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Closure of Constraints in the Earth System: Planetary Biological Organisation Across Biogeochemical Cycles

Alejandro Merlo Oteo

IAS-Research Center for Life, Mind, and Society

Department of Philosophy, University of the Basque Country (UPV/EHU)

20018 Donostia-San Sebastián, Spain

Corresponding author: alejandro.merlo@ehu.eus

ORCID: 0000-0001-7270-5905

Abstract

Closure of constraints characterises the distinctive causal regime of biological systems: a set of constraints, each conserved with respect to the process it constrains and maintained by processes running at another scale, mutually dependent for their maintenance. The framework has been extended above the organism principally to ecosystems, where individuating the systems involved has proved difficult. We argue that the Earth system realises closure of constraints, and is therefore biologically organised in the technical sense defined by the framework. The argument does not locate closure in any biogeochemical cycle. Cycles are regularly dismissed as instances of merely physical circularity, and for any single cycle that dismissal is justified. Closure is realised across a set whose members belong to different cycles: among them, the populations of protein complexes that catalyse the planet's redox transformations, the atmospheric oxygen inventory they sustain, and the surface water inventory the organisation recruits rather than produces. The dependencies among them run in both directions and in both temporal orders. Constraints of this kind are individuated by the transformation they harness and are planetary in extent, so no boundary need be drawn within the system to specify the set. The membership of the set has changed over geological time, the Quaternary being one regime among several. This opens the question of whether the Earth system has norms of its own.

Keywords: closure of constraints; biological organisation; Earth system; biogeochemical cycles; Gaia; philosophy of biology

Introduction

Closure of constraints identifies a distinctive circular causal regime found in living systems: one in which a set of constraints, understood as entities that channel and harness thermodynamic flows while remaining conserved over relevant time scales, mutually depend on one another for their production and maintenance. Building on the autopoietic and biological-autonomy tradition (Maturana and Varela 1980; Rosen 1991; Varela 1979), the concept was developed by Moreno and Mossio (2015) and formalised by Montévil and Mossio (2015), and has since become central to the organisational tradition in philosophy of biology.

Closure of constraints has also been taken beyond the individual organism. Moreno and Mossio hold that ecological systems realise closure, comparing the constraining action of ecological units (groups of organisms) on the flow of matter and energy to that of enzymes, membranes and organs within an organism (2015, pp. 107–108); Mossio and Bich allow that supra-organismal systems could realise closure and so be teleological (2017). The extension has been worked out principally for ecosystems (El-Hani and Nunes-Neto 2020; Nunes-Neto et al. 2014). Since Tansley (1935) coined the term, ecosystems have been understood to include abiotic components such as soils, water bodies, atmospheric gases and dissolved nutrients. Within the closure framework, such components form part of the organisation insofar as they are themselves subject to closure, and belong to its boundary conditions where they are not (El-Hani et al. 2024).

Establishing this distinction can nevertheless be difficult because ecosystems grade into one another at their edges. El-Hani et al. (2024, p. 293) argue that where physical boundaries are fuzzy, functional relationships are often fuzzy as well, making it difficult to determine which constraints belong to which system. At the planetary scale, the difficulty takes a different form: what counts as a constraint can be settled without drawing a boundary within the system, but depends also on the time scales considered.

The biological character of the Earth system has been debated since Lovelock and Margulis (1974) proposed that the Earth's surface environments constitute a system regulated by and for the biota inhabiting it, and thus a “general living system, Gaia” (ibid., p. 4). Gaia has subsequently been characterised in many ways: as a superorganism (Lovelock 1988), an autopoietic system (Margulis 1997), an ecosystem composed of ecosystems (Margulis 1998), a physiology without an organism (Volk 1998), a metabiotic system (Clarke 2020), and an organism (De Castro Carranza 2020; Meynell and Lopez 2025), among others.

Gaia theory also contributed to the development of Earth system science, whose object of study is the integrated whole formed by the lithosphere, atmosphere, hydrosphere and biosphere, together with the dense web of interactions among them (Dutreuil 2024; Jacobson et al. 2000; Lenton 2016; Skinner and Murck 2011; Steffen et al. 2020). Two characteristic explananda are an atmosphere maintained far from

chemical equilibrium and surface conditions maintained within habitable bounds over geological time. These arise from feedbacks and processes in which biotic and abiotic components are jointly implicated. It is this coupled and integrated system that constitutes the unit of analysis throughout this paper¹.

Life's transformation of its environment, and thereby of the Earth system itself, is increasingly clear. What remains contested is whether these transformations can be understood as being “for” life, and thus as functionally or normatively oriented towards its maintenance. The underlying question is whether the vocabulary of function and regulation can be applied literally to the planetary system.

The standard objection to Gaia theory is that it cannot. On the etiological account that predominates in philosophy of biology, functions are conferred by a history of natural selection (Wright 1976; Millikan 1989). The Earth neither reproduces nor belongs to a population, and therefore cannot itself undergo selection in the relevant sense; whatever biogeochemical cycles do, they were not selected for doing it (Dawkins 1982; Doolittle 1981). Much subsequent work has accepted this framing and sought a selection-like process at the planetary scale: differential persistence in place of differential reproduction (Doolittle 2014, 2019), selection across nested scales and sequential selection (Lenton et al. 2018), and, more recently, the persistence of cycles of biogeochemical activity as the relevant entities of selection (Boyle and Lenton 2022). These approaches aim to preserve an etiological account of planetary function.

We take a different route (cf. Rubin and Crucifix 2022). On the organisational approach, what makes a system biological is grounded primarily in its present organisation and capacity for self-maintenance, rather than in the history that produced it. Likewise, the functions and norms of its parts are grounded in their contribution to the maintenance of that organisation rather than in their evolutionary history (Barandiaran 2026; Christensen and Bickhard 2002; Kauffman 2000; Mossio et al. 2009; Rosen 1991).

The organisational approach comprises a family of concepts ordered by dependence. Closure of constraints is its constitutive concept (Moreno and Mossio 2015, p. 197), while autonomy, adaptive regulation and agency denote further levels of organisational complexity. It is therefore premature to ask whether the Earth system is autonomous or agentive before establishing that the organisation presupposed by these concepts is present at all. Moreover, these concepts were developed for cells and organisms, of which there are indefinitely many instances. The Earth system, by contrast, is unique and *sui generis* (Latour and Lenton 2019): the only living planet we know, and therefore

¹Lenton et al. (2020) define Gaia as “Life plus its effects on habitability”, which is formally more restrictive than “the Earth system”, which would include elements that have not been modified by Life in ways that affect habitability. At sufficiently long time scales, however, it is difficult to identify any component of the Earth unaffected by the presence of life or irrelevant to its habitability. We provisionally treat the two as tendentially coextensive (a claim we return to below), and situate the inquiry within Earth system science. On other accounts, the coupled Life-environment system is referred to as the biosphere, which is sometimes also defined as the part of the Earth occupied by living beings. Because of this ambiguity about the inclusion or not of non-organic elements, we prefer to avoid this term when referring to the system at stake.

without a second case against which to test its description. The constitutive question must thus be addressed directly: does the Earth system realise closure of constraints?

This paper brings together two debates. The first concerns the applicability of closure of constraints above the organism, where the ecological case has been the main site of discussion. The accounts developed there locate closure within a larger system which remains unspecified; we propose the planetary set of constraints as a candidate. The second concerns the biological character of the Earth system. Here we defend the thesis that the populations of protein complexes catalysing the planet's redox transformations, the atmospheric oxygen inventory they sustain, and the surface water inventory through which most of the resulting dependencies run constitute a set in which each constraint is both dependent and enabling. Some of the conditions of their existence are not given from outside but maintained within the set. On this account, the Earth system is the largest scale at which biological organisation, understood as closure of constraints, is realised.

Constraints and Closure

The notion of constraint at work in the organisational tradition is a specification of a considerably older and broader one. In classical mechanics, constraints are auxiliary conditions that reduce the degrees of freedom available to the elements of a system. Polanyi (1968) transposed the idea to biology, describing organisms and machines alike as systems under “dual control”, in which a structure serves as a boundary condition harnessing the physical and chemical processes by which the parts perform their functions, with the crucial difference that, in organisms, the harnessing principle is not imposed by a designer. On Pattee's (1972) account, a constraint is a material structure that reduces the degrees of freedom of the entities on which it acts. It differs from a law of nature in several respects: laws are inexorable and incorporeal, whereas constraints are contingent, local and physically embodied; and a constraint provides an alternative description of part of a system, framed at a different level from the detailed dynamics it simplifies. The notion is not proprietary to biology: Pattee's own examples include table tops and switches. Nothing in the concept of a constraint therefore distinguishes the living from the non-living. That work is done by the way constraints are organised. (For an overview of these lineages, see Umerez and Mossio 2013.)

Moreno and Mossio (2015) and Montévil and Mossio (2015) reformulate the organisational tradition's notion of closure in terms of constraints. The reformulation rests on two conditions: a constraint is conserved at the time scale at which it acts on a process, and it is itself produced or maintained by processes operating at a different time scale. An enzyme, for example, is unaffected by the reaction it catalyses at the time scale of that reaction, while it is synthesised and degraded on another. Neither condition applies to an entity as such. A structure counts as a constraint only with respect to a specified process and at the characteristic time of that process, understood as the time in which the process runs its course rather than the period over which the structure happens to endure (Montévil and Mossio 2015, n. 14).

Constraining is likewise the work of specified aspects of an entity, rather than of the entity as a whole. The relevant aspects are those conserved with respect to the process at

the scale at which it runs: in the paradigmatic case of enzymes, the concentration and spatial distribution of a population of enzymes, rather than the individual molecules altered in catalysis (Montévil and Mossio 2015, n. 13). Inputs consumed by a process are therefore excluded. Reactants are material causes, and a constraint plays no part in the balance equation of a reaction (Montévil and Mossio 2015, §3; Moreno and Mossio 2015, p. 50). That a further process replaces what is consumed does not alter this point. Conversely, a quantity temporarily removed from a constraint and returned before the end of the process remains conserved with respect to that process, as ATP does with respect to the transfer of energy from glycolysis to a target reaction (Montévil and Mossio 2015, n. 18).

Dependence between constraints can be of two types, distinguished by which of the two time scales is longer. Where the process that maintains a constraint is slower, the constraint stands as fixed background to what it acts upon: ribosomes and messenger RNA maintain an enzyme over a period spanning many catalytic cycles, while the enzyme's stability costs the system relatively little at the scale of those cycles. Where the maintaining process is faster, by contrast, a structure persisting over a long period does so only because processes much quicker than that period continually restore it. Their rapid turnover must therefore average into something stable at the longer scale. Alkaline phosphatase, produced on the time scale of protein synthesis, constrains the slower process of bone mineralisation (Montévil and Mossio 2015). Stability here is continuously earned, and lapses if the restoring process does.

Closure is then a property of a set of such constraints, in which every constraint is both dependent and enabling. It is dependent because its conditions of existence are produced by processes constrained by other constraints in the set; it is enabling because it constrains processes whose outcomes contribute to the maintenance of other constraints. A closed set must realise both slow and fast dependence (Montévil and Mossio 2015, §5): if every constraint were maintained more slowly than the process it constrains, each would refer for its maintenance to a constraint acting at a still longer scale, and a strictly increasing series of time scales could never return to its origin.

Closure of constraints differs from the closure of processes that Moreno and Mossio find in Varela's account of organisational closure (Moreno and Mossio 2015, §1.1; Varela 1979, p. 55): a loop in which each process contributes to the maintenance of the others, as clouds generate rain and the water returned to the sea regenerates clouds. Moreno and Mossio object that the entities so related do not act as constraints on one another, since each is transformed in producing the next. They therefore locate closure at the level of constraints (2015, §1.1; p. 23, n. 29).

Closure so understood grounds further ascriptions: a constraint has a function, and with it a teleology and a norm, in virtue of its contribution to maintaining the closed organisation to which it belongs (Mossio and Bich 2017; Mossio et al. 2009).

Moreno and Mossio take closure of constraints to be a general invariant of biological organisation across systems and realisations. The constraints subject to closure constitute that organisation and determine the identity of the system (2015, p. 23). In their technical sense, a biological organisation exists just where a set of constraints

realises closure, and every such organisation is closed and functional by definition (2015, p. 72, n. 4). The question of whether the Earth system is biologically organised is therefore a question of whether it realises closure of constraints. This is the question we examine here.

The Hydrological Cycle and its Dependencies

In the organisational literature, biogeochemical cycles, and the hydrological cycle in particular, occupy a curious position. They are regularly invoked as a *reductio*: the hydrological cycle is a circular causal system, yet it is evidently not in itself biological; therefore circularity alone does not suffice for biological organisation, or else it would be too permissive (Moreno and Mossio 2015, p. 4; Mossio and Bich 2017; cf. Fox Keller 2007)². As Moreno and Mossio put it, the entities involved in the water cycle, namely clouds, rain, rivers and seas, are connected in a cycle of transformations, but they do not act as constraints on each other in the requisite sense; the water cycle can be adequately described by appealing to external boundary conditions acting on a single causal regime of thermodynamic changes (Moreno and Mossio 2015, p. 23). The conclusion drawn from the example is that circularity is necessary but not sufficient for biological organisation, with which we agree.

The hydrological cycle thus serves as an uncontroversial example of a system in which circular causality is present without biological organisation. But is the Earth's water cycle really a merely physical, circularly causal cycle and thus clearly not a "specifically biological" process? The assumption deserves examination because it leads directly to the planetary scale.

The example, as illustrated by Moreno and Mossio, is drawn from a schematic cycle of evaporation, condensation, precipitation and runoff, in which water passes over and through the land rather than through anything living. The Earth's terrestrial cycle is not adequately represented by that form: the greater share of evaporation from land is transpiration through vegetation (Good et al. 2015), and evaporation from land supplies some 40% of the precipitation falling on it (van der Ent et al. 2010). This does not make the cycle biological, since life depends on many constraints it does not produce; it means that the description under which the cycle serves as a counterexample is not a description of the cycle the Earth has.

The hydrological cycle does not produce the conditions on which its circularity rests. The same is true of the carbon, nitrogen and phosphorus cycles: none of them establishes by itself the temperature, atmospheric composition or nutrient availability its operation requires. But this is no different from the situation of the parts of a living system. The circulation of blood depends on a temperature, a pressure and a chemistry that it does not itself establish, and taken alone it is equally describable as a loop of transformations under externally given boundary conditions. What that description

² In that context, the hydrological cycle is referred to as belonging to a class of "biologically irrelevant" systems (Moreno and Mossio 2015, p. 4). What is at issue is not whether such systems are biologically relevant. Gravitation is relevant to organisms without being subject to closure (We owe this example to an anonymous reviewer). It is whether their circularity is of the "closure" kind.

leaves out is the larger system in which those conditions are maintained, and how the cycle itself contributes to their maintenance. The question, then, is whether closure of constraints is a property of the planetary system as a whole.

The hydrological cycle does not operate alone. Carbon moves through photosynthesis, which draws CO₂ from the air and builds the compounds heterotrophic life consumes, and returns through respiration and decomposition. The two do not proceed independently, and their dependence is not exhausted by the material they exchange: each requires conditions the other helps maintain. Water circulates only at temperatures at which it is liquid and vapour, and those temperatures depend in part on the carbon dioxide the carbon cycle leaves in the air. Terrestrial photosynthesis requires water and the nutrients that percolating water liberates from rock in place, while runoff carries the remainder to the sea. Much of that water returns to the atmosphere through transpiration, which supplies a substantial share of continental precipitation (Good et al. 2015; van der Ent et al. 2010). In each case, what one process requires is held in place by the operation of another.

These conditions differ from those under which ordinary processes run. A ball rolls as the slope of the plane dictates; a river follows the depression in the ground. These processes may modify their conditions, but do not depend on that modification in order to continue (Mossio and Bich 2017, pp. 1104, 1106). Each cycle proceeds under conditions established by the operation of the others, and the coupling runs in both directions. What needs to be established is what is doing the constraining.

Constraints at the Planetary Scale

Almost every transformation through which carbon, nitrogen, sulphur and oxygen move between the atmosphere, oceans, soils and living matter involves an electron transfer. This is one of the deepest chemical differences life has made to the Earth's surface. Abiotic geochemistry proceeds predominantly through acid–base reactions, involving the transfer of protons without electrons. Life introduced a vast network of catalysed redox transformations, driving elements repeatedly between chemically distinct forms and reservoirs. What catalyses these processes is a small set of multimeric protein complexes, which arose early in microbial lineages and have been conserved since (Falkowski et al. 2008). The lineages carrying them appear and go extinct while the complexes persist, redistributed among whichever organisms currently hold them. What the planet holds fixed is not the carriers but the set of transformations, which is complete only at planetary scale (Smith and Morowitz 2016, pp. 11, 51–52). These protein complexes are the same kind of entity that Montévil and Mossio treat as a constraint: a population of enzymes specified by its concentration and spatial distribution (2015, n. 13), only distributed over a planet instead of over a cell.

Both conditions on a constraint are met at this scale. Without the complexes the transformations remain possible in principle, but occur so slowly as to be quantitatively irrelevant; the causal role of the complexes is to bring them to a rate at which they make a difference (Montévil and Mossio 2015, §3). Nor are the complexes consumed by what they drive. Individual molecules are degraded and replaced, while the concentration and

spatial distribution of the population are conserved with respect to the transformations it catalyses.

A population of enzymes may be renewed more quickly or more slowly than the process it acts upon, depending on which process that is. Montévil and Mossio give both possible orders, and both of their examples concern enzymes: an enzyme referred to the reaction it catalyses is maintained more slowly than that reaction runs, whereas alkaline phosphatase, referred to bone mineralisation, is maintained faster than what it constrains (2015, §4). At the planetary scale, the process at issue is the redistribution of an element between its reservoirs. Such a process runs at the pace at which those reservoirs fill and empty (Montévil and Mossio 2015, n. 14). An element may pass through the atmosphere in years and through the deep ocean in tens of thousands of years. The populations of protein complexes are maintained over the lifetimes of their carriers, and therefore more quickly than these planetary processes. The same kind of entity that stands in slow dependence within a cell thus stands in fast dependence at the planetary scale.

These complexes consequently do more than accelerate isolated chemical reactions. Taken together, they keep the surface of the planet away from chemical equilibrium. Photosynthesis splits water, stores electrons in organic matter and releases oxygen. Respiration and decomposition return those electrons, but a fraction of the organic carbon escapes this return through burial. The result is an oxidised atmosphere and surface ocean coexisting with abundant reduced material, a state that persists only for as long as the transfers continue, and which would not exist in a lifeless Earth (Falkowski et al. 2008). The atmospheric oxygen inventory is accordingly the first non-living constraint in the set, produced through a process constrained by another.

The oxygen inventory acts back on the complexes, but not by being consumed. Individual oxygen molecules are consumed in respiration; the distribution of oxygenated conditions is not. Aerobic respiratory complexes can be maintained only where oxygenated conditions persist. Early in the history of life, aerobic respiration was confined to the immediate vicinity of the cyanobacteria supplying the oxygen, whereas aerobic conditions are now widespread across the surface (Falkowski et al. 2008). The inventory is renewed over millions of years while the populations it permits are rebuilt within days, so the complexes depend on it in the slow way, the inventory standing as fixed background to what it constrains. The set therefore realises dependence of both kinds, as closure requires (Montévil and Mossio 2015, §5).

Water is a constraint of this set that the organisation recruits rather than produces. Consider the removal of carbon dioxide from the atmosphere by silicate weathering and carbonate formation, which runs over hundreds of thousands of years. Liquid water canalises that removal throughout: hydrolysis proceeds in solution, and the transport of dissolved products away from the reacting surface keeps the reaction from saturating. Water is taken up where silicate is hydrolysed and returned where carbonate precipitates, so the overall balance equation, from silicate and carbon dioxide into carbonate and silica, does not contain it. Montévil and Mossio allow for exactly this case: a quantity temporarily removed from a constraint and returned before the process

is complete remains conserved with respect to it, their example being ATP, which constrains the transfer of energy from glycolysis to a target reaction because that transfer leaves it invariant (2015, n. 18). The surface water inventory stands in the same relation to the removal of carbon, a reactant in hydrolysis considered alone, but a constraint on the complete process of which hydrolysis is one part.

The aspect of the inventory on which that role depends is narrower than the inventory as a whole: the presence and turnover of liquid water at the continental surface, where weathering and terrestrial photosynthesis both take place. That aspect is maintained in part within the set. Most of the water leaving the land leaves it through vegetation, and evaporation from land supplies a substantial share of the precipitation returning to it. Water enters more dependencies than any other constraint named here. Montévil and Mossio observe that membranes enter so many dependencies that including them in the graph sharply increases the closure of the volume considered (2015, §6.1). Water seems to occupy that position at the planetary scale. Its circulation is a sequence of physical transformations from beginning to end, and it is the circulation through which most of these dependencies run.

Recruitment of a physical structure to the biological organisation sits inside Montévil and Mossio's account. Their definition of dependence requires that a constraint act on a process producing those aspects of another constraint that are relevant to its role as a constraint, not that it produce the constraint entirely (2015, §4). The set need not produce the water; it is enough that it maintains the aspect of it that does the constraining, namely, water standing and moving at the continental surface in the quantity and at the rate at which it moves there. Their treatment of maintenance points in the same direction: constraints degrade and must be replaced or repaired, and dependence holds where that replacement or repair depends also on the action of another constraint.

Bich (2019, p. 299) treats a case of the same form. A prebiotic system that realises closure but cannot generate a compartment relies on environmental scaffolds for spatial control, recruiting constraints it finds in its surroundings, such as micro-pores in rock, and does not thereby cease to realise closure. The case carries a condition: where the system exerts no influence on the generation of the external constraint, the recruitment does not extend the organisation, and the structure remains external to it. On this criterion, that aspect of the water inventory is maintained in part within the set, and the inventory is therefore a recruited constraint belonging to it³.

The Earth is a physical body before it is a biological one. An organism produces the structures that hold it together and loses them when it dies, whereas the Earth would persist as a planet if life disappeared from it. Recruitment is then a distinctive feature of an organisation of this kind: the structures it harnesses exist independently of it, and it maintains the aspects of them that do the constraining without producing them. Closure

³Harding and Margulis (2010) make a stronger claim, arguing that without life's involvement in geological, atmospheric and metabolic processes the Earth would long since have lost its water and become a dry world comparable to Mars or Venus. On that account, the water inventory could be seen not as recruited but as a constraint produced within the system.

is always realised relative to boundary conditions, and no organisation includes every constraint with which it causally interacts (Moreno and Mossio 2015, p. 23). What separates a closed organisation from a self-organising structure is the takeover of part of those conditions, maintained collectively rather than by any constraint on its own (Moreno and Mossio 2015, p. 17).

The Quaternary as a Regime of Self-maintenance

The constraints described in the previous section have persisted in their mutually constraining configuration for hundreds of millions of years, possibly throughout the Phanerozoic.

The Quaternary concerns a much shorter span. Beginning 2.58 Ma, it is the late phase of a cooling that has run since about 50 Ma. It is characterised by low atmospheric carbon dioxide, permanent polar ice, and highly productive terrestrial biomes (Inglis et al. 2015; Retallack 2001). It features several new entities that act as constraints. Continental ice sheets, maintained over millennia by accumulation and loss, hold the planetary albedo. Deep soils, formed over comparable periods, retain water and nutrients and set the rate at which silicate weathering draws carbon down. Grassland and forest biomes, renewed on much shorter time scales, determine how much water returns to the atmosphere from land. All of these constraints took their present form in the later Cenozoic, over the last 35 million years.

The Quaternary is therefore, in Moreno and Mossio's terms, a regime of self-maintenance: one organisation among those a closed system may pass through as new stable dependencies between constraints are established (2015, p. 33). Montévil and Mossio take closure to be an invariant of biological organisation in a precise sense: a description of closure is available for any interval long enough to contain a sufficient set of constraints and their mutual dependencies (2015, §7). Invariance so understood is compatible with change in the constraints themselves. Their structure and function may alter; and constraints subject to closure enable the emergence of further constraints, so the organisation continues through the acquisition of some functions and the loss of others (2015, §7). The ice sheets, soils and biomes of the later Cenozoic are entries of this kind. The hothouse of the Cretaceous and early Paleogene (roughly 145 to 34 Ma), with high carbon dioxide, ice-free poles and a different distribution of primary production, was another such regime. The deeper constraints were in place then as now; those of more recent standing had not yet entered the set. Both realise closure, but the sets that realise it are not the same.

From Ecosystems to the Planetary Scale

Nunes-Neto et al. (2014, p. 131) define an ecological function as a precise effect of a constraining action on the flow of matter and energy, exerted by an item of biodiversity within an ecosystem closure of constraints. The item may be a trait, a population or a functional group, depending on what is being examined; El-Hani and Nunes-Neto (2020) later extend the class to abiotic items produced within the closure. They model the constraining action on the enzyme: items of biodiversity harness transformations of nutrients that would otherwise proceed very slowly or not at all. The constraint we have

identified at the planetary scale is the same, namely a population of catalytic structures individuated by the transformation it catalyses, taken at the scale at which that transformation is complete.

Two features of the theory help determine the scale at which the closure should be located. The first concerns individuation. El-Hani et al. (2024, p. 302) answer the charge that ecological systems are rarely closed by extending Montévil and Mossio's tendency to closure from symbionts to modules generally: a module with a high degree of internal cohesion is not strictly closed, but tends to closure within a containing system that is itself closed, with closure proper belonging to the maximally closed system, the one including all the mutually dependent constraints a description makes available. The second concerns abiotic items, which are functional only where constraints subject to closure produce them and they enter in turn into the production of others; otherwise they are boundary conditions, although El-Hani et al. (2024, p. 310) add that such an item may be functional if a system at a higher scale is modelled instead. Nunes-Neto et al. (2014, p. 134, n. 9) classify the solar radiation, temperature, rain and wind acting on their example as limiting factors of this kind. Neither account specifies the larger system in which the closure is embedded. We propose the set of constraints described above as a candidate: catalytic populations, the oxygen inventory and the surface water inventory, all of them planetary in extent.

The most fully worked application above the organism is El-Hani and Nunes-Neto's (2020) treatment of the life-clouds system. Marine microbiota release dimethyl sulphide, whose oxidation products seed the clouds that carry sulphur over land, from which rivers return it to the ocean and to the microbiota that emitted it. Microbiota and clouds are each dependent and each enabling, and the clouds bear functions as abiotic items. Their set is planetary in extent, and their question is how a sulphur circuit that was once a closure of processes became a closure of constraints. It remains a single-element cycle, and the conditions under which it runs are not at issue there: the account begins with microorganisms drawing on the resources of an oxidative atmosphere, and the circuit runs throughout in liquid water. Those are among the conditions we have described as maintained.

The continuity with our framework is clearest at the first step of that circuit. Their own example of a constraint is the enzyme with which the life-clouds system begins: DMSP-lyase, individuated by the conversion it catalyses and shared by the algae that perform it (Nunes-Neto et al. 2014, p. 132).

Montévil and Mossio (2015, §6.2) conjecture that two closed regimes constitute distinct levels of organisation where they are both nested and separated, with separation happening where the lower-level units do not act as constraints individually. Individual epithelial cells contribute negligibly to the regulation of insulin levels. The relevant constraints arise only from their collective organisation into tissues and organs. The planetary case has the same structure. No organism constrains the Earth system. What constrains it is the concentration and distribution of a catalytic population across the planet, an aspect that is not defined at the scale of any of its carriers. Planetary closure is

nested with respect to organismic closure and separated from it, and would therefore constitute, on their conjecture, a level of organisation in its own right.

Closure of Constraints and the Question of the Living Earth

The claim that the Earth is alive has usually been made by identifying the Earth system as an instance of a kind: an organism, a cell, a superorganism. Instances of each of those kinds are found within the Earth system, so the whole is described as a larger specimen of one of its own parts. Descriptions of this sort, like Russian dolls, leave unexamined what most needs explaining: how specific levels of biological organisation differ and how they depend on one another.

The same objection could be turned against us, since closure of constraints was worked out for cells and organisms. But closure is not a kind of entity. Montévil and Mossio define it as a causal regime in which the mutual dependence of constraints is organised across a thermodynamic flow, and ask of a given system whether it realises that regime, whatever kind of thing the system is. Cells, organisms and the Earth system may all realise closure without belonging to one kind. The causal property is shared; the kinds remain distinct.

The analogies also answer a different question from ours. Militello (2025, p. 34) sets the two concepts apart by the question each answers: closure of constraints bears on what distinguishes biological from non-biological organisation, functional integration on what makes a biological organisation an individual rather than a collective. Viruses, bacterial colonies and insect colonies would be cases of collective biological organisations. Our argument concerns the first question. That the Earth system realises closure establishes that it is biologically organised; it settles nothing about whether it is an organism, an individual, or autopoietic, and we make no claim on those questions here.

Lovelock and Margulis (1974) proposed that the Earth's surface is regulated by and for the biota inhabiting it. Dutreuil (2024) brings out what the formula settles in advance: regulation takes the environment or the coupled system as its object, never the biota, which is left as the agent of regulation and its beneficiary. Both halves then require an owner: something must do the controlling, and something must benefit. The beneficiary was never identified. Schneider (1986) and Kirchner (1989) asked which organisms gain and which lose when a global variable is held near one value rather than another, and the question has been avoided rather than answered (Dutreuil 2024). The controller has been supplied in two incompatible ways. Either the distinction between the living and its environment is dissolved, the Earth's surface counting as a vital extension of organisms on the model of the termite mound (Lovelock 2000, p. 64; Turner 2000), or it is retained and the abiotic becomes what the biotic builds (as in the beaver's dam), so that ecosystems are constructions rather than superorganisms and Gaia their principal case (Odling-Smee et al. 2003, pp. 334–336). The two answers differ only over whether such structures belong to the living system. Neither disturbs the premise they share: the biotic elements are the source of order, the abiotic the material on which order is imposed.

The constraints identified above do not divide that way. The biotic ones are classes of protein complexes, each individuated by the transformation it catalyses. Taken singly, such a constraint has no detector, no set point and no end of its own, and it constrains as a population of enzymes constrains a reaction, by reducing degrees of freedom rather than by governing. The abiotic ones are not mere products of biotic activity, but constraints acting back on the processes that produce them. Dependence runs in both directions between items of both kinds. Biotic and abiotic name materially different constraints within one organisation, not an agent and its environment. Rubin et al. (2021) reach a convergent result from the autopoietic side: in a model planetary reaction network, self-production is distributed across reaction pathways rather than localised in any unit.

None of this makes life incidental. Nothing else at the Earth's surface does what life does, and the complexes that hold the redox state far from equilibrium do not persist outside organisms. Lineages synthesise them, replace them and pass them on (and around), and only a lineage both maintains itself metabolically and transmits what it has come to do: the crossing of self-organising and evolutionary processes at which the organismic level sits (Ruiz-Mirazo et al. 2000). Organisms are nevertheless not constraints within the planetary closure that has been outlined above: what constrains the Earth system at the longest scale is the distribution of catalytic populations across their carriers, not any carrier, and organismic closure forms a separate level beneath it. Organisms are instead the condition under which the biotic constraints are produced and maintained.

On the organisational account, the “for” points to the maintenance of the organisation, which is what makes functions attributable: a constraint is functional in virtue of its contribution to the closed regime that maintains it, and not in virtue of a benefit accruing to some party (Mossio et al. 2009). Dutreuil sets this route aside, taking the criteria for identifying the Earth system as the same system persisting through time to raise immediate philosophical difficulties, and reduces the good of Gaia to the maintenance of life at the planet's surface (2024). Closure supplies those criteria. What makes the Earth system the same system over time is neither its material composition nor its spatial extent, but the persistence of a regime of mutually dependent constraints across the turnover of the components that realise it.

This allows the question left open in footnote 1 to be stated precisely. Lenton et al. (2020) define Gaia as life together with its effects on habitability, and the definition contains a return: an effect counts only if it feeds back on the conditions of life. Closure states that return formally, with the set of constraints taking the place of life. A component belongs to the organisation if it is maintained, at least in part, by processes constrained by the set, and in turn constrains a process that contributes to maintaining the set. Otherwise it is a boundary condition. That Gaia and the Earth system tend to coincide at sufficiently long time scales is then a conjecture, to be established case by case.

Solar radiation and the Earth's internal heat mark the limits on either side. Solar radiation, with its orbital variation, reaches the organisation from outside the planet;

internal heat reaches it from below. Both condition the organisation without being maintained by it, and both supply energy and periodic forcing rather than organisational constraints. Tectonic processes are the open case. The heat that drives mantle convection is external to the organisation, but the convection it drives is a self-organised structure, of the kind the system can recruit. The surface water inventory is one likely route for the dependency (cf. Harding 2022, p. 402).

Here the Earth system departs most sharply from cells and organisms. Most of what lies outside a cell or an organism is itself organised: tissues, conspecifics, symbionts, prey, relations that are more than thermodynamic. What lies outside the Earth system, at the time scales considered here, is not. It may be the only biological organisation that has no living environment.

The Earth is then alive not by joining the category of cells and organisms, but as the largest scale at which Life, understood as a phenomenon rather than a property (cf. Lenton et al. 2020), is organised in a specifically biological rather than merely physical way, in a form *sui generis* to its conditions. We can therefore ask what functions and norms the Earth system has without asking it to be an organism.

Conclusion

The Earth system realises closure of constraints. It does not realise it within any single biogeochemical cycle, each of which remains describable as a sequence of transformations under externally given boundary conditions. Closure is realised across a set whose members belong to different cycles. Each constraint is conserved with respect to the process it constrains, and maintained by processes running at another scale, and the dependencies among them run in both directions and in both temporal orders. In Moreno and Mossio's technical sense, this is a biological organisation. What this paper has shown is therefore that the Earth system meets a criterion formulated to distinguish biological from merely physical organisation, and formulated for cells and organisms rather than with the planet in view. By that criterion, our planet is living.

We have not specified a complete planetary loop, and the set described (protein complexes, oxygenated atmosphere, surface water inventory) is not offered as a full list. What the argument requires is that constraints of these kinds stand in mutual dependence at the planetary scale, and that the organisation they form has persisted across changes in its membership, of which the Quaternary is one regime among others.

Mossio and Bich (2017) hold that closure grounds teleology: the constraints of a closed organisation exist because of what they do, and what they do is maintain the conditions under which they exist, so that teleological and functional vocabulary applies to such a system literally rather than as a gloss on efficient causation. If the Earth system realises closure, this applies to it as well. Earth system science already describes the planet in these terms (regulation, biogeochemical function, the maintenance of habitable conditions) while treating the vocabulary as shorthand for feedback. On the organisational account it would be warranted, under a criterion that can be applied case by case: a planetary structure is functional where it constrains a process contributing to the maintenance of the set that maintains it, and is a boundary condition otherwise.

None of this yields a prediction or a mechanism that biogeochemistry does not already describe. What changes is what is being said when the operation of these structures is called a function. On the same account, a function comes with a norm. Whether the Earth system has norms of its own, and whether anything (the current climate crisis included) can be good or bad for it, is the question this one leads to, and we pursue it elsewhere.

Declarations

Competing interests

The author has no relevant financial or non-financial interests to disclose.

Funding

A.M. carried out this work in the context of Grant PID2023-147251NB-I00 for project “OUTAGENCIES: Varieties of autonomous agency across living, humanimal and technical systems” (PI Xabier Barandiaran) funded by MCIU/AEI/10.13039/501100011033 and FEDER/EU.

Acknowledgements

Some of the ideas in this paper were first presented, in a much earlier form, at the OUTONOMY workshop (Donostia-San Sebastián, 22–24 June 2022), in a talk titled “Autonomy and the Earth system” co-authored with Xabier E. Barandiaran. I thank the participants for their comments. I am grateful to Xabier E. Barandiaran, Maël Montévil, Sergio Rubin and Kepa Ruiz-Mirazo for their comments on an earlier draft of this paper, and to the editors and two anonymous reviewers of Biological Theory, whose suggestions substantially reshaped it. The views expressed here, and any remaining errors, are mine alone.

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