Closure of Constraints in the Earth System: Biogeochemical Cycles and Planetary-Scale Biological Organisation

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Abstract

The concept of closure of constraints has been developed as a characterization of the distinctive causal regime at work in biological systems. Its extension to ecological systems has been attempted but faces persistent difficulties regarding the individuation of ecosystems and the scope of functional ascription. Meanwhile, the question of the biological character of the Earth system (variously approached through the concepts of organism, autopoiesis, and self-regulation) remains open, and the available frameworks each illuminate certain aspects of the planetary system while leaving others unaddressed. In this paper, I argue that the closure-of-constraints framework provides an especially apt conceptual tool for articulating what is specifically biological about the organisation of the Earth system, and that the planetary scale may provide a more tractable domain for this framework than the ecosystem. The central claim is that organisational closure does not reside in any individual biogeochemical cycle (which are regularly but misleadingly used as examples of merely physical circularity) but in the organisation that the Earth’s biogeochemical cycles form together. Each cycle maintains flows and levels of distinct elements, but can only do so if the others are also functioning; together they sustain system-level properties that are simultaneously conditions and expressions of a determinate organisational regime. I illustrate this with the Quaternary period as an example of an evolved, stable organisational state. The paper contributes both to the ongoing debate on the applicability of closure of constraints to supra-organismal systems and to the broader question of the nature of the living Earth system.

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

1. Introduction

One of the most productive developments in recent philosophy of biology has been the elaboration of the concept of closure of constraints as a characterization of biological organisation. Developed principally by Moreno and Mossio (2015) and formalized by Montévil and Mossio (2015), this concept identifies the distinctive circular causal regime at work in living systems. Closure of constraints designates a situation in which a set of constraints (entities that channel and harness the thermodynamic flow while exhibiting some form of conservation at the relevant time scales) mutually depend on one another for their production and maintenance. The organisation of such constraints achieves self-determination as collective self-constraint (Moreno and Mossio 2015; Mossio and Bich 2017). Unlike cycles of processes describable at a single causal level under externally given boundary conditions, closure involves an inter-level causal regime: constraints at one level maintain themselves by channelling processes and reactions at another (Mossio and Bich 2017). Aiming to ground teleology, normativity, and functionality in a naturalistic manner (Mossio et al. 2009; Mossio and Bich 2017), this concept has become central to the organisational tradition in the philosophy of biology.

In recent years, efforts have been made to extend the concept beyond the individual organism. Nunes-Neto et al. (2014) proposed an organisational theory of ecological functions, and El-Hani et al. (2024) have further developed this framework, responding to criticisms about its scope. These are important steps, but the extension remains tentative and the models rather abstract. A recurring difficulty concerns the individuation of ecosystems: ecological systems interpenetrate at their fringes, their functional boundaries are fuzzy, and their dependence on externally given boundary conditions is pervasive (Lean 2021; Dussault and Bouchard 2017). As El-Hani et al. (2024) themselves acknowledge, ecological systems are more directly determined by external boundary conditions than organisms, and their closure, when it can be identified, is more basic and less tightly integrated.

In parallel, the question of the biological character of the Earth system has been a recurrent theme since Lovelock and Margulis (1974) first proposed that the Earth's atmosphere, oceans, and surface environments form a self-regulating system shaped by the activity of living organisms. This research programme has given rise to the field of Earth system science (Lenton 2016; Steffen et al. 2020; Dutreuil 2024) and to a range of theoretical proposals regarding the nature of the living Earth system, including descriptions of the Earth as an autopoietic system (Margulis 1997; Rubin et al. 2021), as an organism (De Castro 2019; Meynell 2025), and as a self-regulating system whose stability can be accounted for through mechanisms such as sequential selection (Lenton et al. 2020; Rubin and Crucifix 2022). Each of these proposals illuminates certain aspects of the Earth system's distinctive character, but each also leaves important questions open, as I shall discuss below.

In this paper, I contend that the closure-of-constraints framework provides an especially apt conceptual tool for articulating what is specifically biological about the organisation of the Earth system. It does so without requiring the strong claims (that the Earth is an organism, that it is autopoietic in the cellular sense) that have characterised some alternative approaches, while also going beyond a purely thermodynamic description. The central argument is this: the biogeochemical cycles of the Earth system (water, carbon, nitrogen, phosphorus, and others) are regularly invoked in the organisational literature as examples of merely physical or chemical circularity, to be contrasted with the genuine closure found in biological systems (Moreno and Mossio 2015; Ruse 2003; Fox Keller 2007). This dismissal, I argue, is correct at the level of the individual cycle but misleading about the planetary system as a whole. For these cycles are not isolated; they are mutually dependent, and the organisation formed by their interdependence exhibits precisely the kind of closure of constraints that the framework was designed to capture. Each cycle maintains levels and flows of distinct elements, but can only do so if the others are also functioning, and together they sustain system-level properties that are at once conditions for and expressions of the organisational regime. This is the locus of closure: not any individual cycle, but the system of cycles.

This paper thus contributes to two converging debates. It advances the discussion on the applicability of closure of constraints to supra-organismal systems by suggesting that the planetary scale, rather than the ecosystem, may be where this framework proves most productive. And it contributes to the broader question of the nature of the living Earth system by offering a characterization (closure at the system-of-cycles level) that captures its specifically biological organisation without relying on analogies with organisms or cells.

2. Conceptual Analysis

2.1 Biogeochemical Cycles: Between Dismissal and Integration

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 circular, yet it is evidently not a living organisation; therefore circularity alone does not suffice for biological organisation, and something more (closure of constraints) is needed (Moreno and Mossio 2015, p. 2; Ruse 2003; Fox Keller 2007; Mossio and Bich 2017). As Moreno and Mossio put it, the entities involved in the water cycle (clouds, rain, rivers, seas) are connected in a cycle of transformations, but they do not act as constraints on each other in the requisite sense; the system 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 (that circularity is necessary but not sufficient for biological organisation) is sound. However, the argument as typically deployed assumes as a premise a definite position on what we are inquiring: namely, that processes at the planetary scale are not part of a biological organisation. The hydrological cycle is used to show that mere circularity is not enough, but it is simultaneously taken for granted that the cycle is “biologically irrelevant” (Moreno and Mossio 2015, p. 4).

This assumption deserves scrutiny. Two observations are in order. First, the hydrological cycle in its current configuration is deeply reliant on living activity (for instance, evapotranspiration by terrestrial vegetation is a major driver of the cycle’s intensity and geographic distribution (Kleidon 2016; Merlo and Barandiaran 2024)) and, reciprocally, virtually all terrestrial life depends on the hydrological cycle for water and nutrient delivery. One can hardly call a system on which all known life depends, and which is itself substantially shaped by living activity, biologically irrelevant.

Second, and more importantly for the argument of this paper, the water cycle’s circularity depends on conditions (i.e. temperature within the range that allows phase transitions of water, atmospheric composition, the availability of nutrients carried in solution) that are maintained by the operation of other biogeochemical cycles at the planetary scale. The same holds for the carbon cycle, the nitrogen cycle, and the phosphorus cycle. None of these, taken individually, constitute closure of constraints; each is a circular chain of transformations dependent on conditions that it does not itself generate. This is not a novel or contentious observation. The interesting question (which the standard treatment overlooks) is whether the organisation formed by the interdependence of these cycles constitutes a closure of constraints. It is this question that the present paper addresses.

2.2 Closure as a Property of the System of Cycles

To develop the argument, consider first a simplified model of the Earth system reduced to two cycles and their interaction. The hydrological cycle, besides its own causal circularity (evaporation, condensation, precipitation, runoff), constantly delivers water, dissolved nutrients, and erosion products to living organisms and continental surfaces. The quick carbon cycle supplies CO2 to photosynthesis, which produces organic compounds sustaining heterotrophic life; respiration and decomposition return CO2 to the atmosphere. Through the greenhouse effect, the carbon cycle helps maintain a temperature on the Earth's surface warm enough for water to exist in both liquid and gaseous phases — which is precisely what the hydrological cycle requires. The hydrological cycle, in turn, powers evapotranspiration by vegetation and transports sediments and nutrients, thereby sustaining the photosynthetic activity on which the carbon cycle depends.

What appears here is not two cycles running side by side but a mutual dependence irreducible to either one alone. The carbon cycle constrains the conditions under which the hydrological cycle can operate (through temperature regulation), and the hydrological cycle constrains those under which the carbon cycle can operate (through water and nutrient delivery). Each acts as a constraint on the conditions of possibility of the other. Crucially, this is an inter-level causal regime: the boundary conditions of each cycle are not "externally" given but are produced by the constraining activity of the other cycles within the system.

We can develop this picture by bringing in nitrogen and phosphorus. Nitrogen fixation, largely performed by specialised microorganisms, depends on soil moisture, temperature, and organic matter availability — conditions maintained by the hydrological and carbon cycles. The biologically available nitrogen that results is indispensable for protein and nucleic acid synthesis, and hence for the photosynthetic organisms that drive the carbon cycle. Likewise, the phosphorus cycle (set in motion partly by the weathering of rocks, a process that itself depends on the hydrological cycle and on biotic enhancement of weathering) supplies an element without which energy metabolism (ATP) and genetic replication (DNA, RNA) cannot proceed. If phosphorus availability drops, biological productivity collapses, and the biotic contributions to both the carbon and hydrological cycles collapse with it.

These interdependencies span vastly different time scales. The quick carbon cycle (photosynthesis, respiration, decomposition) turns over in years to decades. The slow (so-called "inorganic") carbon cycle (silicate weathering, calcium carbonate sedimentation on the ocean floor, and the eventual return of carbon to the atmosphere through volcanic outgassing) operates over millions of years. This slower cycle is often treated as a purely geological process, but it is in fact substantially powered by living organisms: biotic weathering, carbonate sedimentation by marine organisms, and the formation of carbonate platforms are all processes in which life plays a constitutive role (Lenton 2016; Westbroek 1991). And this slow cycle acts as a long-term thermostat, regulating atmospheric CO2 and thereby safeguarding the conditions for the faster biological cycles. The temporal depth of the interdependence among cycles is thus itself a feature of the organisational regime.

The point, then, is not merely that these cycles are coupled (coupling is an empirical commonplace in Earth system science) but that their coupling has a specific organisational character. Each cycle keeps certain elemental flows and reservoirs within bounds, but can only do so because the other cycles are doing the same. Together they sustain an ensemble of system-level properties: the far-from-equilibrium thermodynamic state of the system (measurable in the coexistence of oxygen and methane in the atmosphere, the stark disequilibrium between atmospheric gases and surface organic compounds), a mean global temperature within the range compatible with liquid water and complex life, the availability of key elements (C, N, P, H2O) in biologically usable forms, and the periodicity and complexity that characterise the Earth's dynamics. These properties are, in different ways, simultaneously conditions for and expressions of the organisational regime. In the language of the closure-of-constraints framework, they result from the collective self-constraining activity of the system of cycles — an organisation in which the conditions of existence of the constitutive constraints are mutually determined within the organisation itself.

The argument can be sharpened with the help of the formal characterization proposed by Montévil and Mossio (2015). In their framework, a constraint Ci acts on a process Pj, and the result of this constrained process contributes to the maintenance of another constraint Ck. Closure obtains when, for each constraint in a set, there exists a path of such dependencies leading back to it: every constraint is both dependent (its existence depends on processes constrained by other constraints in the set) and enabling (it constrains processes whose outcomes contribute to the maintenance of other constraints in the set). Described at the level of individual cycles, each cycle's conditions of existence look like external boundary conditions — given from outside the system. Described at the level of the organisation formed by the interdependence of cycles, those same conditions turn out to be products of the constraining activity of the others. What appeared as external becomes internal.

What remains genuinely external, in this picture, is strikingly simple: the Sun's radiation and the variability of its forcing, together with the slow thermal energy rising from the Earth's core. This simple external input (essentially energy and periodic variation) corresponds well, in fact, to the thermodynamic openness that Moreno and Mossio (2015) establish as the counterpart to the organisational closure of biological systems (see also Ruiz-Mirazo and Moreno 2004). One could even say that this correspondence holds more neatly for the Earth system than for cells or organisms, since these are always embedded in organised species-level and ecological relations that are more than merely thermodynamic. The Earth system, by contrast, may be the only biological entity whose environment is genuinely abiotic.

2.3 The Quaternary as an Organisational Regime

An illustrative case for this argument is the Quaternary period. Over the course of the Cenozoic, the Earth system underwent a long-term cooling trend, culminating in the Quaternary: a period characterised by low atmospheric CO2 concentrations, an oxygenated atmosphere rich in chemical disequilibrium, extensive glaciation, and the development of highly productive terrestrial biomes (Retallack 2001; Inglis et al. 2015). From a thermodynamic perspective, this state can be described as one of increased dissipative activity and complexity, in which the productivity of the whole system has moved toward a maximum (Kleidon 2016; Merlo and Barandiaran 2024).

The Quaternary can be better understood not simply as a climatic state but as an organisational regime. The particular configuration of the carbon, hydrological, nitrogen, and phosphorus cycles during this period (involving, among other things, the the expansion of grasslands, the evolution of complex food webs, the development of deep soils, and the intensification of biological weathering) constitutes a specific realisation of organisational closure at the planetary scale. The system-level properties sustained by this organisation (cool temperatures, ice caps, strong chemical disequilibrium, high biological productivity, slow and regular glacial-interglacial oscillations) are at once the conditions under which the constituent cycles can function in their current form and the emergent outcomes of their collective operation.

3. Discussion

3.1 From Ecosystems to the Planetary Scale

The application of closure of constraints to ecological systems has generated important but contested results. The organisational theory of ecological functions (Nunes-Neto et al. 2014; El-Hani et al. 2024) proposes that ecosystems can realise closure insofar as producers, consumers, and decomposers establish mutual dependencies through their constraining actions on thermodynamic flows. This framework has faced criticisms regarding the difficulty of individuating ecosystems as closed systems. Lean (2021) argues that organisational closure is exceptional in ecological systems and becomes less likely as systems scale up in size and openness. Dussault and Bouchard (2017) have questioned whether the theory is too restrictive to accommodate key aspects of contemporary ecology. El-Hani et al. (2024) have responded by invoking the concept of “tendency to closure” (Montévil and Mossio 2015) and by demonstrating that the organisational framework has more resources than its critics assume.

The recurring difficulty, however, is real: at the ecosystem level, the boundaries of the closed system are fuzzy, functional relationships are modular and nested, and the system is always partially dependent on larger scale ecological relations and changes. These are not merely practical difficulties of description but reflect a genuine feature of ecological systems: they are less tightly integrated than organisms, and their closure, when identifiable, can only be partial and temporary.

The planetary scale offers a strikingly different situation. Here, the question of boundaries is largely resolved: the Earth system is naturally delimited by the planet itself, and the primary external inputs (thermal gradient with the core, solar radiation, cosmic radiation, meteoritic influx) are well defined and limited in kind. The persistent problem of ecosystem individuation (where does one ecosystem end and another begin?) simply does not arise. Moreover, the interdependencies among the biogeochemical cycles at the planetary scale are not partial or modular but pervasive and constitutive: each cycle’s conditions of existence are maintained by the others, and together they sustain system-level properties that cannot be attributed to any single cycle. The closure of constraints that proves difficult to establish and delimit at the ecosystem level becomes identifiable and articulable at the planetary scale. It may therefore be more productive to begin at the planetary scale, where the framework finds a clearer application, and to understand ecosystems as sub-systems or modules within this larger organisational closure. The functional contributions of microbial communities and other biotic components to global biogeochemical cycles can, from this vantage point, be understood as contributions to the maintenance of specific constraints within the planetary closure.

3.2 Closure of Constraints and the Question of the Living Earth

The hypothesis that the Earth is, in some meaningful sense, a living being has had a troubled reception. For neo-Darwinian evolutionary biology, it is largely intractable: the Earth does not reproduce, does not form populations, and is not subject to natural selection in any straightforward sense (Doolittle 2014; Dawkins 1982; see Dutreuil 2024 for a comprehensive review). The hypothesis has proven more productive for systems-oriented thinkers. Lovelock himself drew heavily on cybernetic concepts (self-regulation, homeostasis, feedback) to characterise the Earth’s behaviour (Lovelock and Margulis 1974). This vocabulary gave rise to the flourishing field of Earth system science, but it also had the effect of diluting the claim that the Earth is a living being into something closer to a metaphor: a self-regulating system tractable with dynamical models, but no longer distinctively biological.

Attempts to recover the specifically biological content of the claim have often worked through analogy. The Earth has been described as an organism (De Castro 2020; Meynell 2025), a cell (Margulis 1997), or a superorganism — a concept favoured by Lovelock (2004) himself, who compared the inorganic parts of the Earth system to the mound built by termites, arguing that structures produced by organisms can still count as part of the living system (the superorganism). Each of these comparisons captures something real, but each also risks flattening the ontology of the Earth system. Cells, organisms, ecosystems, and the living planet are different kinds of entities, which work together in specific ways to form an integrated system. In particular, the organismic level (be it uni- or multicellular) seems to play a very specific role, in the crossing of evolutionary (as entities that self-reproduce and undergo selection) and self-organising processes (Ruiz-Mirazo 2000). A “Russian doll” model (in which the parts are of the same kind as the whole) obscures precisely what needs to be understood: the specific way in which different levels of biological organisation need each other and are articulated.

A more formal approach is offered by the concept of autopoiesis. Although the description of autopoiesis is grounded in the functioning of the cell, it is abstract enough that it can be extended to larger entities, such as multicellular organisms. In this vein, Rubin et al. (2021) have argued that the Earth satisfies at least the first condition of autopoiesis, namely self-production. But although the Earth may resemble a cell in certain respects (Margulis 1997), it is also fundamentally different in others. A cell constitutes itself as a physical body through its own activity: when it dies, it disintegrates. The Earth is and will remain a physical body whether or not it harbours life. Its atmosphere, though produced and maintained by living processes, does not serve the same topological function as a cell membrane: it does not constitute the system as a bounded entity in the way that autopoiesis requires. Moreover, cells and organisms are always embedded in organised species-level and ecological relations that are essential for their self-constitution; the Earth system, by contrast, might be the only biological entity that sustains itself in an abiotic environment. The application of autopoiesis to the Earth system thus remains illuminating in certain respects but limited in its capacity to specify the organisational structure that is distinctively at work.

One might object that the argument against analogies could be turned against the present proposal: is closure of constraints not also based on the functioning of the organism, and is applying it to the Earth system not also reasoning by analogy? The answer turns on a distinction. What we are aiming to is not to identify the Earth system as an instance of an already known type of entity, which we can also find as a part part of the system (organism, cell, superorganism). The closure-of-constraints framework identifies a type of causal regime (the mutual dependence of constraints for their maintenance across a thermodynamic flow) and asks whether that regime is present in a given system, whatever kind of entity that system may be. This is what makes the framework genuinely abstract rather than analogical. To say that cells, organisms, and the Earth system all realise closure of constraints is not to say they are the same kind of thing; the causal property is shared, but the kinds remain distinct. The framework can therefore be applied to the Earth system without importing features specific to cells or organisms, and without collapsing the constitutive differences between levels of biological organisation.

To say that the Earth is a living being can, on this account, be better understood not as including the Earth system in the same category as cells and organisms, but as showing that Life (understood as a particular phenomenon rather than as a property; cf. Lenton et al. 2020) is organised at different levels, and that it has achieved at the planetary level a kind of specifically biological (not merely physical or systemic) organisation.

This does not commit us to the claim that the Earth is an organism, or that it is autopoietic in the cellular sense, or that closure of constraints defines life. It identifies one organisational property (a specific causal structure) that is characteristic of biological systems and that, as this paper argues, is also realised at the planetary scale in a form sui generis to its conditions. And because closure of constraints aims to ground teleology, normativity, and functionality in the organisational tradition, the framework opens the way for a principled discussion of planetary-scale functions and norms.

4. Conclusion

The concept of closure of constraints can be productively applied to the Earth system, and may find a more tractable application at the planetary scale than at the ecosystem scale. The biogeochemical cycles of the Earth system, through their mutual dependence across vastly different time scales, constitute a closure of constraints: each cycle constrains the conditions of possibility of the others, and together they harness the thermodynamic flow while sustaining emergent system-level properties that are simultaneously conditions and outcomes of the organisational regime.

The argument also opens questions that exceed the scope of this paper. Among the most pressing is whether the Earth system's organisational closure grounds genuine normativity at the planetary level: whether it is meaningful to say that something (like the current climate crisis) is “good” or “bad” for the Earth system itself, and on what basis such judgements could be made. This question, which lies at the heart of the claim that the Earth is alive, will be pursued in subsequent work.

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