Ecology, Economy and Society–the INSEE Journal 6(1): 53-80, January 2023

RESEARCH PAPER

Sustaining the Terrestrial Biosphere in the Anthropocene: A Thermodynamic Earth System Perspective

Axel Kleidon*

Abstract: Many aspects of anthropogenic global change, such as shifts in land cover, the loss of biodiversity, and the intensification of agricultural production, threaten the natural biosphere. The implications of these specific aspects of environmental change are not immediately obvious; therefore, it is hard to obtain a bigger picture of what these changes imply and distinguish the beneficial from the detrimental, where human impact is concerned. In this paper, I describe a holistic approach that allows us to obtain such a bigger picture and use it to understand how the terrestrial biosphere can be sustained in the presence of increased human activity. This approach places particular emphasis on the free energy generated by photosynthesis—energy that is required to sustain both the dissipative metabolic activity of ecosystems and human activities (with the generation rate being restricted by the physical constraints of the environment). Thus, one can then identify two types of human influence on the biosphere and their resulting consequences: the detrimental effects caused by enhanced human consumption of this free energy and the beneficial effects that allow for more photosynthetic activity and, therefore, more dissipative activity within the biosphere. I use examples from the terrestrial biosphere to illustrate this view and global datasets to indicate how this can be quantified. Thereafter, I discuss how certain aspects of modern technology can enhance free energy generation within the terrestrial biosphere, which can, in turn, safeguard its sustenance even as human activity increasingly shapes the functioning of the Earth system.

Keywords: Global change, Sustainability, Maximum power, Exergy, Planetary boundaries

1. SUSTAINABLE ENERGY AS THE CORE PROBLEM OF THE ANTHROPOCENE

---

* Max-Planck-Institut für Biogeochemie, Hans-Knöll-Str. 10, 07745 Jena, Germany, akleidon@bgc-jena.mpg.de

Published by Indian Society for Ecological Economics (INSEE), c/o Institute of Economic Growth, University Enclave, North Campus, Delhi 110007.

ISSN: 2581–6152 (print); 2581–6101 (web).

DOI: https://doi.org/10.37773/ees.v6i1.915

Energy is at the core of many aspects of global change we currently face, including those that challenge the functioning of the biosphere. What I aim to show here is that a focus on energy and how it is variously transformed within the Earth system helps us to get a clearer, bigger picture of how current human activity inevitably results in a diminished biosphere. However, using certain forms of technology, we can make informed choices that will contribute to supporting and sustaining the natural biosphere as human activities increasingly shape planetary functioning.

Let us first look at how current global changes are related to energy with the help of a few examples. An obvious place to start is with global climate change or global warming. The increased consumption of fossil fuels directly relates to the increased energy needs that human societies have to fuel their socioeconomic activities. The inevitable consequence of this is increased greenhouse gas concentrations within the atmosphere, which consequently causes the climate to change. Thus, increased human energy consumption has a direct connection to global warming.

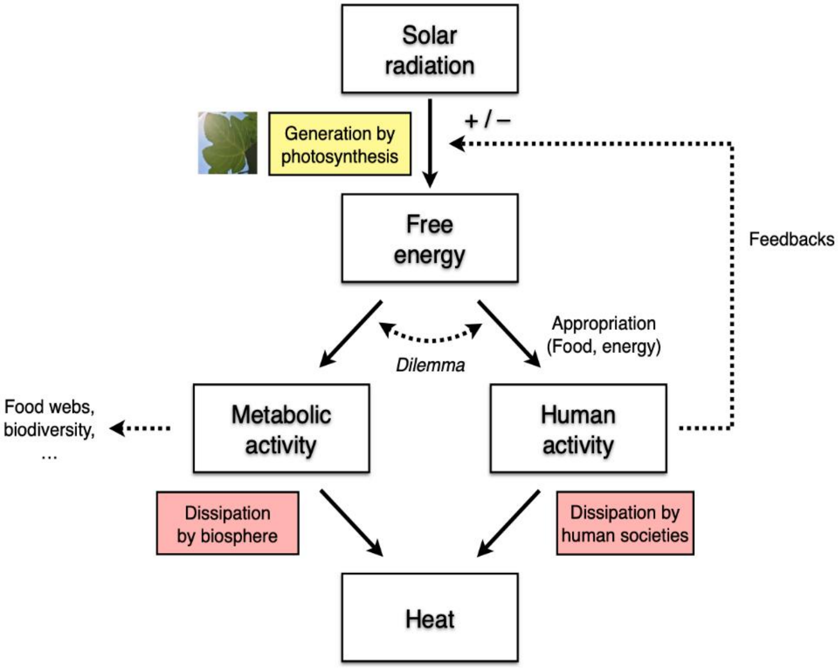
The link is not as obvious when we look at tropical deforestation as another example. Tropical deforestation is mainly caused by the conversion of natural forests into pastures and croplands. This conversion aims at producing more food, which relates to calories that human metabolism needs for sustenance. Thus, an expansion of agricultural area relates to an increase in food production, which is equivalent to the energy stored in chemical compounds in food. Thus, tropical deforestation can also be linked directly to increased human energy needs.

The loss of biodiversity is the last example I would like to examine. While many factors are considered detrimental to biodiversity (IPBES 2019), such as land cover shifts, habitat destruction, and intensified agriculture, energy is a central factor at play. Each organism needs chemical energy to sustain its metabolism, and this energy comes from photosynthesis. Several hypotheses explain biodiversity patterns in terms of energy (for example, reviews by Currie *et al.* 2004 and Clarke and Gaston 2006). In essence, these hypotheses start by recognizing that tropical regions have more energy available due to their higher productivity. Sunlight and water are abundantly available throughout the year, resulting in high sustained rates of photosynthesis by terrestrial ecosystems. This higher rate of photosynthesis generates more free energy, allowing tropical ecosystems to sustain the metabolisms of more organisms, and, thus, higher diversity levels, which is reflected, for instance, in greater species richness. Therefore, when humans convert and use land more intensively for food production, there is less energy available for the metabolic activities of the natural biosphere. Hence, the loss of biodiversity with increased and intensified land use also seems to be a direct consequence of greater human energy demands.

These examples illustrate a general dilemma resulting from human activity. As human activity increasingly appropriates energy from the biosphere, less energy remains for the sustenance of the natural biosphere (Figure 1). A key element of this dilemma is that the biosphere's productivity has natural limits set by the environment. This, in turn, sets limits to the sustainable growth of human societies, as described in detail in the seminal work *The Limits to Growth* by Meadows *et al.* (1972). When human societies grow and develop, and increasingly appropriate their energy from the biosphere, this inevitably results in a deteriorated energy supply for the natural biosphere, thus posing a serious threat.

I propose a general approach to understand how this deterioration of the natural biosphere can be avoided by decoupling an increase in energy consumption by human societies from a proportional decrease for the rest of the biosphere. To do so, we need to evaluate how technology can be used to enhance photosynthesis beyond its natural limits, thus ensuring that a larger amount of energy would be available for use by human societies without compromising on the share available to the natural biosphere (marked in Figure 1 as 'Feedback'). Such technologies have been used in the past. Irrigation-based agricultural techniques (using river water or manmade reservoirs) have been in use for thousands of years to enhance agricultural productivity. The river Nile in Egypt is a good example of this. Diversion makes water available for terrestrial productivity that cannot be achieved by natural means, that is, without the technology associated with building dams and irrigation channels. In the future, technologies may be used to accomplish this task with a much greater impact, particularly, by using methods related to seawater desalination and photovoltaics. Seawater desalination by membranes is a more efficient means of desalination than the natural hydrologic cycle of evaporation and subsequent precipitation. Similarly, photovoltaics is much more efficient than natural photosynthesis for energy generation. These technologies can decouple the energy and water needs of human societies from natural systems and simultaneously provide an immense boost to energy availability for human societies. This would then allow for a large amount of naturally generated energy to be available to sustain the natural biosphere, potentially resulting in positive feedback (as indicated by the dotted line in Figure 1).

Figure 1: A Basic Dilemma Emerges from How the Energy Generated by Photosynthesis Is Being Used to Sustain Nature or Human Societies



Source: Author

To substantiate this approach and its implications for a more optimistic, sustainable future, it is necessary to clarify the use of the term "energy". The focus here is on free energy—energy generated by work that can perform further work. Examples of free energy include the kinetic energy of atmospheric winds and river currents as well as the chemical energy stored in the molecular bonds of carbohydrates. Other examples include power generated by transforming the chemical energy in fossil fuels into electricity in power plants or transforming solar energy into electrical energy using photovoltaics. The energy that human societies need for food and various other activities, as indeed does the rest of the biosphere, is free energy. Therefore, we need to understand how free energy is generated by the Earth system by transforming energy received by the sun and how technological innovations can help us perform this very same task with a higher degree of efficiency.

This paper is accordingly structured as follows. In the next section (Section 2), I will start by describing how free energy is generated in general from solar forcing. In Section 3, I then describe how photosynthesis generates free energy from sunlight and provide an explanation as to why it has such a low degree of efficiency. This proposition is substantiated using maps derived from a simple physical description of this limitation, which can be used to provide first-order estimates of the magnitude of free energy generation by the natural, terrestrial biosphere. In Section 4, I will use an example to illustrate how the biosphere has the means to push its physical limits to higher levels, thereby altering environmental conditions such that they are more conducive to performing photosynthesis and, thus, generating more energy to fuel greater activity. This example can substantiate the notion that natural systems have a tendency to push their physical limits, which is very likely a general feature of an evolving thermodynamic system that may also apply to human systems. In Section 5, I will describe the rate of energy consumption by human societies and estimate the level of damage the terrestrial biosphere has suffered as a result of human activities. These estimates exemplify how important human activity has become as an Earth system process in quantitative, physical terms. I will then provide a few examples in Section 6 examining how manmade technologies can meet the demands of human energy consumption and, at the same time, sustain or enhance the activity of the natural biosphere. I will close with a summary and conclusions.

2. HOW TO GENERATE FREE ENERGY FROM SOLAR FORCING

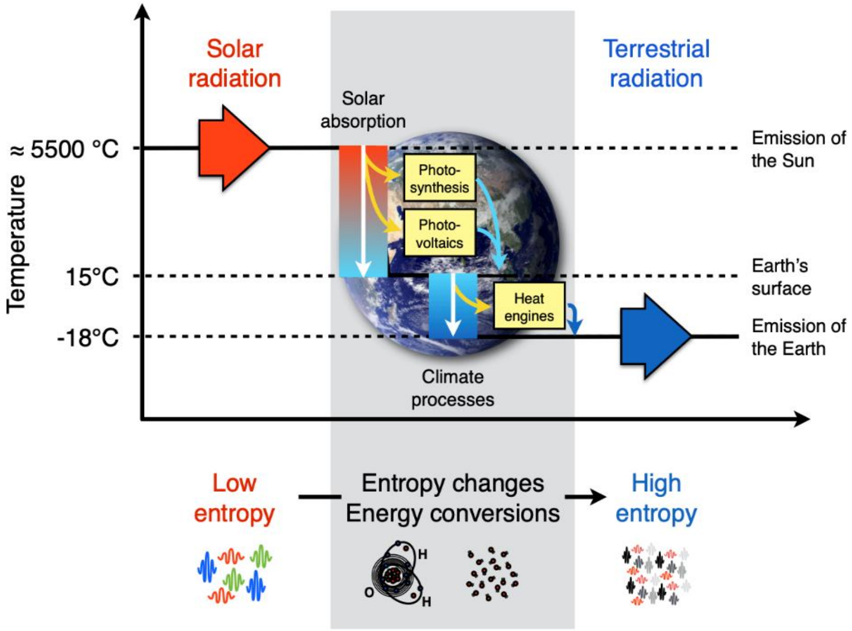
Before I describe how photosynthesis generates free energy, it is important to define this term briefly, to explain what makes it so different from "just" energy and to understand how Earth system processes generate it. Free energy is simply energy without entropy, capable of performing work, resulting in so-called dissipative dynamics. It is sometimes referred to as "exergy" (for example, in Hermann 2006). The kinetic energy associated with atmospheric motion is an example of free energy, which is dissipated by friction (that is, converted into heat), as is the chemical energy stored in carbohydrates and biomass, which is dissipated by metabolisms or by combustion. Free energy plays a central role in the dynamics of the Earth system, driving the physical dynamics that shape climate, biospheric dynamics with their associated food chains, as well as socioeconomic dynamics. These dynamics are driven by the dissipation (or consumption) of this free energy, forming dissipative systems that are thermodynamically very different from those in thermodynamic equilibrium.

To understand how free energy is generated from solar forcing, we need to look at entropy—a key aspect of energy. Entropy was introduced empirically with the growing popularity of steam engines in the nineteenth century, to describe how much work could be derived from a heat source. The concept received a physical interpretation due to the work of Boltzmann in the late nineteenth century; Planck subsequently extended this theory to apply it to the treatment of radiation, together with the notion that energy at the atomic scale came in discrete amounts called "quanta". This set the foundation for the revolution of quantum physics in the early twentieth century. In modern physics, entropy plays a key role in describing many facets of the quantum world of atoms and molecules in terms of comparatively simple, macroscopic characteristics that describe how energy is stored and converted by solids, liquids, and gases.

As stated, at the microscopic atomic scale, energy comes in discrete amounts called quanta. Energy as radiation is in the form of photons distributed across different wavelengths, and energy in chemical bonds represents the discrete distribution of electrons across different atomic shells, while heat refers to the random motion, vibrations, or rotations of molecules. All these microscopic aspects are represented by discrete amounts of energy being distributed over a finite number of states. They can thus be counted and assigned probabilities as to certain ways of distributing these quanta of energy across states. At the macroscopic scale, however, we are typically not interested in these details. Then, we can assume that a given amount of energy is distributed in the most probable way. This is measured by entropy, as expressed by Boltzmann's famous equation, $S = k \log W$, where S represents entropy, k is a constant, and W is the number of possible ways to distribute energy. The assumption of the most probable distribution represents a maximum in entropy and is referred to as the so-called thermodynamic equilibrium. Since, at the microscopic scale, energy is distributed across photons, electrons, and molecules, we have three forms of entropy that are important to Earth system science: radiative, molar, and thermal entropy.

Systems become interesting when they are not in equilibrium, and this brings us to the concept of free energy. For disequilibrium to occur, we need to have differences in entropy. Here, the second law of thermodynamics applies, requiring that whatever will happen, it needs to yield an overall increase in entropy. For the Earth system, the major driver for disequilibrium is the difference in the kind of radiation that the Earth receives and emits to space (Figure 2). At the planetary scale, energy fluxes are roughly balanced such that about as much solar radiation enters the Earth system as is reflected and emitted to space. But these energy fluxes differ vastly in their radiative entropies. Solar radiation is emitted from the sun at a very high emission temperature of about 5500°C, which results in radiation with short wavelengths, mostly in the visible range, comparatively few photons of high energy, and very low radiative entropy when this radiation reaches the Earth's orbit. After absorption and further transformation, the Earth emits this energy as terrestrial radiation at a much lower radiative temperature of about -18°C. This radiation is represented by infrared wavelengths, many more photons of lesser energy, and thus has a much higher level of entropy. This results in a massive thermodynamic disequilibrium between the solar radiation the Earth receives and the radiation the Earth emits.

Figure 2: Planetary Energy Conversions on Earth Are Driven by the Difference in Entropy between Solar and Emitted Radiation



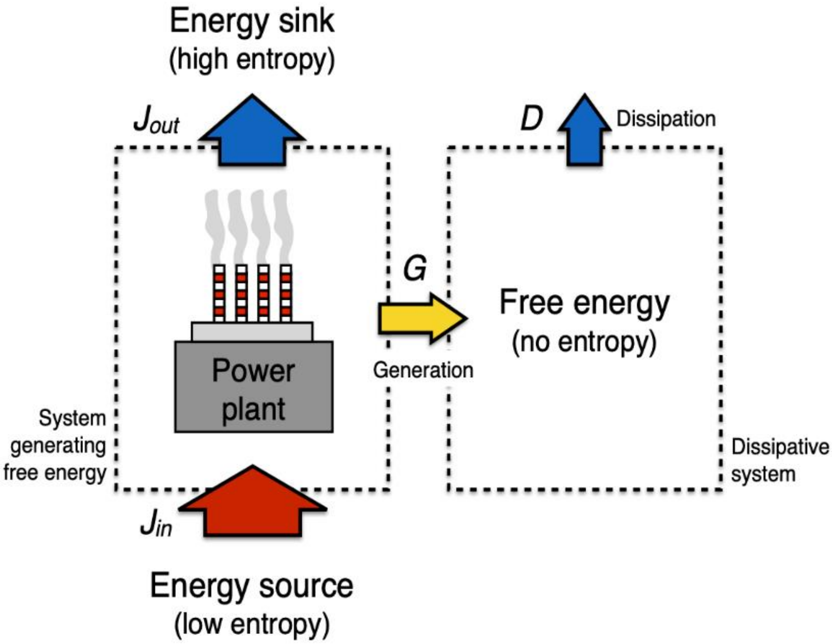
Source: Author

The simplest way to destroy this disequilibrium is to absorb and re-emit radiation at a lower temperature. This increases the level of entropy yet does not drive dissipative dynamics. More relevant are the cases in which this disequilibrium is used to generate free energy. There are various mechanisms by which this can be accomplished (yellow boxes in Figure 2); yet, the rules for these mechanisms are the same and are set by the laws of thermodynamics.

The physical mechanism to generate free energy can be illustrated by a conventional power plant (Figure 3). Heat is generated by fuel combustion at a high temperature, yielding heat at a low entropy level. That it has a low entropy level can be seen by Clausius' expression, which defines a change in entropy as $\Delta S = \Delta Q/T$, with ΔQ being the heat added or removed and T being the temperature (in units of Kelvin) at which heat is exchanged. Since combustion occurs at a high temperature, the added level of entropy to the power plant is comparatively small. The steam released by the cooling towers expels some of that heat from the power plant but at much colder temperatures, thus exporting heat with a much higher level of entropy. To fulfil the second law of thermodynamics, at least as much entropy must be released from the cooling towers as is added by combustion. When these entropy fluxes balance each other, with entropy entering the power plant at the same rate as entropy exiting through the cooling towers, this yields the upper limit on how much energy without entropy can be generated—free energy. This limit is known as the Carnot limit. It limits how much work can best be performed and how much electricity—free energy in electric form—can best be generated by the power plant.

The physical Earth system operates much like such a power plant. The heat source is the absorption of solar radiation at the surface (as opposed to being released by combustion) and the emission of radiation from the atmosphere serves as a cooling tower that exports entropy from the Earth system to space in the form of radiation. The work done is that of generating motion, whether in the form of buoyancy, driving vertical convective motions, or horizontally, in the form of regional circulations (such as a sea breeze system), even large-scale circulations (such as the Hadley circulation), or mid-latitude winds. Comparison to observations indicates that atmospheric motion operates at this thermodynamic limit, working as hard as it can (Kleidon 2021a). This maximization of power is reflected in characteristic surface energy balance partitioning, temperature patterns, and evaporation rates that fit very well with observations (Kleidon 2021b).

Figure 3: Free Energy Generation by a Power Plant and Its Subsequent Dissipation by a Dissipative System[1]



Source: Author.

This motion then drives other physical processes, such as the generation of waves over the ocean, hydrologic cycling, and the production of renewable wind energy. Or, it is dissipated back into heat via friction. The work involved is, however, relatively small and the conversion has low efficiency. This is because only differences in radiative heating and cooling serve as a heat source and the temperature differences are relatively smaller when compared to that of a power plant. This amounts to an overall low conversion efficiency of less than 1% of the incoming solar radiation, which is converted to free energy as kinetic energy.

This low conversion efficiency for physical Earth system processes is inevitable. Once solar radiation is absorbed by the Earth's surface and converted into heat, most of its low entropy is already lost because the Earth's surface

---

[1] Illustration of free energy generation using a power plant as an example (as seen in the box on the left). The same thermodynamic rules also apply to energy conversions within the Earth system. Once free energy is generated, it drives the dynamics of dissipative systems (as seen in the box on the right).

is at a much colder temperature than the emission temperature of the sun. Absorption thus turns solar radiation into the heat of relatively high entropy. The temperature differences when converting this energy further are thus set by the difference between the Earth's surface temperature and the Earth's radiative temperature (for vertical motion) or the difference in temperatures between the tropics and polar regions (for horizontal motion). This difference is relatively small (about 33 K) and yields a low conversion efficiency.

Thus, to enhance the conversion efficiency of solar radiation into free energy, certain mechanisms are necessary to circumvent the intermediate step of conversion into heat. Two such alternatives are shown in Figure 2 (in the yellow boxes): photosynthesis and photovoltaics. I will now turn to photosynthesis, as this is the process by which free energy is generated from sunlight for dissipative activities within the biosphere.

3. ENERGY GENERATION BY THE NATURAL BIOSPHERE AND ITS PHYSICAL LIMITS

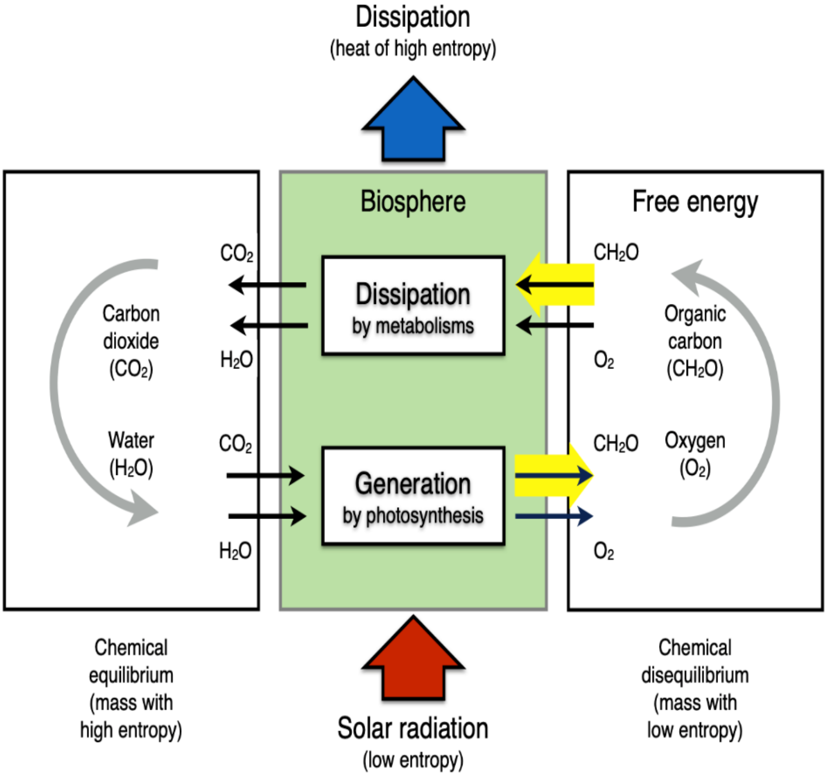
To evaluate the biosphere's capacity for converting solar energy into chemical energy using this thermodynamic approach, the key question is how and how much free energy can be generated by photosynthesis, which then constrains the level of metabolic activity within the biosphere. Photosynthesis is generally described as a chemical conversion process that converts carbon dioxide and water into carbohydrates and oxygen, using solar radiation as the energy source. The resulting carbohydrates then contain about 40 kJ of chemical free energy per gram of carbon. This energy feeds the metabolic activities of producers—known as autotrophic respiration—as well as those of living organisms—or heterotrophic respiration—which make up the biosphere (Figure 4). This metabolic activity uses the chemical free energy contained in the organic carbon compounds generated by photosynthesis as well as oxygen and dissipates this free energy back as heat, thereby producing entropy. While this examination of photosynthesis does not tell us how and how many organisms are being fed by this chemical free energy, its generation nevertheless creates thermodynamic disequilibrium (in the form of reduced organic carbon compounds and atmospheric oxygen) and it sets a limit for dissipative activities within the biosphere. Thus, we will first look at the energy conversions involved in photosynthesis in somewhat greater detail, estimate their conversion efficiencies, and evaluate whether these operate at their thermodynamic limit, just as atmospheric motion does in the climate system.

The first step of photosynthesis involves light reactions in photosystems during which light is absorbed. Here, light does not turn into heat—the random motion of molecules—but instead performs photochemistry as it splits water into its compounds and further splits hydrogen into its negatively charged electron and its positively charged nucleus. In other words, the photosystems perform the work of charge separation, generating electricfree energy. Photosynthesis requires about 8–10 quanta of light of wavelengths of about 700 nm to split the hydrogen atoms involved in binding one molecule of carbon, as described by the well-established concept of quantum yield efficiency (Emerson 1958). These quanta carry about 1.8 eV of energy each, with 1 eV = 1.6×10^{-19} J being a unit of energy at the quantum scale and the amount calculated by $h\ c\ /\ \lambda$, with $h \approx 6.63 \times 10^{-34}$ J being the Planck constant, $c \approx 3 \times 10^{8}$ m s^{-1} the speed of light, and $\lambda = 700 \times 10^{-9}$ m being the wavelength of the photon. Taken together, this yields energy from absorbed radiation of about 14.4–18 eV. For comparison, this amount is slightly more than the bare minimum of 13.6 eV, which is needed to perform the work of charge separation of the hydrogen atom. On a mol basis, photosynthesis uses at least $N_a \times 14.4$ eV = 1387 kJ mol^{-1} to split one mol of water, with N_a being the Avogadro constant, $N_a = 6.022 \times 10^{23}$ mol^{-1}. Hence, this first step is highly efficient, with a conversion efficiency of about 76–94%.

The generated electric energy is then incorporated into longer-lived chemical compounds, like NADP and ATP, before these are used (as per the Calvin cycle) to convert this energy further and store it in the form of carbohydrates. This requires carbon dioxide, which needs to be taken in from the surrounding air. This particular step is far less efficient. Using the 1,387 kJ of energy from the absorbed photons, this cycle produces one mol of carbon in the form of glucose with an energy content of merely 480 kJ. This corresponds to an overall conversion efficiency (from radiative to chemical energy) of 480 kJ/1387 kJ = 34%. Laboratory measurements in low-light conditions have found that plants operate close to this efficiency (Hill and Rich 1983). When we consider that photosynthesis can only utilize about 55% of the solar spectrum (photosynthetically active radiation or PAR), the efficiency of carbon fixation is reduced to less than 19% for converting the energy contained in sunlight into carbohydrates.

However, observations from terrestrial ecosystems indicate that, in general, the efficiency of photosynthetic carbon uptake is substantially lower than this efficiency, with values typically falling under the 3% mark (Monteith 1972, 1977; Kleidon 2021b). This much lower efficiency can be attributed to the restrictive role of the gas exchange associated with carbon and water between the vegetation canopy and the surrounding air (Kleidon 2021b). Vegetation needs to take in carbon dioxide from the air, and while doing so, it inadvertently loses water vapour. This gas exchange with the atmosphere occurs at a relatively fixed ratio of about 2 grams of carbon taken in for each kg of water evaporated—the water use efficiency (Law *et al.* 2002). It can be inferred that when we want to identify the primary limitation for photosynthesis, and thus for the free energy generation within the biosphere, we need to understand what limits the gas exchange between the surface and the atmosphere or the closely associated rate of evaporation.

Figure 4: Generation and Dissipation of Free Energy by the Biosphere and Its Relation to Chemical Disequilibrium



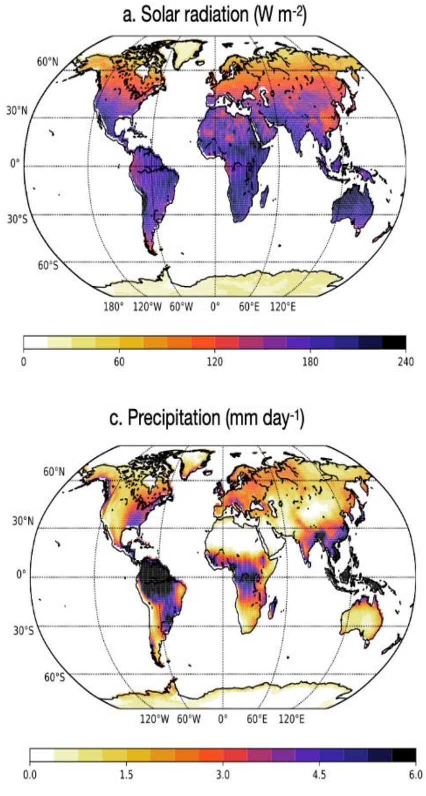
Source: Author

This brings us back to the restrictive role of thermodynamics, not in terms of the energy conversion from sunlight to carbohydrate but in terms of how motion is generated, which simultaneously sustains the gas exchange to supply vegetation with the carbon dioxide it needs to assimilate and allows vegetation to evaporate water into the atmosphere. This evaporation rate from the surface to the atmosphere is strongly controlled by thermodynamics when water is sufficiently available and this control enters twice in the process. First, when solar radiation heats the surface, it generates buoyancy and vertical, convective motion. The more updrafts develop, the greater the quantity of heat and moisture taken from the surface into the atmosphere and carbon dioxide is replenished near the surface. With stronger updrafts, however, the surface is cooled more efficiently. This leads to a maximum power limit, as in the case of large–scale motion, determining the magnitude of turbulent fluxes at the surface. The second instance where thermodynamics acts as a constraint is in the partitioning of the absorbed radiation into heating and moistening the near-surface air. At thermodynamic equilibrium, this sets up a partition between the sensible and latent heat fluxes, known in micrometeorology as equilibrium partitioning. The fluxes drawn from these thermodynamic constraints fit very well with observations (Kleidon *et al* 2014; Conte *et al* 2019). This implies that thermodynamics imposes a major constraint on the biosphere through the gas exchange of water vapour and, thus, for carbon dioxide, limiting the rate at which the terrestrial biosphere can use the absorbed solar energy in photosynthesis to generate chemical-free energy.

I illustrate this reasoning with data from continental-scale estimates of the energy balance and the water and carbon cycles (Stephens *et al* 2012; Oki and Kanae 2006; Beer *et al* 2010) and then go into greater detail using global radiation and precipitation datasets (Loeb *et al.* 2018; Kato *et al* 2018; Adler *et al* 2016), as in Kleidon (2021b). Continental evaporation is estimated to be about 66 x 10^{12} m^3/a (Oki and Kanae 2006). If we assume that the majority of evaporation takes place through the vegetative cover and apply the mean water use efficiency as 2 gC/kg H_2O, we obtain a gross photosynthetic uptake of 131 x 10^{15} gC/a. This estimate corresponds with the estimate of 123 x 10^{15} gC/a by Beer *et al* (2010). Bearing in mind that each gram of carbon contains about 40 kJ of energy in the form of carbohydrates, this corresponds to a power of 152 x 10^{12} W. When we then divide this power by the 165 W m^{-2} of energy absorbed as solar radiation at the surface (Stephens *et al* 2012) and the land area (29% of 511 x 10^{12} m^2), we obtain a mean efficiency of 0.6% of the photosynthetic land carbon uptake. This confirms the very low efficiency by which the biosphere generates free energy from sunlight, as mentioned earlier.

This estimate is, of course, very rough, as it neglects, for example, variations in water availability across regions. These drawbacks can be seen when this analysis is conducted spatially using global datasets. Such an analysis is represented in Figure 5 using annual means, as in Kleidon (2021b) and as summarized in Table 1. This estimate uses the absorbed solar radiation at the surface (Figure 5a) from the CERES global radiation dataset (Loeb *et al* 2018; Kato *et al* 2018) as the starting point, estimates evaporation from the maximum power limit without water limitation (the so-called potential evaporation rate, as seen in Figure 5b) and uses the mean precipitation rate (Figure 5c) taken from the GPCP dataset (Adler *et al.* 2016) to restrict evaporation in the presence of water availability, thus yielding the so-called actual evaporation rate (Figure 5d).

Figure 5: Maps of (a) Mean Annual Solar Radiation, (b) Potential Evaporation, (c) Precipitation, and (d) Actual Evaporation Estimated by the Maximum Power Limit and Water Availability



a. Solar radiation (W m^{-2})

b. Potential evaporation (mm day^{-1})

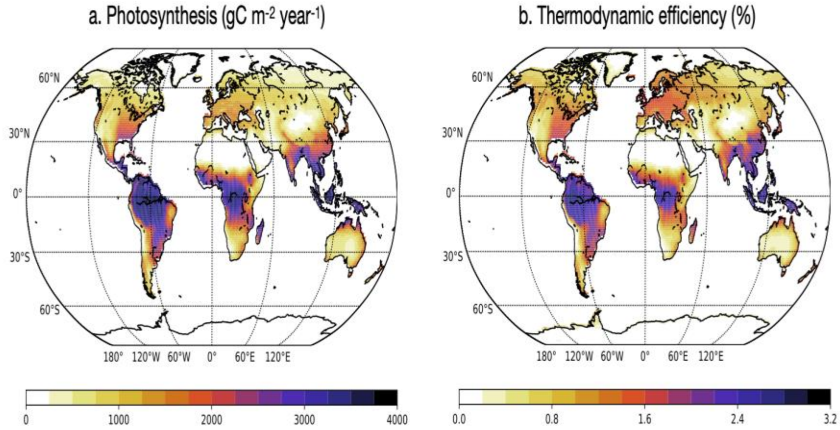
c. Precipitation (mm day^{-1})

d. Evaporation (mm day^{-1})

Source: Author

Applying the observed mean water use efficiency value to the thermodynamically–derived evaporation rate then yields an estimate for the photosynthetic carbon uptake and its associated thermodynamic conversion efficiency (Figure 6). We can see that there are clear variations in efficiency among regions, with humid regions indicating a greater efficiency of up to 3%, while desert regions have no marked productivity due to the lack of water there. This supports the well–established notion that water availability is a major issue for the terrestrial biosphere, shaping the spatiotemporal patterns of its productivity. What this estimate implies is that the limits set by gas exchange and water availability can clearly explain the observed patterns of carbon uptake in the terrestrial biosphere.

Figure 6: Maps of (a) Mean Annual Photosynthetic Carbon Uptake and (b) Thermodynamic Efficiency Estimated from the Evaporation Rate Shown in Figure 5



Source: See Footnote[2]

To conclude this discussion on free energy generation by the terrestrial biosphere, it should be noted that thermodynamics does not act directly to limit energy conversions from sunlight to carbohydrates. After all, photosystems are highly efficient when it comes to the first step to converting solar energy. It would seem, then, that it is the rate of gas exchange that limits photosynthetic carbon uptake, as it provides the necessary supply of carbon dioxide from the surrounding air. This interpretation can explain the very low efficiency in observed photosynthetic carbon uptake rates within natural ecosystems. It represents an indirect thermodynamic constraint that requires an Earth system view, which describes biosphere productivity as a process that is intimately linked to, and constrained by, physical transport processes within the Earth's environment.

---

[2] After Kleidon (2021b), uptake (via photosynthesis) of terrestrial vegetation is estimated from constant water use efficiency and the thermodynamically constrained evaporation rate as shown in Figure 5(b). The thermodynamic efficiency with regard to converting absorbed solar radiation into chemical free energy is based on Kleidon (2021b).

Table 1: Summary of Annual Mean Estimates of Energy-, Water-, and Carbon Fluxes Described in the Text

Natural limits of terrestrial productivity		
Absorbed solar radiation	141 W/m^2 20,726 TW	Calculated directly from CERES (Loeb *et al* 2018; Kato *et al* 2018). Shown in Figure 5a.
Potential evaporation	2.84 mm/day 153 x 10^3 km^3/year 12,091 TW	Calculated from the maximum power limit and thermodynamic equilibrium partitioning using CERES forcing.
Precipitation	2.18 mm/day 117 x 10^3 km^3/year	Calculated directly from GPCP (Adler *et al* 2016).
Evaporation	1.65 mm/day 88 x 10^3 km^3/year 7,015 TW	Calculated by gauging the minimum of potential evaporation and precipitation at the annual scale. Shown in Figure 5d. Compare to the observed estimate of 66 x 10^3 km^3/year (Oki and Kanae 2006).
Gross primary productivity (Net photosynthesis)	405 gC/m^2/year 177 GtC/year 224 TW	Calculated by converting evaporation to carbon uptake with a fixed water use efficiency of 2 gC/kg H_2O. Shown in Figure 6a. Compare to the observed estimate of 120 GtC/year (Beer *et al* 2010).
Net primary productivity (Biomass production)	202 gC/m^2/year 89 GtC/year 112 TW	50% dissipation by autotrophic respiration by plants.
Pushing the limits using seasonal soil water storage		
Evaporation without seasonal water storage	1.47 mm/day 79 x 10^3 km^3/year 6244 TW	Calculated by presupposing that monthly evaporation is the minimum of potential evaporation and precipitation (i.e., no seasonal water storage).
Enhancement by vegetation	0.18 mm/day +12% 9 x 10^3 km^3/year 711 TW	Calculated by presupposing that evaporation is the minimum of potential evaporation and precipitation at the annual scale (i.e., seasonal water deficits are compensated by water storage variations within the rooting zone).

Enhancement of net primary productivity	25 gC/m^2/year +12% 10 GtC/year 12 TW	Converted with a fixed water use efficiency of 2 gC/kg H_2O.
Human appropriation of productivity		
Absorbed solar radiation	111 W/m^2 5,449 TW	The weighted average over the cropland and pastures as shown in Figure 7.
Evaporation	1.38 mm/day 24.8 x 10^3 km^3/year 1,963 TW	The weighted average over the cropland and pastures as shown in Figure 7.
Net primary productivity	503 gC/m^2/year 25 GtC/year 31 TW	Calculated by converting evaporation to carbon uptake with a fixed water use efficiency of 2 gC/kg H_2O. Reduced by 50% dissipation via autotrophic respiration by plants.
Pushing limits using technology		
Runoff potentially available for irrigation and additional evaporation	0.53 mm/day 29 x 10^3 km^3/year +32%	Difference between current climatological precipitation and evaporation on land.
Enhancement of terrestrial net primary productivity	193 gC/m^2/year 28 GtC/year 36 TW +32%	Calculated by converting evaporation to carbon uptake with a fixed water use efficiency of 2 gC/kg H_2O. Reduced by 50% dissipation via autotrophic respiration by plants.
Area needed for photovoltaics to generate current human primary energy demand of 18 TW	550 000 km^2	Calculated using the global mean absorption of solar radiation of 165 W m^{-2} and photovoltaic efficiency of 20%.

Area needed for generating as much freshwater by seawater desalination as is currently in continental runoff	177 000 km^2	Calculated using an energy demand of 4 kJ per litre of desalination using membrane technology and energy generation by photovoltaics, using 165 W m^{-2} and an efficiency of 20%.

Source: Author

4. THE BIOSPHERE PUSHES ITS LIMITS

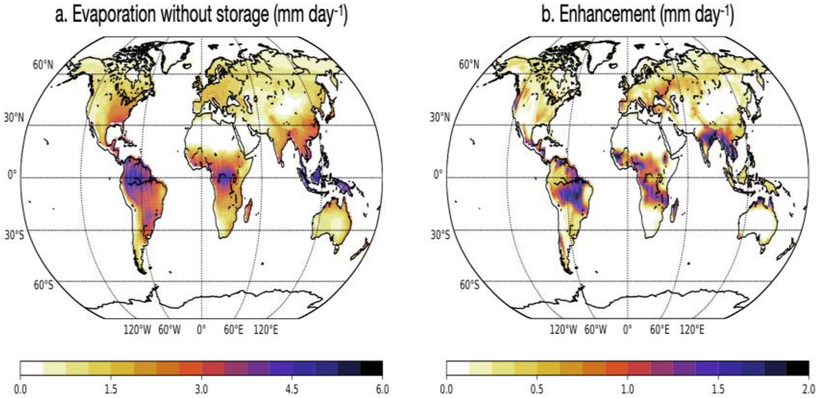
While these constraints limit the activity of the terrestrial biosphere, the latter nevertheless acts and affects the environment in such a way that pushes these limits further to achieve higher levels of activity. The means and mechanisms employed are different compared to the atmospheric heat engines described above. This relates to the effects biotic activity has on the environment and the consequences of these for the conditions required to generate and dissipate free energy. The overall dynamics surrounding the concept of "pushing the limit" appear to reflect, nevertheless, the same underlying evolutionary dynamics as the physical dynamics of the climate system: to maximize power and dissipation.

To illustrate this push, I will take the example of the depths of the rooting zone of vegetation and its effects. As plants grow, they allocate some of their energy to growing rooting systems in the soil. A deeper rooting zone allows them to access a greater amount of the water stored in the soil for evaporation, particularly during dry periods. These periods are characterized by potential evaporation exceeding the rate of precipitation. Water stored within the soil can be used to compensate for this lack of precipitation input, allowing vegetation to maintain evaporation during such periods.

By building root systems and enhancing soil water storage, the biosphere benefits by elongating the period over which gas exchange can be maintained and productivity sustained. It thus makes the biosphere more productive. However, this enhancement is not infinite but limited by the climatological water balance. In humid regions with dry periods, vegetation needs only to store the water required to overcome the water deficit during the dry season. In arid regions, vegetation cannot store more water than the water surplus during the wet season. The required water storage volume needed for this seasonal compensation reproduces the observed rooting depths in different vegetation types quite well (Kleidon and Heimann 1998). Figure 7 illustrates these considerations, using monthly mean fields of precipitation and the thermodynamically–constrained evaporation estimate to infer the actual evaporation rate in the absence of seasonal water storage and its enhancement through soil water storage facilitated by root systems. This effect of rooting systems enhances terrestrial carbon uptake by roughly 10% (Table 1), increasing the power and dissipative activity of the terrestrial biosphere.

Other biotic effects can act similarly to enhance terrestrial productivity. Vegetated surfaces are typically darker (they have a lower surface albedo) than bare ground, enhancing surface heating as a driver for gas exchange, an aspect that has not been considered here. The highly heterogeneous canopies of forested surfaces represent a much greater leaf surface area, which facilitates a higher rate of gas exchange. Stomates, small openings in the leaves which regulate gas exchange, can vary in size and number and operate to maximize the carbon gain while water is evaporated by the leaves (Cowan and Farquhar 1977; Medlyn *et al* 2011). This means enhancing productivity comes with environmental consequences, such as enhanced moisture recycling on land. On longer time scales, the activity of the biosphere has profoundly altered the atmospheric composition and the strength of the greenhouse effect, changing the planetary disequilibrium state and energy fuels for the biosphere (Judson 2017). These effects all influence the physical environment and provide means to maximize free energy generation further, resulting in environmental conditions that sustain the current high (possibly even maximized) levels of biotic activity on the planet. Even though the means by which the biosphere would achieve this maximization are very different from physical heat engines, the outcome would be the same: to maximize free energy generation and its dissipation.

Figure 7: Effects of deep-rooted vegetation on evaporation and associated gas exchange as an example of how the biosphere pushes its limits



Source: Author

5. HUMAN SOCIETIES AS ADDITIONAL ENERGY DISSIPATION PROCESSES

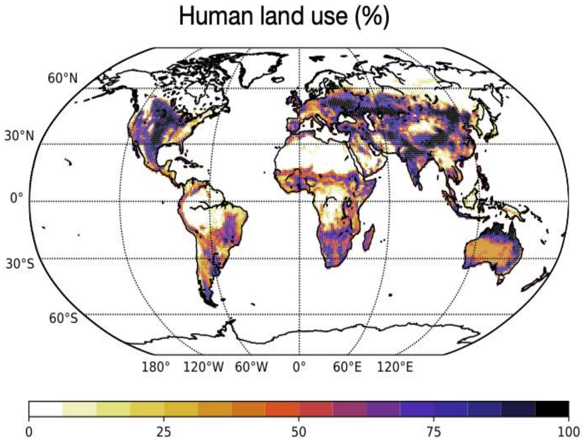
Let us now turn to human activity as a thermodynamic Earth system process. To do so, we must start with the consumption of free energy, which is at the very core of human existence as well as our socioeconomic activities. Humans need energy to sustain their metabolism, just like any other living organism. This energy comes in the form of the food we eat as reflected in the calories that food contains (1 cal = 4.184 J). As this energy is consumed by metabolic activity, it converts the chemicalfree energy associated with the disequilibrium of carbohydrates and oxygen back into carbon dioxide, water, and heat. Likewise, human societies consume free energy mostly in the form of chemical energy stored in fossil fuels. Upon combustion, this free energy is converted into heat and subsequently into work, for example, by generating motion, electricity, or transforming materials. Thus, primary energy consumption correlates strongly to economic activity (e.g., Cleveland *et al* 1984; Ayres and Nair 1984). Viewing human activity primarily through the lens of energy allows us to describe it as a dissipative Earth system process and place it into the same thermodynamic framework we utilized above for physical and biotic Earth system processes. Using this framework, we will evaluate whether human activity acts to deplete or enhance the dissipative activity of the biosphere and link this to sustaining the biosphere.

Human activity dissipates the free energy generated by the Earth system, specifically the chemicalfree energy generated through photosynthesis. Photosynthesis fuels the plants grown in agriculture and the resulting products feed livestock and human metabolisms. A fraction of the productivity of the biosphere is thus appropriated by agricultural activities. This share—the human appropriation of net primary productivity (Vitousek *et al.* 1986; Haberl, Erb, and Krausmann 2014)—is considerable, estimated to be 13–25% of the total terrestrial productivity. The free energy associated with this productivity is thus diverted to direct or indirect human use, such as food production, feeding livestock, or biofuel production. It is no longer available to the natural biosphere, reducing its level of dissipative activity and sustaining fewer natural living organisms.

To illustrate the magnitude of human appropriation using the aforementioned estimates, I used the land cover datasets provided by Ramankutty *et al* (2008) as masks to describe where terrestrial productivity is appropriated by human use, either in croplands or rangelands (Figure 8). The estimate of carbon uptake shown in Figure 6a was reduced by 50% to account for the metabolic activity of the producers (the autotrophic respiration) and then summed up over the areas of human land use, yielding the estimates shown in Table 1. It indicates that in these human-dominated areas, about 31 TW (or 28%) of the net primary productivity on land takes place—an estimate that is consistent with the more elaborate estimates by Haberl, Erb, and Krausmann (2014). It must be noted, however, that at present, not all of this energy is appropriated for human use, as some of it feeds natural grazers (or “pests”) or is used in the decomposition of belowground organic carbon by soil organisms that also draw from this free energy to sustain their metabolisms. Yet, with the intensification of agricultural activity, which aims at increasing yield, this will inadvertently result in a greater share of human appropriation instead of feeding the natural biosphere. We can thus anticipate that with agricultural expansion and intensification, the trend of greater appropriation will continue, depleting the likelihood of feeding the dissipative activity of the natural biosphere further.

The consumption of primary energy due to socioeconomic activities represents further energy consumption by human societies. At present, this consumption amounts to about 18 TW, which is mostly consumed in the form of fossil fuels. This chemical energy was generated by photosynthesis in the Earth’s geological past, followed by the subsequent burial of a fraction of the resulting biomass by geologic processes, thus creating the chemical disequilibrium of hydrocarbons in the geological reservoirs and atmospheric oxygen. Using fossil fuels depletes this disequilibrium. It increases the atmospheric concentration of carbon dioxide, enhances the associated greenhouse effect, and causes global warming. Irrespective of these global effects, fossil fuels are a finite resource and their use (at current rates) is not sustainable. If, for simplicity's sake, we were to assume that this use of energy was being replaced by appropriating more of the net primary productivity as an energy resource (for example, firewood or biofuels), this would draw away another substantial fraction of the free energy available to the natural biosphere. Thus, this would further deplete the ability to sustain the dissipative activity of the natural biosphere.

Figure 8: Human Impact on the Terrestrial Biosphere as Reflected by Its Land Use in Croplands and Rangelands



Source: Datasets from Ramankutty *et al.* (2008)

This description of human activity as an additional dissipative Earth system process suggests that more human activity would inevitably come at the expense of diminished biospheric activity. Since terrestrial productivity operates at its limit, the total consumption of the generated free energy to either sustain the dissipative activity of the natural biosphere or human activity is fixed and appears to be a zero-sum game. It seems to imply that the only way to improve and sustain the conditions of the natural biosphere would be for human societies to consume less energy.

6. TECHNOLOGY PUSHES THE LIMITS TO HIGHER LEVELS

There is another route by which to sustain the biosphere and that relates to mechanisms that may "push the limit", which is similar to how the biosphere pushes its limits. This involves certain types of manmade technologies. Examples of existing technologies include the use of river water for irrigation in arid regions or the damming of water flow to form reservoirs for irrigation during dry periods. This makes water available for enhancing plant productivity at places or times in which the precipitation input is too low to meet the potential evaporation rate. The additional water made available through the use of these technologies can act to enhance productivity by supplementing the means of storing and redistributing water that was previously unavailable to the natural biosphere. This water can then push the limit of productivity to a higher level by making more water available.

A look at Table 1 gives us a broad estimate of the magnitude by which such technologies could, in principle, enhance terrestrial productivity by storing or redistributing water. If we consider all of the continental river discharge (or runoff), which, in the climatological mean, balances the difference between precipitation and evaporation on land and make it available for evaporation by storing or redistributing it, this would enhance continental evaporation by 32%. Utilizing the water use efficiency for conversion into a productivity increase, as was done before, would yield about three times as much productivity enhancement due to the seasonal water storage maintained by deep-rooted vegetation. What is not accounted for here are possible climate effects. The enhanced evaporation would result in more continental moisture recycling, cloud cover, and precipitation, thus altering the environmental conditions on land. Nevertheless, this example is put forward simply to indicate that existing technology can provide alternative means to enhance productivity and its human appropriation that does not come at the cost of appropriating more of the natural productivity of the biosphere.

When we look into the future, a far greater effect can be achieved with modern technology. Photovoltaics provides technology that generates free energy directly from sunlight much more efficiently than heat engines or photosynthesis can achieve. Solar radiation is directly converted into electricity, avoiding the inevitable, irreversible losses through conversion into heat. Thus, photovoltaics is much more efficient than heat engines of the atmosphere. Additionally, energy generation by photovoltaics is not constrained by gas exchange and water availability, as is the case for photosynthesis—because photovoltaics exports its free energy in the form of electricity—and does not require gas exchange. With photovoltaics, human societies can become producers of free energy for the Earth system and thereby decouple their demand from the supply by the biosphere. In other words, human societies can sustainably grow further for some time but this does not need to come at the expense of the biosphere.

It would require relatively little area to meet the current demands for primary energy using photovoltaics. With a typical efficiency of about 20% for solar panels and a mean absorption of solar radiation of 165 W m^{-2}, it would merely require about 550,000 km^2 or less than 0.4% of the land surface to meet the current primary energy consumption. The use of photovoltaics would thus eliminate the pressure imposed due to meeting the primary energy consumption via the appropriation of energy from the biosphere, such as fossil fuels or biofuels, or via the renewable energy generated directly or indirectly by the heat engines of the atmosphere, such as wind or hydropower.

This novel supply of primary energy can then be supplemented by other technologies to alleviate other natural limits of the biosphere, particularly the ones imposed by water availability. Seawater desalination using membrane technologies requires a very small fraction of the energy involved in the natural desalination process using evaporation and subsequent precipitation. While it takes about 2.5 MJ to evaporate and desalinate a litre of seawater—known as the latent heat of vaporization—membranes only require about 4 kJ to achieve the same result (Elimelech and Phillip 2011). To put these numbers in a global perspective, at present, it requires 3650 TW of solar energy or 3% of the absorbed solar radiation to evaporate water to feed the net convergence of moisture transport to land of 46 x 10^3 km^3 per year (Oki and Kanae 2006; estimate in Table 1 is 29 x 10^3 km^3 per year). To obtain the same freshwater production rate by seawater desalination using membrane technology, it would require 6 TW of energy, which could be achieved by photovoltaics installed over 177,000 km^2 of area (using global means).

These are, of course, rough estimates that do not take into account the many practical challenges that must be overcome to make this a reality. Changing the terrestrial hydrologic cycle at this magnitude would result in climatological changes, likely enhancing continental precipitation. Yet, the observation I wish to put forward with these estimates is that there are manmade technologies already available that can achieve the outcome of natural processes with much greater efficiency. This, in turn, could decouple the growth in food and energy needs of human societies from their natural sources, decreasing the magnitude of appropriation while potentially resulting in positive feedback on photosynthetic carbon fixation (cf. Figure 1). This decoupling could reduce the impact on the natural biosphere by allowing it to use its free energy to feed the dissipative activity of its natural food webs and thus sustain the activity of the natural biosphere at higher levels.

7. A SUSTAINABLE FUTURE FOR THE TERRESTRIAL BIOSPHERE

I used a thermodynamic Earth system perspective to evaluate how the activity of the natural biosphere could be sustained in the presence of increasing human activities. I first reviewed the application of thermodynamics to indicate to what extent it restricts the physical functioning of the climate system and, thereby, the activity of the terrestrial biosphere. This results in a basic trade-off: increased human appropriation of energy seems to come at the cost of reducing the dissipative activity of the natural biosphere. The solution to this dilemma is by using novel technology, particularly photovoltaics. This allows human societies to generate free energy from sunlight more efficiently than we do by using natural means, particularly unproductive areas that are currently not generating free energy, such as deserts. The use of this energy can then decouple human energy needs from the supply by the natural biosphere. It is through this decoupling that human activity could, in principle, grow sustainably to some extent, with this growth coming not at the expense of shrinking the natural biosphere further but by providing a possibility to sustain and even enlarge the natural biosphere in the Anthropocene.

Such a trajectory of sustainable growth would likely lead to quite a different physical environment. When this energy is used to generate more resources, such as freshwater, to extend agriculture into arid regions instead of further deforesting humid regions, it would simultaneously strengthen hydrologic cycling and alter the physical climate system. Yet, human activities consume energy at rates of a similar magnitude to natural processes. It is hard to imagine that this consumption could voluntarily be drastically reduced in the future. With this impediment, it would seem inevitable that to preserve the natural biosphere, the only option left to human societies would be to "enlarge" the biosphere into areas that are not currently productive, such as desert regions, to sustain the dissipative activity of the natural biosphere at current levels.

I hope that this energy-oriented view of the biosphere and sustainability of human activity at the very large planetary scale can serve as a useful model for practical applications to evaluate human interactions and how detrimental or beneficial these may be for the natural biosphere to persist in times of greater human influences.

DATA AVAILABILITY

The datasets used to create the figures and to make the estimates shown in Table 1 are available at https://doi.org/10.17617/3.F0Q6X2 .

REFERENCES

Adler, Robert, Jian-Jian Wang, Matthew Sapiano, George Huffman, Long Chiu, Ping-Ping Xie, Ralph Ferraro, *et al.* 2016. "Global Precipitation Climatology Project (GPCP) Climate Data Record (CDR), Version 2.3 (Monthly)." *NOAA National Centers for Environmental Information*. https://doi.org/10.7289/V56971M6.

Ayres, Robert U, and Indira Nair. 1984. "Thermodynamics and Economics." *Physics Today* 37: 62–71. https://doi.org/10.1063/1.2915973.

Beer, Christian, Markus Reichstein, Enrico Tomelleri, Philippe Ciais, Martin Jung, Nuno Carvalhais, Christian Rödenbeck, *et al.* 2010. "Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate." *Science* 329 (5993): 834–838. https://doi.org/10.1126/science.1184984.

Clarke, Andrew, and Kevin J Gaston. 2006. "Climate, Energy and Diversity." *Proceedings of the Royal Society B* 273 (1599): 2257–2266. https://doi.org./10.1098/rspb.2006.3545.

Cleveland, Cutler J, Robert Costanza, Charles A S Hall, and Robert Kaufmann. 1984. "Energy and the U.S. Economy: A Biophysical Perspective." *Science* 225 (4665): 890–897. https://doi.org/10.1126/science.225.4665.890.

Conte, Luigi, Maik Renner, Paulo Brando, Claudinei Oliveira dos Santos, Divino Silvério, Olaf Kolle, Susan E Trumbore, and Axel Kleidon. 2019. "Effects of Tropical Deforestation on Surface Energy Balance Partitioning in Southeastern Amazonia Estimated from Maximum Convective Power." *Geophysical Research Letters* 46 (8): 4396–4403. https://doi.org/10.1029/2018GL081625.

Cowan, Ian R, and Graham D Farquhar. 1977. "Stomatal Function in Relation to Leaf Metabolism and Environment." *Symposia of the Society for Experimental Biology* 31: 471–505.

Currie, David J, Gary G Mittelbach, Howard V Cornell, Richard Field, Jean-Francois Guégan, Bradford A Hawkins, Dawn M Kaufman, *et al.* 2004. "Predictions and Tests of Climate-based Hypotheses of Broad-scale Variation in Taxonomic Richness." *Ecology Letters* 7: 1121–1134. https://doi.org/10.1111/j.1461-0248.2004.00671.x.

Elimelech, Menachem, and William A Phillip. 2011. "The Future of Seawater Desalination: Energy, Technology and the Environment." *Science* 333 (6043): 712–717. https://doi.org/10.1126/science.1200488.

Emerson, Robert. 1958. "The Quantum Yield of Photosynthesis." *Annual Review of Plant Physiology* 9: 1–24. https://doi.org/10.1146/annurev.pp.09.060158.000245.

Haberl, Helmut, Karl-Heinz Erb, and Fridolin Krausmann. 2014. "Human Appropriation of Net Primary Production: Patterns, Trends, and Planetary Boundaries." *Annual Review of Environment and Resources* 39: 363–391. https://doi.org/10.1146/annurev-environ-121912-094620.

Hermann, Weston A. 2006. "Quantifying Global Exergy Resources." *Energy* 31 (12): 1685–1702. https://doi.org/10.1016/j.energy.2005.09.006.

Hill, Robert, and Peter R Rich. 1983. "A Physical Interpretation for the Natural Photosynthetic Process." *Proceedings of the National Academy of Sciences* 80 (4): 978–982. https://doi.org/10.1073/pnas.80.4.978.

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). 2019. "Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services." IPBES. Germany. https://doi.org/10.5281/zenodo.3553579.

Judson, Olivia P. 2017. "The Energy Expansions of Evolution." *Nature Ecology & Evolution* 1 (0138). https://doi.org/10.1038/s41559-017-0138.

Kato, Seiji, Fred G Rose, David A Rutan, Tyler J Thorsen, Norman G Loeb, David R Doelling, Xianglei Huang, William L. Smith, Wenying Su, and Sueng-Hee Ham. 2018. "Surface Irradiances of Edition 4.0 Clouds and the Eart's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Data Product." *Journal of Climate* 31 (June): 4501–4527. https://doi.org/10.1175/JCLI-D-17-0523.1.
Kleidon, Axel. 2021a. "Physical Limits of Wind Energy Within the Atmosphere and its Use as Renewable Energy: From the Theoretical Basis to Practical Implications." *Meteorologische Zeitschrift* 30 (3): 203–225. https://doi.org/10.1127/metz/2021/1062.

———. 2021b. "What Limits Photosynthesis? Identifying the Thermodynamic Constraints of the
Terrestrial Biosphere Within the Earth System." *Biochimica et Biophysica Acta (BBA) - Bioenergetics* 1 (1862). https://doi.org/10.1016/j.bbabio.2020.148303.

Kleidon, Axel, and Martin Heimann. 1998. "A Method of Determining Rooting Depth from a Terrestrial Biosphere Model and its Impacts on the Global Water and Carbon Cycle." *Global Change Biology* 4 (3) (March): 275–286. https://doi.org/10.1046/j.1365-2486.1998.00152.x.

Kleidon, Axel, Maik Renner, and Phillip Porada. 2014. "Estimates of the Climatological Land Surface Energy and Water Balance Derived from Maximum Convective Power." *Hydrology and Earth System Sciences* 18: 2201–2218. https://doi.org/10.5194/hess-18-2201-2014.

Law, Beverly E, Eva Falge, Lianhong Gu, Dennis D Baldocchi, Peter Bakwin, P Berbigier, Kenneth Davis, A Johannes Dolman, *et al.* 2002. "Environmental Controls over Carbon Dioxide and Water Vapor Exchange of Terrestrial Vegetation." *Agricultural and Forest Meteorology* 113 (1–4): 97–120. https://doi.org/10.1016/S0168-1923(02)00104-1.

Loeb, G Norman, David R Doelling, Hailan Wang, Wenying Su, Cathy Nguyen, Joseph G Corbett, Lusheng Liang, Cristian Mitrescu, Fred G Rose, and Seiji Kato. 2018. "Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Top-of-Atmosphere (TOA) Edition 4.0 Data Product." *Journal of Climate* 31 (2): 895–918. https://doi.org/10.1175/JCLI-D-17-0208.1.

Meadows, H Donella, Dennis L Meadows, Jørgen Randers, and William W Behrens III. 1972. *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind.* New York: Universe Books.

Medlyn, Belinda E, Remko A Duursma, Derek Eamus, David S Ellsworth, I Colin Prentice, Craig V M Barton, Kristine Y Crous, Paolo de Angelis, Michael Freeman, and Lisa Wingate. 2011. "Reconciling the Optimal and Empirical Approaches to Modelling Stomatal Conductance." *Global Change Biology* 17 (6): 2134–2144. https://doi.org/10.1111/j.1365-2486.2010.02375.x.

Monteith, John Lennox. 1972. "Solar Radiation and Productivity in Tropical Ecosystems." *Journal of Applied Ecology* 9 (3): 747–766. https://doi.org/10.2307/2401901.

———. 1977. "Climate and the Efficiency of Crop Production in Britain." *Philosophical Transactions of the Royal Society B* 281 (980): 277–294. https://doi.org/10.1098/rstb.1977.0140.

Oki, Taikan, and Shinjiro Kanae. 2006. "Global Hydrological Cycles and World Water Resources." *Science* 313(5790): 1068–1072. https://doi.org/10.1126/science.1128845.

Ramankutty, Navin, Amato T Evan, Chad Monfreda, and Jonathan A Foley. 2008. "Farming the Planet: 1. Geographic Distribution of Global Agricultural Lands in the Year 2000." *Global Biogeochemical Cycles* 22 (1). https://doi.org/10.1029/2007GB002952.

Stephens, L Graeme, Juilin Li, Martin Wild, Carol Anne Clayson, Norman Loeb, Seiji Kato, Tristan L'Ecuyer, Paul W Stackhouse Jr, Matthew Lebsock, and Timothy Andrews. 2012. "An Update on Earth's Energy Balance in Light of the Latest Global Observations." *Nature Geoscience* 5: 691–696. https://doi.org/10.1038/NGEO1580.

Vitousek, Peter M, Paul R Ehrlich, Anne H Ehrlich, and Pamela A Matson. 1986. "Human Appropriation of the Products of Photosynthesis." *BioScience* 36 (6): 368–373. https://doi.org/10.2307/1310258.