantages of the *MEP* hypothesis which should not only apply to biotic systems, but to any nonequilibrium thermodynamic system with sufficient degrees of freedom.

The *MEP*-based hypotheses regarding the role of the biota in Earth system processes also emphasize two important points: (a) a broad system view, focussing on the whole biota, rather than on isolated individuals; and (b) a probabilistic view, focussing on states which are the most probable ones under given constraints. Both of these points have been suggested in the recent discussion (Kleidon, 2002; Lenton, 2002; Lenton and Wilkinson, 2003), but isolated examples have been used to reject Gaian hypotheses (Kirchner, 1989, 2002). When evaluating optimum conditions for life, it has been argued before that what is good for one individual species may be bad for another. Schneider (1986) used the example of the transition to an oxic atmosphere about 2.2 billion years ago. While the high abundance of reactive oxygen was highly beneficial for some species, it was detrimental for others. Kirchner (1989) illustrated this point by stating that ‘the Earth’s physical environment is obviously not favorable for penguins'. It is important to distinguish the role of optimum conditions for particular individuals from optimum conditions for the overall activity of *all* individuals at the global scale. Naturally, optimum conditions for global productivity are unlikely to translate into optimum conditions for each individual. In fact, biodiversity research at the ecosystem scale generally points out the opposite: While biodiversity tends to increase productivity and the stability of productivity of the whole ecosystem, individuals are actually doing worse (Pimm, 1984; Naeem et al., 1994; Tilman et al., 1996; McGrady-Steed et al., 1997). When testing general trends of biotic effects at the planetary scale it is crucial to maintain the view of the whole and not of its individual parts (Lovelock, 2003). In addition, following Dewar's (2003) work, the *MEP* hypothesis should be viewed from a probabilistic perspective, that is, that states of MEP are the most probable, and are therefore emerge from the system dynamics in steady state. However, it only applies to systems in steady state. In evaluating hypotheses with respect to *MEP*, one has to be careful and not use examples from transition periods (see also discussion on anthropogenic changes below).

4.2.3. *Biotic Effects, Gaian Feedbacks and Natural Selection*

Kleidon (2002) used *GPP* as a measure of biotic activity in combination with extreme climate model simulations to show that biotic effects tend to enhance *GPP*. This notion is supported here when biotic activity is viewed as a dissipative process which, with sufficient degrees of freedom, evolves toward a state of *MEP*. Kleidon's (2002) conclusion was criticized by Kirchner (2002) in which he argued that "Gaian feedbacks can evolve by natural selection, but so can anti-Gaian feedbacks" and also in Volk's (1998, 2002) interpretation of 'Gaia is (probably) build from free by-products'. Both of these statements imply that biotic effects would be random, outcomes of coincidences, and do not point in a particular direction. In the context of entropy production, Kirchner's and Volk's arguments suggest that biotic effects which enhance entropy production are as likely (or probable) to emerge as those ones which decrease entropy production. The lack of direction of biotic effects would be in contradiction to the *MEP* hypothesis. In the context of the energetics of biological evolution it has been suggested otherwise for a long time (Lotka, 1922a):

> 'It has been pointed out by Boltzmann that the fundamental object of contention in the life-struggle, in the evolution of the organic world, is available energy. In accord with this observation is the principle that, in the struggle for existence, the advantage must go to those organisms whose energy-capturing devices are most efficient in directing available energy into channels favorable to the preservation of the species.'

This puts a "preferred" direction on natural selection for those organisms which increase degradation of free energy, or equivalently, entropy production. Again, citing Lotka (1922a,b):

> '... *natural selection* tends to make the energy flux through the system a maximum, so far as compatible with the constraints to which the system is subject.'

This latter point agrees with Dewar's (2003) general interpretation of *MEP* from information theory, that is, that nonequilibrium systems with sufficient degrees of freedom evolve to a state of *MEP* given certain constraints on system functioning. What has essentially been done in Section 3.4 is to extend Lotka's reasoning to the planetary level. For photosynthetic life, those individuals which can absorb more solar radiation and convert it into organic compounds do not just enhance their own evolutionary benefit, but they would also tend to enhance total absorption of solar radiation of the Earth system. At the planetary scale, this would then imply that the energy flux through the biota is maximized by minimizing the planetary albedo, which, at the same time, leads to a maximization of entropy production of the whole Earth system.

A common criticism of the Gaia hypothesis is the notion that it implies teleological goal-seeking and thereby refutes natural selection as an evolutionary process (e.g. Kirchner, 1989, 2002). First, Lotka's interpretation, as cited above, clearly labels the process of natural selection as evolving towards a "goal", namely to maximize the energy flux through the system (or closely associated, the maximization of entropy production). This 'goal seeking' is not teleological, but should rather be seen as an evolution towards more probable states along the lines of the statistical interpretation of thermodynamics. Traditionally, thermodynamics describes the behavior of a large ensemble of individual molecules. All molecules interact, and when their paths are followed within the gas, they seem random. What thermodynamics embodies is that there are general rules emerging from the dynamics of the large number of interacting molecules despite the seemingly chaotic microscopic behavior. Specifically, in order to derive the system properties and behavior in thermodynamic equilibrium, the common practice in statistical physics is to maximize the entropy of the system subject to given constraints, such as the conservation of energy and matter. It is through these constraints that the macroscopic system behavior can be derived. It would seem that the assumption of a state of maximum entropy for a thermodynamic system in equilibrium would imply teleology. A state of maximum entropy is, however, the natural outcome of the system dynamics in equilibrium, and applying maximum entropy therefore only represents a convenient "short-cut" to describe the system in equilibrium. Dewar (2003) extended this thermodynamic approach to nonequilibrium systems in steady state to derive the *MEP* hypothesis. Therefore, the *MEP* hypothesis should not be seen as implying teleology, but also as a convenient short-cut to describe the macroscopic behavior of a nonequilibrium system in steady state (with sufficient degrees of freedom). What this further implies for such a system in steady state is that the response of the system to external perturbations is dominated by negative feedbacks (i.e. those that maintain states of *MEP*), which, again, is similar to the original Gaia hypothesis. Some work has been done on the causes of these feedbacks within the context of poleward heat transport (e.g. Lorenz, 1960; Paltridge, 2001; Shimokawa and Ozawa, 2001, 2002; Ozawa et al., 2003). More work would be necessary to identify the nature of the feedbacks for the cases of *MEP* discussed here.

In their recent comments, both, Kirchner (2003) and Volk (2003a,b) maintain their strong emphasis on individuals, ignoring the importance of emergent, macroscale behavior as it is to be expected from a thermodynamic system. Kirchner (2003) wrote that "traits that benefit the individual may also *coincidentally* enhance the environment", and Volk (2003a,b) that "effects that enhance life as a whole are not specifically created by metabolisms evolved for the function of making those effects." I disagree with these perspectives. If we assume that "enhancing the environment" means leading to an environment with a higher rate of entropy production, then biotic effects do not *coincidentally* enhance the environment, they are also not *not created* for enhancing the environment, but individuals which enhance the environment have a *higher probability to emerge* than those which do not "enhance" the environment. By using the above definition, environment-enhancing individuals (a) have a higher individual fitness and (b) lead to an environment with a higher rate of entropy production of the overall Earth system. Environmental homeostasis, large-scale, life-enhancing effects, and evolution by natural selection do not contradict each other, but are just different reflections of biotic activity as a thermodynamic process which evolves to a state of *MEP*.

4.2.4. *Resistance and Resilience of Earth*

Drawing from examples in the ecological literature (Pimm, 1984), Lenton (2002) proposed hypotheses regarding the role of life in the overall behavior of the Earth system in terms of its resistance to perturbation and its speed of recovery after perturbation. Lenton (2002) suggested that the environment of the Earth's surface is likely to be more resistant and resilient with life than without. The hypothesis of a more resistant Earth with life fits well to the interpretation presented here. Adding degrees of freedom to Earth system processes allow processes to evolve to *MEP* states. And with sufficient degrees of freedom it should allow these processes to evolve to a new *MEP* state if external forcing is changed, therefore making the overall system more resistant, that is, the value of entropy production would change less with more degrees of freedom because it allows the system to adjust to a new *MEP* state under the altered forcing. The emergence of homeostatic behavior from *MEP* in Section 3.4 can of course be seen as an extreme form of resistance. However, it is difficult to say whether the Earth is more resilient with life, since the nonequilibrium state of the Earth is actively maintained largely by the biota. An Earth without life in steady state would have less degrees of freedom associated with the global carbon cycle, and would unlikely evolve to a state of *MEP* in the first place. But that would seem to counter the point made above that the Earth's environment intrinsically allows for life to emerge and that it is a highly probable characteristic of Earth.

4.2.5. *By-products and "Wasteworld" Earth*

Volk (2002) suggested the metaphor of Earth being a "Wasteworld" made of free by-products. While there is some resemblance with a "Wasteworld" notion in the sense that the outcome of *MEP* is associated with the largest amount of "waste" being produced (i.e. largest degradation of free energy), the Earth itself is far from being in a "Wasteworld" state. "Waste" does not remain on Earth but is re-radiated into space as longwave radiation, and the degradation of free energy is (usually) not a "waste" of energy in that it allows for performing work, and build order. Therefore, a maximum in entropy production is associated by the largest amount of available work. In that sense, the metaphor of a "Wasteworld" would miss the crucial point that the Earth exhibits life! In addition, the term "by-product" suggests that the direction of biotic effects are unexpected. This is in contrast to the interpretation proposed here (see section on natural selection above).

4.2.6. *Thermodynamics of Anthropogenic Global Change*

During the last century or so, human activity has profoundly affected the Earth's environment. Clearly, anthropogenic effects have altered, for instance, atmospheric carbon dioxide concentrations to a level which has not occurred during at least the past 400 000 years (Petit et al., 1999). Kirchner (2002) used anthropogenic change as an example that the Earth's environment is not tightly regulated by the biota on human time scales. There is no doubt that the elevated concentration of atmospheric carbon dioxide will eventually decline to probably pre-industrial levels through oceanic carbon uptake on the scale of hundreds of years, and by rock weathering on the time scale of millions of years. So in this sense it is a transient phenomenon and it should not be used to reject the notion of environmental homeostasis in steady state on a long time scale. But anthropogenic change, in terms of changing the Earth's atmosphere and land surface by human actions, also leads to the wider question of whether human effects on Earth system functioning are consistent in terms of entropy production and states of *MEP*. One could imagine a similar application of the concept of *MEP* to the processes within the anthroposphere. Many aspects of present-day global environmental changes are related to increased dissipation of energy associated with human activity (analogous to biotic activity discussed in Section 3): the burning of fossil fuels which lead to elevated atmospheric carbon dioxide and greenhouse warming; the depletion of natural resources, e.g. global fisheries, as food sources; and land cover change (e.g. forest conversion to pasture and agriculture) and the enhanced nitrogen cycle to increase food production. The listed changes can all be related to an increased dissipation of free energy/production of entropy associated with human activity. Enhanced dissipation allows for more work, thus higher order. On the other hand, land cover change from forests to pastures may possibly lead to less entropy production of the Earth system (drawing from the example of a "Desert World" versus the "Present-Day" climates in Section 3.3). But it is important to keep in mind that all of these changes are still of transient nature and may not be maintained when fossil fuel sources are depleted. At that point, the higher level of entropy production would possibly not be sustained, i.e. it would not lead to a new steady state. Considering the transient nature of these changes it would seem that anthropogenic modifications of the environment do not outrightly contradict the *MEP* hypothesis.

4.3. IMPLICATIONS OF MEP FOR MODELING THE EARTH SYSTEM AND GLOBAL CHANGE

The *MEP* hypothesis was applied to rather conceptual models in Sections 2 and 3. A natural next step would be to test and confirm the *MEP* hypothesis, and the hypotheses regarding biotic effects of Section 3.1, by using more detailed simulation models, for instance, atmospheric or oceanic General Circulation Models (GCM's), dynamic global vegetation models or models of biogeochemistry. In the following, I discuss how these models can be used to test *MEP* and what the potential implications of *MEP* states are for simulating the Earth system response to global change.

Model formulations can be divided into parameterizations of dynamical constraints, for instance regarding the energy and water balance, and parameterizations of the dynamics of the entities that are involved in the energy transformations, such as individual atmospheric eddies or biotic organisms. The *MEP* hypothesis should apply to the latter type of parameterizations. States of *MEP* may result in two different ways, depending on how the dynamics are parameterized (Figure 6).

4.3.1. *Type I:* MEP *by Optimization*

When relatively simple formulations are used, in which the dynamics are characterized essentially by one fixed parameter, *MEP* can be achieved by maximizing entropy production with respect to this parameter. Such a parameterization represents no degrees of freedom, since the one, prescribed parameter is usually not allowed to change (unless it is tuned by the optimization process to yield *MEP*). In the examples in Section 2, the dynamics of turbulence are represented by an effective conductivity parameter k (Equations (6) and (13)). Carbon uptake and respiration in Section 3 are represented by similarly simple parameterizations. *MEP* was applied to biotic carbon exchange by tuning the effective respiration coefficient ρ, which characterizes the overall respiration activity of a large number of individual, diverse organisms (see Equation (14)). The justification for conducting the optimization is that if many degrees of freedom were explicitly simulated, *MEP* should emerge from the dynamics in steady state. The use of the optimization should therefore be viewed as a convenient short-cut to represent the dynamics of a complex system with a relatively simple parameterization. There are several previous studies where similar optimization approaches have successfully been used in deriving dynamic characteristics of the biota (e.g. Cowan, 1977; Cowan and Farquhar, 1977; Loreau, 1995; Kleidon and Heimann, 1998). Cowan (1977) and Cowan and Farquhar (1977)

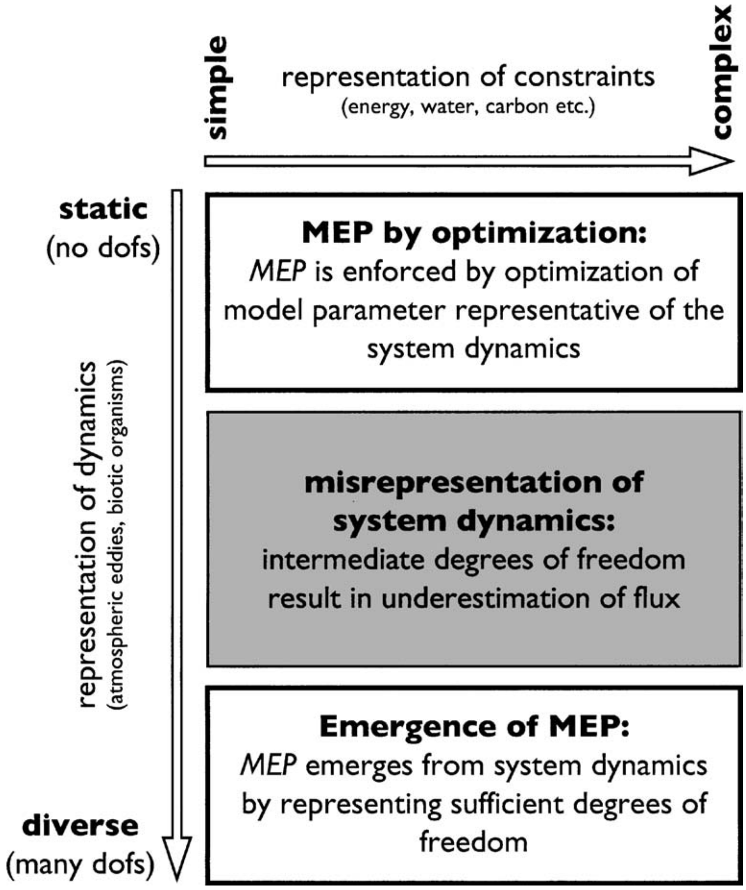


Figure 6. Conceptual diagram summarizing how states of maximum entropy production (*MEP*) should emerge from the dynamics of Earth system models. Model parameterizations can be grouped into ones representing dynamical constraints (horizontal axis, for instance formulating the energy, water and carbon balance) and the dynamics of individual entities that perform energy conversions (vertical axis, for instance individual large-scale eddies in the atmosphere, biotic organisms). If the dynamics are represented by a static, macroscopic parameterization that does not account for the individual-based nature of the dynamics (with zero degrees of freedom), states of *MEP* can be enforced by parameter optimization. If sufficient degrees of freedom are represented (e.g. spatial degrees of freedom for the atmospheric flow, functional diversity for biotic carbon exchange), *MEP* should emerge from the system dynamics. When *MEP* states are not represented, this is likely to lead to an underestimation of the flux and a misrepresentation of the dynamics. This should apply to models with any formulation of dynamic constraints, whether simple or complex. See text for further explanations.

derived functional relationships of the plant's stomata to environmental conditions from the assumption that the carbon gain for a given amount of water loss is maximized. This approach can be interpreted as the emergence of biotic *MEP* (cf. Equation (16)) associated with carbon uptake from the dynamics of a large number of individual stomata that may have diverse responses to environmental conditions.

Kleidon and Heimann (1998) used a simulation model of terrestrial productivity and derived rooting depths by maximization of biotic productivity with respect to rooting depth and subject to energy and water constraints. In their approach, the macroscopic parameter "rooting depth" usually describes the effective soil water holding capacity of a large region, representing the integration over many individual plants with possibly diverse rooting strategies. Maximization of productivity would then imply that the dynamics of many individual plants would result in a steady state of biotic *MEP*.

4.3.2. *Type II: Emergence of* MEP

When the dynamics of individuals are explicitly simulated, for instance individual large-scale eddies in the mid-latitudes in a GCM or individual plants in an individual-based model of plant communities, we should expect *MEP* to emerge from the simulated dynamics if sufficient degrees of freedom are represented. Some recent research has utilized such simulation models to demonstrate the outcome of *MEP* in steady state. Shimokawa and Ozawa (2001, 2002) included entropy production calculations into the MOM ocean GCM, that is, a model which explicitly simulates the dynamics of large-scale eddies of the ocean circulation. Shimokawa and Ozawa (2002) showed with ocean model simulations that perturbations from a steady state in the model led to less entropy production. The simulated dynamics transitioned to a *MEP* state, therefore demonstrating the overall negative feedback associated with perturbations of a *MEP* state. Kleidon et al. (2003) confirmed the existence of a *MEP* state with respect to atmospheric heat transport with a simplifed atmospheric GCM. They argued that by increasing the model's spatial resolution, more spatial degrees of freedom are provided to the atmospheric flow, so that entropy production should increase with model resolution until sufficient degrees of freedom are resolved. Model simulations confirmed this line of reasoning, that is, an increase in entropy production up to a spectral resolution of T42, beyond which entropy production remained constant with further increases in the spatial resolution. Recent advances in modeling biotic diversity with individual-based models (e.g. Downing and Zvirinsky, 2000; Kleidon and Mooney, 2000; Schwinning and Ehleringer, 2001; Pachepsky et al., 2001) would allow us to explicitly include degrees of freedom into simulation models of the biosphere. States of *MEP* in these models should then emerge from the individual-based dynamics of biological communities.

4.3.3. MEP *and Adaptation to Global Change*

If we assume that *MEP* states are representative of the steady-state of nonequilibrium systems, then reproducing these states with numerical simulation models is important for representing the current climate and the Earth system response to global change. In type I parameterizations, not representing *MEP* would simply lead to a misrepresentation of the dynamics. Depending of whether the dynamical parameter is less or greater than the optimum value would lead to either underestimating or overestimating the fluxes, implying that the process is either not "working as hard as it could" or "working harder than thermodynamically possible." This is likely to result in model errors. In type II parameterizations, not representing sufficient degrees of freedom are likely to result in an underestimation of fluxes. This was shown by GCM simulations (Kleidon et al., 2003) for the case of atmospheric heat transport. In comparison to the simulated climate representing *MEP*, all other simulated climates exhibited lower magnitudes of poleward heat transport and therefore showed a greater equator–pole temperature gradient (with important climatic consequences). A similar example can be set up for the response of the biosphere to global change: In terrestrial vegetation, the allocation of photosynthesis products to belowground and aboveground growth is associated with an important trade-off when water limits productivity: more aboveground growth leads to greater absorption of sunlight, but more belowground growth enables better capture of water. For a given mean climate, there is likely an optimum allocation strategy leading to maximum carbon uptake (i.e. a *MEP* state), and an actual community of plants with a diverse range of individual allocation strategies may represent this state. If climate changes to drier conditions, water becomes a more limiting factor for productivity, and more allocation to belowground should enhance productivity. If climate changes to wetter conditions, more light can be absorbed by enhanced allocation to aboveground, leading to enhanced productivity. In both cases, the community dynamics are likely to adjust (or, "adapt") to the change, thus resulting in increased productivity when compared to the community configuration without adjustment. In other words, both cases show that productivity would be underestimated if a type I parameterization is not adjusted to represent *MEP*. These errors result no matter how complex the representation of the system constraints are, whether for instance a bucket model is used to simulate soil moisture or a multi-layer soil diffusion model. Even though parameter optimization can lead to a *MEP* state, it would ultimately seem advantageous to explicitly simulate the degrees of freedom of the system (i.e. a type II parameterization). Such a parameterization would explicitly allow for simulating the transient response to global change while parameter optimization of a type I parameterization requires steady-state conditions. Also, certain aspects of global change, such as the loss of biodiversity and the likely reduction of biotic degrees of freedom could explicitly be accounted for. For such diverse model parameterization, the emergence of *MEP* for natural, steady-state conditions would then serve as a benchmark of whether models are sufficiently diverse in their formulation.

5. Summary and Conclusion

Practically all Earth system processes convert energy at subsequently lower temperatures, thereby producing entropy. The *MEP* hypothesis states that processes with sufficient degrees of freedom evolve to states at which the production of entropy is maximized. This hypothesis has been applied here to investigate the role of biotic effects in the production of entropy by the Earth system, such as the exchange of carbon dioxide and the partitioning of energy at the land surface. It is argued that the biota add degrees of freedom to these processes and that therefore these can be expected to evolve to states of higher entropy production. The general direction of biotic effects from this perspective is demonstrated with conceptual models and evaluations of extreme climate model simulations of a "Desert World" and a "Green Planet." One example illustrates how the contrasting effects of convective clouds and snow on the planetary albedo may result in a state of *MEP* with respect to overall absorption of solar radiation, and that the biotic influence on the global carbon cycle may play the role of a regulatory process. This particular example shows how overall homeostatic behavior, in terms of global mean temperature, may result from a state of *MEP*. The conceptual treatment of these processes clearly imposes some limitations on these results, for instance the lack of inclusion of rock weathering and the carbonate–silicate cycle in the description of the long-term carbon cycle in Section 3. Further investigations with comprehensive, process-based models would be needed to substantiate the applicability of the *MEP* hypothesis to biotic effects and Earth system functioning in general (as outlined in Section 4.3).

If we accept the validity (and applicability) of the *MEP* hypothesis and assume that the Earth's planetary albedo has a minimum with respect to global mean temperature, then there is a *MEP* state associated with absorption of solar radiation. This state would result in homeostasis "by and for the biosphere" as argued by the Gaia hypothesis. In the simple model used in Section 3, homeostasis is maintained "by" the biosphere through the addition of biotic degrees of freedom to the global carbon cycle, which allows the coupled atmosphere–biosphere system to evolve to the *MEP* state. It is maintained "for" the biosphere since the homeostatic conditions are the result of maximization of photosynthetic activity. At the state of *MEP*, the system would be dominated by negative feedbacks, as it is the case with turbulence. However, in contrast to the Gaia hypothesis, *MEP* as a physical hypothesis should have a much wider range of applicability and it should be possible to confirm it for many different diabatic processes. The interpretation proposed here also emphasizes the role of the Earth's environment, in terms of a temperature-dependent planetary albedo, for the planet's habitability in that it would allow for the addition of biotic degrees of freedom in the first place, thus making photosynthetic life a highly probable phenomenon on Earth.

The *MEP* hypothesis also has potentially important practical implications for global change research. Sufficient degrees of freedom allow systems to "adapt," that is, to evolve to new states of *MEP* when external forcing is changed. These degrees of freedom for biotic activity have been interpreted here in terms of the diversity of the Earth's biota, pointing out the fundamental importance of diversity for biotic effects and states of *MEP*. Even though comprehensive models of Earth system processes, such as coupled atmosphere–ocean general circulation models, models of terrestrial biogeochemistry, or dynamic global vegetation models may include a wealth of processes and exhibit high levels of complexity, it is not clear whether the model formulations of the dynamics allow for sufficient degrees of freedom for these systems to select states of *MEP*. If the degrees of freedom considered are not sufficient, the overall flux associated with the process is likely to be underestimated under global change. This points out potentially important limitations in the models that we use to investigate the Earth system response to global change.

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