



Does the biosphere lift nutrients against gravity, or redirect solar energy? A thermodynamic reframing of planetary biogeowork

Shigeo Kaneko

Independent Researcher, Saitama, Japan

5 ORCID: 0009-0008-3403-3659

Correspondence to: Shigeo Kaneko (taizor@msn.com)

Abstract. We use the term *biogeowork* for the thermodynamic work performed by the biosphere in shaping the Earth's energy and entropy budgets — whether supplied by metabolism or mediated through biological structures. Biological work at the Earth's surface is often imagined as mass transport against gravity — from whale pumps to plant transpiration — yet this framing conflates fundamentally different energy pathways. The biosphere shapes these budgets far beyond its own metabolic energy supply, yet biological energy supply and biologically mediated solar fluxes have not been clearly separated in a single quantitative framework. We propose a three-component decomposition of the biosphere's thermodynamic role: (i) active biogeowork, W_A , the mechanical work performed using metabolic free energy derived from gross primary production (GPP); (ii) mediated biogeowork, $\Delta\Phi_M$, the solar-driven flux redirected through biological structures — dominated by the biogenic enhancement of latent heat flux, ΔLE_{bio} , relative to an abiotic counterfactual land surface; and (iii) the resulting entropy-export enhancement, $\Delta\dot{S}_{\text{bio}}$. Using published global datasets, we estimate $W_A \sim 10^{20} \text{ J yr}^{-1}$ ($\approx 2\%$ of GPP), $\Delta LE_{\text{bio}} \sim 5 \times 10^{23} \text{ J yr}^{-1}$ ($\approx 30\%$ of global latent heat flux of $1.3 \times 10^{24} \text{ J yr}^{-1}$), and $\Delta\dot{S}_{\text{bio}} \sim 2 \times 10^{20} \text{ J K}^{-1} \text{ yr}^{-1}$ ($\approx 1\text{--}2\%$ of total planetary entropy production). The dimensionless leverage ratio $A_{\text{bio}} \equiv \Delta\Phi_M / W_A \sim 5 \times 10^3$ (range: $3\text{--}7 \times 10^3$) quantifies the amplification by which biological infrastructure redirects solar energy per unit metabolic investment. The decomposition clarifies the distinct pathways through which the biosphere shapes the planetary energy budget, links biosphere degradation to planetary-scale thermodynamic consequences, and yields testable predictions connecting land-cover change, Bowen-ratio variability, and planetary-scale entropy export.

1 Introduction

The Earth system operates far from thermodynamic equilibrium, sustained by incoming low-entropy solar radiation and the continuous export of high-entropy infrared radiation to space (Kleidon, 2010, 2016). Within this steady state, the biosphere is not merely a passive recipient of energy but an active participant in how energy is absorbed, partitioned, and dissipated (Makarieva and Gorshkov, 2007; Kleidon, 2016). A long-standing question in Earth system science concerns how to quantify the biosphere's role in planetary-scale energy transformation, particularly because observed biological effects on



latent heat flux, surface temperature, and atmospheric moisture transport appear to exceed the biosphere's own metabolic
30 energy budget by several orders of magnitude.

A natural way to quantify biological work is to ask how much the biosphere lifts against gravity. Migrating salmon, whale
pumps, seabird colonies, and megafauna (Roman et al., 2014; Doughty et al., 2016; Estes et al., 2011) return matter from
deep or downstream reservoirs to sites of primary production — apparent examples of mechanical work against the
gravitational default. At global scale, plant transpiration alone lifts $\approx 6 \times 10^{16}$ kg of water per year through canopies
35 averaging 15 m (Jasechko et al., 2013), dwarfing the animal contributions. Summing such mass-lifting work yields a
tempting candidate for a total biogeowork, yet this accounting conflates two physically distinct energy pathways. The
present Perspective aims to resolve two conceptual confusions inherent in such an accounting.

The first confusion concerns the energy source. A naive formalisation of such work — $\dot{W} = \sum_i \dot{m}_i g h_i$ across biologically
mediated vertical transport — treats every term as metabolically powered. Yet plant transpiration, which dominates this sum,
40 is not powered by metabolic energy at all. Cohesion–tension theory establishes that the ascent of xylem water is driven by
leaf-level evaporation, itself powered by absorbed solar radiation (latent heat of vaporisation $L_v \approx 2.26 \times 10^6$ J kg⁻¹). The
gravitational potential energy $gh \approx 150$ J kg⁻¹ for a 15 m canopy is $\sim 10^{-4}$ of the latent heat content and already embedded in
the solar energy budget of evaporation. Treating it as a separate biological energy supply double-counts the same solar input.

The second confusion concerns the scale at which biological effects are compared to planetary fluxes. On the modern Earth
45 — a water planet — this comparison is dominated by the hydrological cycle: the global latent heat flux of ≈ 80 W m⁻²
(Trenberth et al., 2009) amounts to $\sim 1.3 \times 10^{24}$ J yr⁻¹, of the same order as absorbed solar radiation (≈ 240 W m⁻²) and three
orders of magnitude larger than the mechanical power of the hydrological cycle ($\sim 3 \times 10^{20}$ J yr⁻¹; Kleidon, 2016). Biological
influence on this flux structure is channelled through transpiration, canopy hydraulics, and the surface partitioning of
absorbed radiation between latent and sensible heat (Murota, 1985; Makarieva and Gorshkov, 2007); the framework below is
50 accordingly developed for this water-mediated regime.

We therefore propose a reframing in which the biosphere's thermodynamic role is decomposed into three physically
independent components: active biogeowork (W_A , supplied by metabolism), mediated biogeowork ($\Delta\Phi_M$, solar flux
redirected by biological structures), and entropy-export enhancement ($\Delta\dot{S}_{\text{bio}}$, the planetary-scale consequence of $\Delta\Phi_M$).
Together with a dimensionless leverage ratio $\mathcal{L}_{\text{bio}} \equiv \Delta\Phi_M / W_A$, this framework preserves the long-standing intuition
55 (Lovelock, 1979; Kleidon, 2010) that small biological energy investments drive large planetary effects, while distinguishing
the energy sources of each pathway and rendering the resulting amplification directly estimable. Sect. 2 develops the
framework, Sect. 3 provides first-order global estimates, Sect. 4 discusses implications for biosphere degradation, and Sect. 5
identifies testable predictions.

2 A three-component framework



60 We decompose biogeowork — the thermodynamic work performed by the biosphere in shaping planetary energy and entropy flows — into three physically independent components: active biogeowork (metabolic supply), mediated biogeowork (solar-flux redirection), and entropy-export enhancement (the resulting entropic consequence).

2.1 Active biogeowork

We define active biogeowork W_A as the mechanical work performed using free energy derived from biological metabolism:

$$65 \quad W_A = \iint \eta_{\text{mech}}(r, t) \cdot \text{GPP}(r, t) \, dA \, dt \quad (1)$$

where r is the horizontal position, t is time, the double integral is taken over Earth's land and ocean surface and the integration period, and η_{mech} is the local efficiency with which gross primary production (expressed as an area-specific energy flux) is converted into mechanical work. For autotrophs, η_{mech} captures the fraction of GPP expended on root elongation, xylem tension generation, stem growth against gravity, stomatal actuation, and active transmembrane transport.

70 Plant-physiological estimates place η_{mech} in the range 0.01–0.03 (Amthor, 2000). For heterotrophs, η_{mech} represents the fraction of consumed metabolic energy converted into locomotion, bioturbation, and behavioural work; although individual values can exceed 0.1, population-level contributions are small because animal biomass is roughly two orders of magnitude less than plant biomass. Terrestrial plants comprise $\approx 80\%$ of Earth's biomass (Bar-On et al., 2018) and dominate solar-powered metabolic work; the deep subsurface biosphere is geothermal-driven and outside this framework's scop (Falkowski et al., 2008).

Although globally small, the animal-mediated gravitational transport phenomena that motivated this Perspective (Sect. 1) are regionally significant. They are catalogued in the ecological literature — anadromous fish migration (Quinn, 2005), cetacean nutrient transport (Roman et al., 2014), seabird marine-to-terrestrial nutrient transfer, and megafaunal biomass redistribution (Doughty et al., 2016) — all of which belong to this category. They constitute

$$80 \quad W_A^{(\text{anim,grav})} = \sum_i \dot{m}_i \cdot g \cdot \bar{h}_i \quad (2)$$

where i indexes distinct animal-mediated transport processes, \dot{m}_i is the mass transport rate of process i , g is the gravitational acceleration, and \bar{h}_i is the mean vertical displacement. Eq. (2) thus defines a subset of W_A in which metabolically powered locomotion results in gravitational potential-energy gain of transported matter. Globally, $W_A^{(\text{anim,grav})} \approx 10^8\text{--}10^{12} \text{ J yr}^{-1}$, several orders of magnitude smaller than plant-level W_A , but regionally dominant in cross-boundary nutrient fluxes (Estes et al., 2011; Doughty et al., 2016).

2.2 Mediated biogeowork

In contrast to W_A , we define mediated biogeowork $\Delta\Phi_M$ (where the subscript M denotes *mediated*) as the difference between the observed solar-driven energy flux and that of an abiotic counterfactual land surface:



$$\Delta\Phi_M = \Phi_{\text{observed}} - \Phi_{\text{abiotic}}^{\text{cf}} \quad (3)$$

90 The dominant term is the biogenic enhancement of latent heat flux,

$$\Delta LE_{\text{bio}} = LE_{\text{vegetated}} - LE_{\text{abiotic}}^{\text{cf}} \quad (4)$$

Here, the biosphere supplies no energy: solar radiation drives evaporation in both states, and the planetary hydrological cycle is the working medium. The biosphere instead provides the hydraulic infrastructure — xylem conduits, rooting networks, canopy coverage, and stomatal regulation — that changes where, and how efficiently, absorbed solar energy is partitioned
95 into latent rather than sensible heat. The partitioning is directly observable through the Bowen ratio $\beta = H / LE$, which ranges from $\beta \approx 0.1$ – 0.3 in tropical forests to $\beta > 2$ in deserts and bare-soil landscapes.

2.3 Entropy-export enhancement

Because LE transports thermal energy from the warm surface to the cooler free troposphere where it is radiated at $T_{\text{rad}} \approx 255$ K, the biogenic enhancement of LE produces a diagnostic enhancement of planetary entropy export,

$$100 \quad \Delta\dot{S}_{\text{bio}} = \Delta LE_{\text{bio}} \cdot (1/T_{\text{rad}} - 1/T_{\text{surf}}) \quad (5)$$

with $T_{\text{surf}} \approx 288$ K. This quantity is not an independent energy flux but a thermodynamic consequence of $\Delta\Phi_M$.

2.4 Consistency with the surface energy balance

The land-surface energy balance

$$R_n = H + LE + G + W_A \quad (6)$$

105 closes with $W_A \ll R_n$ (typically $W_A / R_n \lesssim 10^{-3}$), where R_n is net radiation at the land surface, H is sensible heat flux, and G is the ground heat flux. Note that R_n differs from R_{abs} (Sect. 3): R_n is the net radiative balance at the land surface, whereas R_{abs} is the top-of-atmosphere absorbed short-wave flux. Eq. (6) confirms that biological metabolism does not meaningfully contribute to the surface energy balance. The LE term, however, contains a substantial biogenic component ΔLE_{bio} that reflects biosphere-determined energy partitioning. The biosphere's thermodynamic significance thus lies not in how much
110 energy it supplies, but in how it structures the flow of solar energy through the coupled surface–atmosphere system.

2.5 Leverage

The relative magnitudes of W_A and $\Delta\Phi_M$ define a dimensionless leverage ratio

$$A_{\text{bio}} \equiv \Delta\Phi_M / W_A \quad (7)$$



We interpret A_{bio} as the amplification factor by which biologically supplied metabolic work reorganises solar-driven energy fluxes. A A_{bio} much greater than unity indicates that the biosphere functions primarily as a flux mediator rather than an energy supplier — a quantitative expression of the long-standing intuition (Lovelock, 1979; Kleidon, 2010) that life exerts disproportionate control over planetary conditions. The resulting three-to-four-orders-of-magnitude separation between W_A and $\Delta\Phi_M$ is visualised in Fig. 1 (see Sect. 3.1 for the underlying estimates).

The three components are physically independent: W_A draws on metabolic (GPP-derived) free energy, $\Delta\Phi_M$ draws on solar radiation mediated by biotic structures, and $\Delta\dot{S}_{\text{bio}}$ is a diagnostic derived from $\Delta\Phi_M$. They should not be summed as a single biogeowork total. Their ratio, however, is physically meaningful and quantifies the leverage exerted by the biosphere.

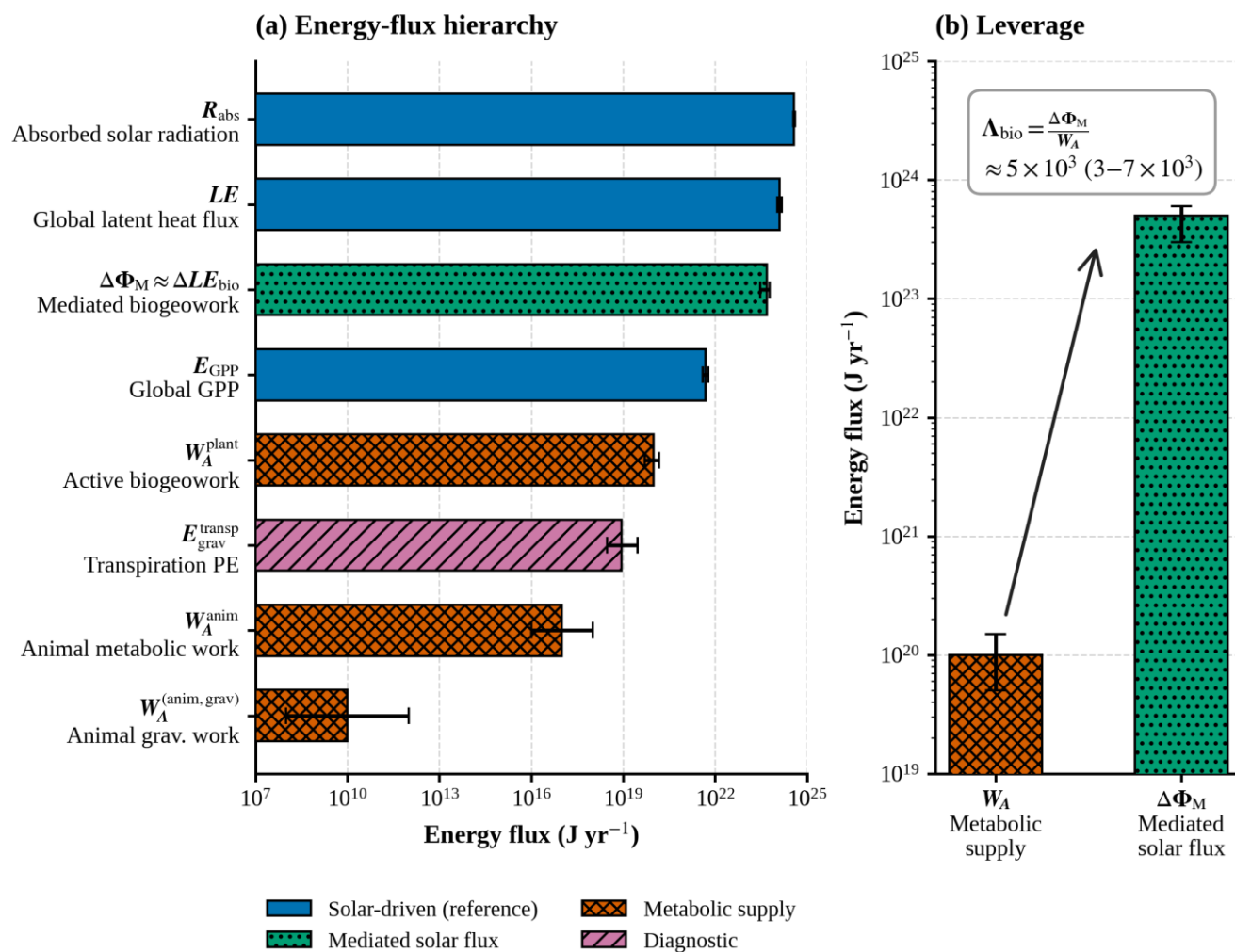
3 Quantitative estimates

3.1 Global values

Table 1 summarises first-order global estimates derived from published datasets. Fig. 1 displays the same quantities graphically: panel (a) arrays eight energy fluxes on a common logarithmic scale, spanning the metabolic, mediated-solar, and reference-flux regimes; panel (b) isolates the dimensionless leverage ratio $A_{\text{bio}} = \Delta\Phi_M / W_A \approx 5 \times 10^3$ (range: $3\text{--}7 \times 10^3$).

Table 1. Global estimates of biosphere thermodynamic components. All energy fluxes are in J yr^{-1} unless otherwise specified.

Quantity	Symbol	Central value	Units	Source
Absorbed solar radiation	R_{abs}	3.8×10^{24}	J yr^{-1}	Trenberth et al. (2009)
Global latent heat flux	LE	1.3×10^{24}	J yr^{-1}	Trenberth et al. (2009)
Global GPP (energy-equivalent)	E_{GPP}	4.8×10^{21}	J yr^{-1}	Beer et al. (2010)
Active biogeowork (plants)	W_A^{plant}	$\approx 1 \times 10^{20}$	J yr^{-1}	$2\% \times \text{GPP}$; Amthor (2000)
Active biogeowork (animals)	W_A^{anim}	$\approx 1 \times 10^{17}$	J yr^{-1}	Doughty et al. (2016)
Biogenic LE enhancement	ΔLE_{bio}	$\approx 5 \times 10^{23}$	J yr^{-1}	Shukla & Mintz (1982); Bonan (2008)
Entropy-export enhancement	$\Delta\dot{S}_{\text{bio}}$	$\approx 2 \times 10^{20}$	$\text{J K}^{-1} \text{yr}^{-1}$	Eq. (5)
Leverage ratio	A_{bio}	$\approx 5 \times 10^3$ ($3\text{--}7 \times 10^3$)	–	Eq. (7)



130 **Figure 1.** Energy-flux hierarchy and biospheric leverage in the Earth system. (a) Global, annual-mean energy fluxes on a logarithmic scale
 (J yr⁻¹). Bars show central estimates; horizontal black lines indicate first-order uncertainty ranges. Fill patterns distinguish four categories:
 solar-driven reference fluxes (R_{abs} , LE , E_{GPP}); the biogenic enhancement of latent heat flux treated here as mediated biogeowork $\Delta\Phi_M \approx$
 ΔLE_{bio} ; active biogeowork (W_A) supplied by metabolism, with its animal sub-components W_A^{anim} and $W_A^{\text{(anim, grav)}}$; and the gravitational
 135 potential energy of transpired water $E_{\text{grav}}^{\text{transp}}$, shown as a diagnostic that is not an independent energy term (see text, Sect. 3.3). Estimates
 combine published land-surface modelling and observational datasets (Shukla and Mintz, 1982; Bonan, 2008; Beer et al., 2010; Trenberth
 et al., 2009; Jasechko et al., 2013). (b) The dimensionless leverage ratio $\Lambda_{\text{bio}} \equiv \Delta\Phi_M / W_A \approx 5 \times 10^3$ (range: $3-7 \times 10^3$), expressing the
 amplification by which metabolic work reorganises solar-driven energy fluxes.

3.2 Supporting calculations



Global GPP, expressed in carbon units, is $\approx 120 \text{ Pg C yr}^{-1}$ (Beer et al., 2010). Using a mean free-energy yield of $\approx 40 \text{ kJ per g}$
140 C fixed by photosynthesis, $E_{\text{GPP}} \approx 4.8 \times 10^{21} \text{ J yr}^{-1}$. Applying a mean mechanical-conversion efficiency $\eta_{\text{mech}} \approx 0.02$ (Amthor,
2000) yields $W_{\text{A}}^{\text{plant}} \approx 10^{20} \text{ J yr}^{-1}$. Since terrestrial plants dominate the metabolic budget ($W_{\text{A}}^{\text{plant}} \gg W_{\text{A}}^{\text{anim}}$), we use $W_{\text{A}} \approx$
 $W_{\text{A}}^{\text{plant}}$ as the central estimate in the text and tables.

The biogenic LE enhancement is estimated from counterfactual land-surface modelling. Shukla and Mintz (1982) showed
that eliminating continental evapotranspiration roughly halves global precipitation and raises surface temperature. More
145 recent land-surface model studies that systematically manipulate vegetation cover (Kleidon et al., 2000; Bonan, 2008)
converge on $\Delta LE_{\text{bio}} / LE_{\text{total}} \approx 0.25\text{--}0.50$. Adopting a central value of 0.35 yields $\Delta LE_{\text{bio}} \approx 5 \times 10^{23} \text{ J yr}^{-1}$.

Inserting this into Eq. (5) with $T_{\text{rad}} = 255 \text{ K}$ and $T_{\text{surf}} = 288 \text{ K}$ gives $\Delta \dot{S}_{\text{bio}} \approx 5 \times 10^{23} \times 4.5 \times 10^{-4} \approx 2 \times 10^{20} \text{ J K}^{-1} \text{ yr}^{-1}$,
corresponding to 1–2 % of total radiative entropy production in the Earth system (Kleidon, 2016). The leverage ratio is $A_{\text{bio}} \approx$
 $5 \times 10^{23} / 10^{20} \approx 5 \times 10^3$, indicating that one unit of metabolic work is associated with approximately five thousand units of
150 solar energy redirected through the latent-heat pathway (Fig. 1b).

3.3 Uncertainties and boundary conditions

The largest sources of uncertainty are: (i) η_{mech} , for which direct empirical constraints are limited (uncertainty factor ~ 3); (ii)
the abiotic counterfactual LE , which depends on land-surface-model assumptions about bare-soil evaporation, surface albedo,
and aerodynamic roughness (uncertainty factor ~ 2); and (iii) the representative radiating temperature T_{rad} , which varies
155 spatially and seasonally ($\pm 5\%$ on $\Delta \dot{S}_{\text{bio}}$). All three warrant dedicated sensitivity analyses in follow-up work.

The gravitational potential energy of transpired water, $E_{\text{grav}}^{\text{transp}} = \dot{m}_{\text{transp}} \cdot g \cdot \bar{h}_{\text{canopy}} \approx 9 \times 10^{18} \text{ J yr}^{-1}$ for a global transpiration
flux of $\approx 6 \times 10^{16} \text{ kg yr}^{-1}$ (Jasechko et al., 2013) and a mean canopy height of 15 m, is a diagnostic of biospheric spatial
structuring but does not belong to any of the three components. It is a solar-driven by-product, not an independent
biogeowork term (shown as a diagnostic bar in Fig. 1a).

160 4 Planetary implications

4.1 Biosphere degradation as a thermodynamic phenomenon

The three-component framework clarifies how biosphere degradation propagates through the planetary energy budget.
Deforestation primarily reduces ΔLE_{bio} by replacing high-transpiration vegetation with surfaces that partition absorbed solar
energy toward sensible heating. The direct metabolic loss (reduced W_{A}) is a negligible term of the land-surface energy
165 balance, but the loss of mediated flux is substantial: converting a tropical forest to bare soil locally doubles the Bowen ratio
and reduces local LE by a factor of 2–3. Regional reductions in ΔLE_{bio} propagate through atmospheric circulation, altering
precipitation and downwind climate (Makarieva and Gorshkov, 2007).



Megafaunal decline and defaunation (Estes et al., 2011; Doughty et al., 2016) affect primarily $W_A^{(anim,grav)}$ — globally small but locally dominant in cross-ecosystem nutrient transfer. The spatial redistribution of nutrients by large animals generates
170 hotspots of primary productivity that may locally increase ΔLE_{bio} , suggesting a coupling between the two biogeowork components that warrants explicit quantification.

4.2 Relationship to prior frameworks

An important precedent for the present framework is the Japanese entropy school of ecological thermodynamics, most clearly articulated in English by Murota (1985). Murota classified annual entropy generation at the Earth's surface into eight
175 components, estimating a total entropy generation $S_g \approx 9 \times 10^{20} \text{ J K}^{-1} \text{ yr}^{-1}$ and a photosynthesis-specific term $S_{(pho)} \approx 6.5 \times 10^{18} \text{ J K}^{-1} \text{ yr}^{-1}$ (0.7 % of S_g). Our $\Delta S_{bio} \approx 2 \times 10^{20} \text{ J K}^{-1} \text{ yr}^{-1}$ is a broader counterfactual quantity — the biogenic difference between observed LE and that of an abiotic land surface — and is therefore expected to be approximately an order of magnitude larger than Murota's $S_{(pho)}$. The two estimates nonetheless agree on the qualitative conclusion that biologically mediated entropy generation is a quantitatively modest but structurally significant share (order of one percent) of total
180 planetary entropy production. The structural significance, rather than the absolute magnitude, is what makes this share consequential: the same 1–2 % is concentrated in transpiration-dominated regions (tropical forests, mid-latitude vegetation) where local Bowen-ratio modifications and downwind atmospheric coupling propagate the biospheric signature far beyond its globally averaged value. The present three-component decomposition sharpens this early classification by separating biological energy supply (W_A) from biological flux mediation ($\Delta \Phi_M$), and by introducing the dimensionless leverage ratio
185 A_{bio} .

The framework further integrates several established strands. Kleidon (2010, 2016) established the thermodynamic view of the biosphere as an active planetary participant; the present three components make explicit and separable the biological supply and mediation implicit in that treatment. The Gaia framework (Lovelock, 1979) intuited that life exerts disproportionate planetary control; the leverage ratio A_{bio} offers a quantitative expression of this intuition. Makarieva and
190 Gorshkov's (2007) biotic pump addresses horizontal moisture transport; the present $\Delta \Phi_M$ captures the linked vertical latent-heat component. Doughty et al. (2016) quantified animal-mediated nutrient-transport fluxes, which the framework places within $W_A^{(anim,grav)}$. Michaelian (2011), in an early contribution to this journal, articulated a thermodynamic view at the origin-of-life scale, proposing that maximising photon dissipation shaped early evolution; the present framework concerns the analogous role of the modern biosphere in flux mediation. Prigogine's (1977) dissipative structures and related statistical-
195 mechanical perspectives (England, 2013) provide theoretical context for why biologically mediated flux redirection emerges, although we do not rely on any specific principle such as maximum entropy production (Martyushev and Seleznev, 2006) in the present framework.

A parallel intuition was articulated for the marine atmosphere by the CLAW hypothesis (Charlson et al., 1987), in which oceanic phytoplankton mediate cloud albedo through DMS-derived sulfate aerosol — a flux-mediation pathway analogous to



200 $\Delta\Phi_M$ but operating through aerosol–cloud rather than latent-heat coupling. Recent work in the Amazon shows that biogenic volatile organic compounds released by the forest canopy drive frequent new particle formation (Kirkby et al., 2016; Machado et al., 2024; Meller et al., 2026), suggesting that an aerosol-mediated component of $\Delta\Phi_M$ may be quantitatively non-negligible. The present water-mediated framework can be extended along this axis once biogenic CCN production is constrained globally; we restrict the present analysis to the water-mediated regime for tractability.

205 **4.3 Sustainability as flux maintenance**

The framework supports a reinterpretation of sustainability as the maintenance of thermodynamic flux structure rather than the preservation of material stocks alone. Stocks of carbon, nutrients, or biomass constitute the biophysical infrastructure that sustains W_A and $\Delta\Phi_M$; their decline is significant because it degrades the leverage A_{bio} through which life exerts control over planetary energy partitioning. This perspective complements carbon-stock-based sustainability indicators (e.g. HANPP; Running, 2012) and biophysical economic approaches (Georgescu-Roegen, 1971; Ayres and Warr, 2009) with flux-based
210 indicators such as regional Bowen ratio, latent-heat-flux intensity, and the integrity of hydrological continuity.

While anthropogenic global change is conventionally framed in terms of carbon-cycle dynamics and radiative forcing, this thermodynamic framing provides a complementary biophysical context. It emphasises that land-system alterations impact the planetary energy budget not only through carbon-mediated radiative effects but also via direct modifications to surface
215 energy partitioning and the resulting hydrological and thermal feedbacks — processes not fully captured by carbon accounting alone.

4.4 Limitations

The global estimates presented here are order-of-magnitude. The abiotic counterfactual is inherently model-dependent and cannot be directly observed. The decomposition assumes a clean separation between metabolic and solar energy sources,
220 which is a useful idealisation; in practice, biological structures (xylem, leaves, canopies) are constructed from GPP-derived matter, so there exists a secondary coupling whereby $\Delta\Phi_M$ depends on cumulative W_A investment in biomass. Quantifying this biomass-mediated coupling is beyond the scope of this Perspective but represents an important direction for follow-up work.

5 Testable predictions

225 The framework yields concrete predictions that can be evaluated against existing and forthcoming observations.

5.1 Deforestation signals in latent heat flux



Land-use change from forest to cropland or bare soil should produce a local reduction in LE proportional to the site-specific ΔLE_{bio} . Satellite-based LE products (MOD16; GLEAM) combined with forest-cover change records (Hansen et al., 2013) enable direct testing. The framework predicts LE reductions exceeding those attributable to radiative forcing alone, with the excess attributable to biogeowork loss. Tropical deforestation hotspots should show larger ΔLE signals than their temperate or boreal equivalents, reflecting regional gradients in ΔLE_{bio} .

5.2 Bowen ratio as a biospheric diagnostic

Across the FLUXNET network, the Bowen ratio should correlate negatively with site-level GPP, with the strength of the correlation reflecting the product of η_{mech} and the leverage coupling. We predict that β versus GPP regressions across ecosystems will collapse onto a single log-linear relationship once corrected for climate variables (vapour pressure deficit, net radiation). Departures from this relationship would flag ecosystems where $\Delta \Phi_M$ is anomalously high or low relative to W_A — candidate biospheric leverage hotspots warranting process-level investigation.

5.3 Megafaunal decline and local productivity

In ecosystems where megafaunal extirpation has been documented (e.g. pre- versus post-industrial Arctic whale populations; Roman et al., 2014), historical reconstructions should show reduced local $W_A^{(\text{anim,grav})}$ and, in hydrologically linked downstream ecosystems, reduced primary productivity through nutrient-subsidy loss. The framework predicts that ecosystems with historically high cross-boundary animal transport — coastal upwelling zones with historically high cetacean populations, anadromous fish river systems, seabird islands — should show larger productivity declines than comparable ecosystems without such transport.

5.4 Counterfactual land-surface experiments

Systematic intercomparison of land-surface models (e.g. within the TRENDY framework) run with and without vegetation should yield convergent estimates of ΔLE_{bio} . The framework predicts that model spread will be dominated by parameterisations of bare-soil evaporation and root-zone hydrology rather than by photosynthesis parameterisations, making bare-soil process representation a priority for reducing uncertainty in ΔLE_{bio} estimates.

5.5 Planetary entropy-export trends

The framework predicts that progressive biosphere degradation will produce detectable trends in planetary entropy export. Combining satellite-observed top-of-atmosphere outgoing longwave radiation (partitioned by latitude and season) with land-cover change records should permit attribution of $\Delta \dot{S}_{\text{bio}}$ to specific degradation fronts. Although the relative magnitude is small (1–2 % of total entropy production), the spatial pattern — concentrated in tropical deforestation regions — provides a distinctive signal.



6 Conclusions

The biosphere does not so much lift nutrients against gravity as redirect solar energy: its thermodynamic role in the Earth system is better described as flux mediation than as energy supply. By decomposing this role into active biogeowork ($W_A \sim 10^{20} \text{ J yr}^{-1}$), mediated biogeowork (solar flux redirected through biology, $\Delta LE_{\text{bio}} \sim 5 \times 10^{23} \text{ J yr}^{-1}$), and the resulting entropy-export enhancement ($\Delta \dot{S}_{\text{bio}} \sim 2 \times 10^{20} \text{ J K}^{-1} \text{ yr}^{-1}$), a dimensionless leverage ratio $A_{\text{bio}} \sim 5 \times 10^3$ (range: $3\text{--}7 \times 10^3$) emerges: each unit of metabolic work is associated with thousands of units of redirected solar flux. This decomposition clarifies the distinct pathways through which the biosphere shapes planetary fluxes, establishes a direct link between biosphere degradation and planetary-scale thermodynamic consequences, and yields concrete testable predictions connecting land-cover change, Bowen-ratio variability, and planetary-scale entropy export.

Future work should refine η_{mech} through plant-physiological measurements, improve abiotic counterfactual estimates through coordinated land-surface-model experiments, and explore the secondary coupling between W_A and $\Delta \Phi_M$ mediated by biomass construction. The framework builds directly on the thermodynamic foundation established by Kleidon (2010, 2016), adding an explicit three-component decomposition and the associated leverage ratio as operational diagnostics applicable to satellite observations, flux-tower networks, and Earth system models. On the modern Earth, these diagnostics are fundamentally water-mediated: A_{bio} operates through the hydrological cycle, and biosphere–hydrosphere coupling is the working substrate through which planetary biogeowork operates.

Data and code availability

No new primary data were generated. All numerical estimates are derived from published sources cited in the reference list. Supplementary calculations are provided as a Jupyter notebook archived at Mendeley Data (Kaneko, 2026, <https://doi.org/10.17632/ggb79kcc2c.3>), which reproduces all numerical values in Sect. 3 and Fig. 1. The dataset is released under CC BY 4.0.

Author contributions

Shigeo Kaneko conceived the framework, performed the calculations, and drafted the manuscript.

Competing interests

The author declares no competing interests.

Acknowledgements



The author acknowledges the interactive review community of Earth System Dynamics for constructive engagement on an earlier draft. Generative AI tools (Anthropic Claude, Google Gemini) were used assistively for language refinement, organisation of existing literature, and verification of arithmetic in Sect. 3, in accordance with the ESD AI policy. All scientific interpretations, physical derivations, and quantitative claims are the responsibility of the author.

References

- Amthor, J. S.: The McCree–de Wit–Penning de Vries–Thornley respiration paradigms: 30 years later, *Ann. Bot.*, 86, 1–20, <https://doi.org/10.1006/anbo.2000.1175>, 2000.
- Ayres, R. U. and Warr, B.: *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*, Edward Elgar, Cheltenham, 2009.
- Bar-On, Y. M., Phillips, R., and Milo, R.: The biomass distribution on Earth, *Proc. Natl. Acad. Sci. USA*, 115, 6506–6511, <https://doi.org/10.1073/pnas.1711842115>, 2018.
- Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rödenbeck, C., Arain, M. A., Baldocchi, D., Bonan, G. B., Bondeau, A., Cescatti, A., Lasslop, G., Lindroth, A., Lomas, M., Luysaert, S., Margolis, H., Oleson, K. W., Rouspard, O., Veenendaal, E., Viovy, N., Williams, C., Woodward, F. I., and Papale, D.: Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate, *Science*, 329, 834–838, <https://doi.org/10.1126/science.1184984>, 2010.
- Bonan, G. B.: Forests and climate change: forcings, feedbacks, and the climate benefits of forests, *Science*, 320, 1444–1449, <https://doi.org/10.1126/science.1155121>, 2008.
- Charlson, R. J., Lovelock, J. E., Andreae, M. O., and Warren, S. G.: Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate, *Nature*, 326, 655–661, <https://doi.org/10.1038/326655a0>, 1987.
- Doughty, C. E., Roman, J., Faurby, S., Wolf, A., Haque, A., Bakker, E. S., Malhi, Y., Dunning, J. B., and Svenning, J.-C.: Global nutrient transport in a world of giants, *Proc. Natl. Acad. Sci. USA*, 113, 868–873, <https://doi.org/10.1073/pnas.1502549112>, 2016.
- England, J. L.: Statistical physics of self-replication, *J. Chem. Phys.*, 139, 121923, <https://doi.org/10.1063/1.4818538>, 2013.
- Estes, J. A., Terborgh, J., Brashares, J. S., Power, M. E., Berger, J., Bond, W. J., Carpenter, S. R., Essington, T. E., Holt, R. D., Jackson, J. B. C., Marquis, R. J., Oksanen, L., Oksanen, T., Paine, R. T., Pickett, E. K., Ripple, W. J., Sandin, S. A., Scheffer, M., Schoener, T. W., Shurin, J. B., Sinclair, A. R. E., Soulé, M. E., Virtanen, R., and Wardle, D. A.: Trophic downgrading of planet Earth, *Science*, 333, 301–306, <https://doi.org/10.1126/science.1205106>, 2011.
- Falkowski, P. G., Fenchel, T., and Delong, E. F.: The microbial engines that drive Earth's biogeochemical cycles, *Science*, 320, 1034–1039, <https://doi.org/10.1126/science.1153213>, 2008.
- Georgescu-Roegen, N.: *The Entropy Law and the Economic Process*, Harvard University Press, Cambridge, MA, 1971.
- Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, S. V., Goetz, S. J., Loveland, T. R., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O., and Townshend, J. R. G.: High-resolution global maps of 21st-century forest cover change, *Science*, 342, 850–853, <https://doi.org/10.1126/science.1244693>, 2013.



- Jasechko, S., Sharp, Z. D., Gibson, J. J., Birks, S. J., Yi, Y., and Fawcett, P. J.: Terrestrial water fluxes dominated by transpiration, *Nature*, 496, 347–350, <https://doi.org/10.1038/nature11983>, 2013.
- Kaneko, S.: Supplementary code and data for "Does the biosphere lift nutrients against gravity, or redirect solar energy? A thermodynamic reframing of planetary biogeowork", *Mendeley Data* [data set], V3, <https://doi.org/10.17632/ggb79kcc2c.3>, 2026.
- Kirkby, J., Duplissy, J., Sengupta, K., Frege, C., Gordon, H., Williamson, C., Heinritzi, M., Simon, M., Yan, C., Almeida, J., Tröstl, J., Nieminen, T., Ortega, I. K., Wagner, R., Adamov, A., Amorim, A., Bernhammer, A.-K., Bianchi, F., Breitenlechner, M., Brilke, S., Chen, X., Craven, J., Dias, A., Ehrhart, S., Flagan, R. C., Franchin, A., Fuchs, C., Guida, R., Hakala, J., Hoyle, C. R., Jokinen, T., Junninen, H., Kangasluoma, J., Kim, J., Krapf, M., Kürten, A., Laaksonen, A., Lehtipalo, K., Makhmutov, V., Mathot, S., Molteni, U., Onnela, A., Peräkylä, O., Piel, F., Petäjä, T., Praplan, A. P., Pringle, K., Rap, A., Richards, N. A. D., Riipinen, I., Rissanen, M. P., Rondo, L., Sarnela, N., Schobesberger, S., Scott, C. E., Seinfeld, J. H., Sipilä, M., Steiner, G., Stozhkov, Y., Stratmann, F., Tomé, A., Virtanen, A., Vogel, A. L., Wagner, A. C., Wagner, P. E., Weingartner, E., Wimmer, D., Winkler, P. M., Ye, P., Zhang, X., Hansel, A., Dommen, J., Donahue, N. M., Worsnop, D. R., Baltensperger, U., Kulmala, M., Carslaw, K. S., and Curtius, J.: Ion-induced nucleation of pure biogenic particles, *Nature*, 533, 521–526, <https://doi.org/10.1038/nature17953>, 2016.
- Kleidon, A.: Life, hierarchy, and the thermodynamic machinery of planet Earth, *Phys. Life Rev.*, 7, 424–460, <https://doi.org/10.1016/j.plrev.2010.10.002>, 2010.
- Kleidon, A.: *Thermodynamic Foundations of the Earth System*, Cambridge University Press, Cambridge, <https://doi.org/10.1017/CBO9781139342742>, 2016.
- Kleidon, A., Fraedrich, K., and Heimann, M.: A green planet versus a desert world: estimating the maximum effect of vegetation on the land surface climate, *Clim. Change*, 44, 471–493, <https://doi.org/10.1023/A:1005559518889>, 2000.
- Lovelock, J. E.: *Gaia: A New Look at Life on Earth*, Oxford University Press, Oxford, 1979.
- Machado, L. A. T., Unfer, G. R., Brill, S., Hildmann, S., Pöhlker, C., Cheng, Y., Williams, J., Hartwig, H., Andreae, M. O., Artaxo, P., Curtius, J., Franco, M. A., Cecchini, M. A., Edtbauer, A., Hoffmann, T., Holanda, B., Khadir, T., Krejci, R., Kremper, L. A., Liu, Y., Meller, B. B., Pöhlker, M. L., Quesada, C. A., Ringsdorf, A., Riipinen, I., Trumbore, S., Wolff, S., Lelieveld, J., and Pöschl, U.: Frequent rainfall-induced new particle formation within the canopy in the Amazon rainforest, *Nat. Geosci.*, 17, 1225–1232, <https://doi.org/10.1038/s41561-024-01585-0>, 2024.
- Makarieva, A. M. and Gorshkov, V. G.: Biotic pump of atmospheric moisture as driver of the hydrological cycle on land, *Hydrol. Earth Syst. Sci.*, 11, 1013–1033, <https://doi.org/10.5194/hess-11-1013-2007>, 2007.
- Martyushev, L. M. and Seleznev, V. D.: Maximum entropy production principle in physics, chemistry and biology, *Phys. Rep.*, 426, 1–45, <https://doi.org/10.1016/j.physrep.2005.12.001>, 2006.
- Meller, R., Franco, M. A., Pöhlker, C., Pöhlker, M. L., Artaxo, P., and Andreae, M. O.: Quiet new particle formation is a significant aerosol source in the Amazon boundary layer, *Atmos. Chem. Phys.*, 26, 4885–4902, <https://doi.org/10.5194/acp-26-4885-2026>, 2026.
- Michaelian, K.: Thermodynamic dissipation theory for the origin of life, *Earth Syst. Dynam.*, 2, 37–51, <https://doi.org/10.5194/esd-2-37-2011>, 2011.



- Murota, T.: Heat economy of the water planet Earth: Part II/Revision and some new results, *Hitotsubashi J. Econ.*, 26, 181–185, 1985.
- Prigogine, I.: *Self-Organization in Nonequilibrium Systems: From Dissipative Structures to Order through Fluctuations*, Wiley, New York, 1977.
- Quinn, T. P.: *The Behavior and Ecology of Pacific Salmon and Trout*, University of Washington Press, Seattle, 2005.
- Roman, J., Estes, J. A., Morissette, L., Smith, C., Costa, D., McCarthy, J., Tinker, M. T., Nicol, S., and Smetacek, V.: Whales as marine ecosystem engineers, *Front. Ecol. Environ.*, 12, 377–385, <https://doi.org/10.1890/130220>, 2014.
- Running, S. W.: A measurable planetary boundary for the biosphere, *Science*, 337, 1458–1459, <https://doi.org/10.1126/science.1227620>, 2012.
- Shukla, J. and Mintz, Y.: Influence of land-surface evapotranspiration on the Earth's climate, *Science*, 215, 1498–1501, <https://doi.org/10.1126/science.215.4539.1498>, 1982.
- Trenberth, K. E., Fasullo, J. T., and Kiehl, J.: Earth's global energy budget, *B. Am. Meteorol. Soc.*, 90, 311–324, <https://doi.org/10.1175/2008BAMS2634.1>, 2009.

365