

Why Everything is Connected to Everything Else

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Abstract

In Earth surface systems (ESS), everything is connected to everything else, an aphorism often called the First Law of Geography and of ecology. Such linkages are not always direct and unmediated, but many ESS, represented as networks of interacting components, attain or approach full, direct connectivity among components. The question is how and why this happens at the system or network scale. The crowded landscape concept dictates that linkages and connections among ESS components are inevitable. The connection selection concept holds that the linkages among components are advantageous to the network and are selected for and thereby preserved and enhanced. These network advantages are illustrated via algebraic graph theory. For a given number of components in an ESS, as the number of links or connections increases, spectral radius, graph energy, and algebraic connectivity increase. While the advantages (if any) of increased complexity are unclear, higher spectral radii are directly correlated with higher graph energy. The greater $E(g)$ is associated with more intense feedback in the system, and tighter coupling among components. This in turn reflects advantageous properties of more intense cycling of water, nutrients, and minerals, as well as multiple potential degrees of freedom for individual components to respond to changes. The increase of algebraic connectivity reflects a greater ability or tendency for the network to respond in concert to changes.

Key words: First Law of Geography, First Law of Ecology, Earth surface systems, environmental networks, connectedness, algebraic graph theory

Introduction

Everything is connected to everything else has been called the First Law—of ecology, of geography, and of environmental science (e.g., Tobler, 1970; Commoner, 1971). At a conceptual or pedagogic level this is virtually axiomatic. In real-world systems the first law (TFL) is generally true, though the connections may not be direct, and for particular purposes of study or analysis some can be ignored. Given the essential truth of TFL for Earth surface systems (ESS), the question addressed here is *why* everything becomes interrelated.

A two-part explanation is explored here, recognizing that there may exist alternatives. The first is limited space and time, labelled the *crowded landscape hypothesis*. Many entities comprise ESS, and some of them are constantly or intermittently in motion in space. Given that there is limited space and limited time for these entities to exist in, they inevitably come in contact with each other and become connected in various ways (as described below). The second, the *connection selection hypothesis*, holds that high degrees of interrelationship confers advantages to the connected entities that make their survival, persistence, recurrence, and reproduction more likely, and are thus selected for (see Phillips, 2021 for discussions of selection in landscapes and ESS). The two hypotheses are likely to be strongly interrelated. Happenstance connections in crowded landscapes may not persist unless reinforced by positive feedback or selection, and as many ESS relationships involve non-sentient elements, there might be little to select without happenstance links in crowded landscapes.

The discussion and analysis will be framed in terms of graph theory. ESS can be readily and accurately enough characterized as networks, and thus as (mathematical) graphs. The elements or constituents of an ESS are referred to here as components, corresponding to nodes or vertices in graph theory terminology. The connections between components are links, also called edges in graph theory. Components may be locations or areas, individuals, taxa, ecological communities, landscape features (e.g. landforms, soils, vegetation cover types, geological formations), system components (e.g., source-transfer-sink zones, trophic levels, functional taxonomic groups), or process types or categories (e.g., erosion, deposition, evapotranspiration, infiltration)(Figure 1).



Figure 1. Linkages among ESS components, subchannel of the Navasota River, Texas: Local & watershed sediment yields; sediment transport capacity of flow; main channel-subchannel; riparian vegetation; woody debris; alluvial sediment.

Advantages of connections

Why would increased connectivity among landscape components be advantageous? Connections of any of the types outlined in the next section can qualify as exchanges of *information*. When components are connected, the state of or changes in one component can give indications of the other components connected to it (Figure 2). This is consistent with one (of several) definitions of information from the *Oxford Dictionary*: “what is conveyed by a particular arrangement or sequence of things.” When biological components are involved, information in the form of messages may be involved. Thus, for example, links among components allow a plant to sense an oncoming soil moisture deficit, which may be communicated to other plants via mycorrhizal networks.



Figure 2. Simple example of Earth surface system components providing information on other components. Curved trunks in Razula forest, Czech Republic indicate active soil creep on the hillslope.

Many connections directly or indirectly involve transfers and transformations of energy and mass. Increased connectivity may allow for more rapid and efficient transfers, thus favoring the survival (and possible growth) of both the system itself and of individual components.

More links to other portions of the ESS may also allow for more options (degrees of freedom) in adjusting or responding to changes or disturbances. For instance, a beach linked to multiple sediment sources (e.g., offshore, longshore, and inland, such as dune fields) will have more options for recovery from erosion or overwash events; an organism linked to multiple food sources will be better able to adapt to disruptions in a source; and stream channels have multiple potential modes of adjustment to changes in runoff or incoming flows due to the interconnectivity of width, depth, velocity, flow resistance, and slope. Higher connectivity may also promote greater synchronization of responses among ESS components, which may be advantageous to the system as a whole.

Where connections involve fluxes of energy and mass, the principle of gradient selection is involved, whereby more efficient transport paths are (on average) more likely to persist, grow, and recur.

More links may also be related to less *vulnerability*. Highly connected systems are better able to survive and recover if a particular node is lost or fails, and does not rely on critical nodes whose disruption or loss endangers the entire system. However, Strydom et al. (2021) found that more complex ecological networks are not necessarily more robust to extinction (removal of individual species), though they focus on a measure of complexity that is nonstructural and analyzed only networks of species interactions. There is a large literature on the relationship between stability and complexity in ecological systems, which can only be treated at the cost of a long and complicated discourse. Without delving into that, suffice it to say here that having a variety of components, no one of which is necessary to the survival of the network/system, reduces the vulnerability to loss, inhibition, or deactivation of any single component.

This issue is revisited in the discussion.

Types of connections

Components of ESS can be connected in a number of different ways, as outlined in Table 1. Perhaps most common and straightforward are transfers (transportation and transformation) of energy, mass, and information. These may be one-way, as links in food webs and gravity-driven fluxes, or two-way, as in exchanges of carbon, nutrients, and water in mycorrhizal networks and tidal fluxes. They may be irreversible due to the role of unidirectional forces such as gravity, or reversible, such as upward or downward heat flux in soil as temperature gradients change. Transfer-type connections may involve transformations, as in biogeochemical cycles or state-changes of water, or not, as in granular or liquid water flows. The components linked by transfer connections can be solely or primarily sources, sinks or destinations, or pass-through, and these roles may be fixed or variable over time.

Table 1. Types of connections between components in Earth surface systems.

Type of connection	Examples
<i>Transfer of matter, energy, information</i> 1-way vs. 2-way Irreversible vs. reversible Transformative vs. non-transformative Source, pass-through, sink	Hydrological flows Sediment transport Nutrient fluxes Food webs & trophic pyramids Heat flux
<i>Competition among biota</i>	Competition for resources Predator-prey or consumer-producer Allelopathy
<i>Biological reproduction</i>	Gene flow Population dynamics
<i>Partition of mass, energy</i>	Runoff vs. infiltration Solar radiation energy budget Sediment budgets
<i>Mutual adjustments</i>	Hydraulic geometry Predator-prey populations
<i>Symbiotic relationships</i> Biota Abiotic mutual reinforcement	Biological symbiosis Erosion & weathering Fingered flow Weathering fronts
<i>Self-limiting relationships (non-biological)</i>	Floodplain elevation vs. overbank flow Marsh surface elevation vs. inundation Weathering vs. weatherable minerals
<i>Limits</i> Absolute limits Limiting factors Saturation & depletion	Base level & fluvial incision Population & carrying capacity Resources: space, water, light, nutrients
<i>Oppositional: fluxes & movements in opposite directions along same pathways</i>	River flows & tides Downstream flow & backwater effects Reversing winds Percolation & water table rise
<i>Process effects</i>	Erosion & vegetation cover Evapotranspiration & vegetation cover Soil CO ₂ & dissolutional weathering Slope gradient & gravitational mass flux
<i>Facilitation</i>	Ecological succession Biota & preferential flow paths Plant-soil interactions Passive ecosystem engineering
<i>Self-reinforcement via intermediaries</i>	Active ecosystem engineering
<i>Intersections: crossing or convergence of otherwise unrelated movements, fluxes, or features</i>	Faunal trails or pathways Geological joints Antecedent & superimposed streams
<i>Spatial adjacency or contiguity</i>	Soils, landforms, ecological communities, land use
<i>Anthropic</i> Biological, economic, social, political, etc. Deliberate vs. incidental/accidental	See discussion in text

Other interconnections involve biological interactions, such as competition, symbiosis (other cooperative-type relationships are lumped in here), and reproduction. In addition to mass and energy fluxes and transformations, connections between predominantly biotic and abiotic components occur in the form of active and passive ecosystem engineering, and abiotic limits on biological and geochemical and geophysical processes. Facilitation, where environmental effects allow and promote establishment of subsequent effects, is best known in classical theories of ecological succession. However, it also occurs in other contexts, such as unstable wetting fronts and fingered flow phenomena, and creation or facilitation of subsurface preferential flow paths by roots and faunal burrowing.

Yet other connections arise due to spatial co-occurrence. This arises due to spatial adjacency of various landscape elements, intersections of flow and travel paths or structural features, and opposing transport along the same pathways (e.g., tidal channels or reversing wind directions).

Connections associated with human actions are listed as the last entry of Table 1. Some anthropic connections can be accommodated in the other categories (e.g., inputs to agricultural systems). Others, however, may deserve separate consideration due to the strong influence of economic and cultural factors. They are included here to acknowledge the pervasive effects of human activities on ESS, but are not discussed in detail to keep the focus on general principles of ESS connections, and—frankly—to avoid the extensive and often bewildering parsing of terminology that often occurs in social sciences and humanities.

Table 2 links the types of connections in Table 1 to the general types entities or components that may be linked. These include geographical locations or areas; specific landscape features (e.g., landforms, hydrological features, soils, biological communities, geological formations); generalized components of (for instance) hydrological, geomorphological, and ecosystems; individual organisms; taxonomic groups; and process types or regimes.

Table 2. General types of Earth surface system components associated with the connections listed in Table 1.

Type of connection	Components (nodes)
<i>Transfer of matter, energy, information</i> 1-way vs. 2-way Irreversible vs. reversible Transformative vs. non-transformative Source, pass-through, sink	Geographical locations or areas Landscape features System components Process types Individuals
<i>Competition among biota</i>	Individuals Taxa
<i>Biological reproduction</i>	Individuals
<i>Partition of mass, energy</i>	Landscape features System components Process types
<i>Mutual adjustments</i>	Landscape features System components Process types
<i>Symbiotic relationships</i> Biota Abiotic mutual reinforcement	Landscape features System components Process types Individuals Taxa
<i>Self-limiting relationships (non-biological)</i>	System components Process types
<i>Limits</i> Absolute limits Limiting factors Saturation & depletion	System components Process types
<i>Oppositional: fluxes & movements in opposite directions along same pathways</i>	Process types
<i>Process effects</i>	Process types
<i>Facilitation</i>	System components Process types Individuals Taxa
<i>Self-reinforcement via intermediaries</i>	System components Process types Individuals Taxa
<i>Intersections: crossing or convergence of otherwise unrelated movements, fluxes, or features</i>	Landscape features System components
<i>Spatial adjacency or contiguity</i>	Geographical locations or areas Landscape features System components
<i>Anthropic</i> Biological, economic, social, political, etc. Deliberate vs. incidental/accidental	See discussion in text

Crowded landscapes

Take, for example, any given patch (say 1 m²) of a terrestrial landscape. That patch will be associated with at least one each of a landform, soil type, underlying geology, vegetation cover, faunal community, microbial community, microclimate, hydrological status and function, and so on. With varying frequencies and intensities (both within and between landscapes and patches), it will be the site of any number of movements and fluxes at, above, and below the surface, and in many directions. These include water movements driven by gravity, capillary forces, root suction and other biological water use, vapor transport, and state changes. They also include plant growth (e.g., root extension), faunal digging and burrowing, and faunal transit. Many sites will experience significant transport by wind and mass movement, as well as gravitational settling, and movements due to factors such as shrink-swell and ice formation and melting. Humans and other animals may deliberately or accidentally transport objects or material, and plants may do so locally due to mass displacement.

In short, even in a small patch of landscape, there is a lot going on (Figure 3). There exist innumerable opportunities for entities and processes to come into proximity and direct contact, and to influence each other. This does not necessarily ensure that coincidences and influences become persisting interrelationships, or that everything becomes connected to everything else. However, the crowded landscape (portion of the) hypothesis does provide necessary, though not sufficient, preconditions for TFL to emerge.



Figure 3. Vertical and lateral connectivity among surface & subsurface processes, geology, hydrology, soil, vegetation and other biota (Sumava Mountains, Czech Republic).

Biogeographic and ecological models often assume biological saturation--that is, that as ecological systems evolve and as new habitats are colonized all available niches are eventually occupied. Hydrological models and theories often assume that flow networks develop to become space-filling; that is, they expand to the maximum density of channels that can be supported by the runoff production. If erosion is absent or not too severe, soils and regolith profiles become deeper and thicker (though in some cases limited by the depth of landscape incision). Fluvial and karst erosion processes generally often involve progressive downcutting, until limited by base levels. All these processes indicate that connectivity within ESS is likely to increase as landscapes evolve (though regressive development and clock-resetting disturbances are also possible).

Connection and selection

The second (portion of the) hypothesis holds that at least some connections are advantageous in terms of increasing the odds of survival, reproduction, recurrence, and expansion of one or both entities involved, or of the entire system/network. Selection operates so as to (on average) preserve and sometimes enhance connections that increase resistance, stability, and efficiency. Selection also does not promote, and sometimes reduces or eliminate those that do not.

For the case of connections involving biological entities, this is well established. At the individual level, if the connection confers survival or reproductive advantages to the organisms involved, it is more likely to be preserved (Figure 1). This is achieved via Darwinian natural selection, which can also work at the level of species or higher taxa. Selection can also occur in the form of ecological filtering. Just as habitat characteristics and resources can encourage some and discourage other organisms from establishing or thriving at a site, so they can foster or stifle interrelationships. Selection also occurs at the ecosystem level, whereby relationships such as those involved in biogeochemical and energy cycling may be selected for when they maximize efficiency and stability (Lotka, 1922; Patten, 1995; Lapenis, 2002; Eagleson, 2002; Fath et al., 2004; Wilkinson, 2003; del Jesus et al., 2012; Verboom and Pate, 2013; Cong et al., 2017; Zhang et al., 2021; Phillips, 2022)(Figure 2).

Selection also operates on largely or purely abiotic aspects of ESS, mainly via gradient, resistance, and efficiency selection and the least action principle (for reviews see Nanson and Huang 2018; Phillips, 2021, ch. 8).

Encounters happen and connection are made in ESS (crowded landscape concept), and some links are preserved and enhanced by selection (connection selection concept). What remains is to assess whether more connections are advantageous to an ESS (represented as a network) as a whole. We will explore this from the perspective of algebraic graph theory.

Networks and algebraic graph metrics

An ESS can be represented as a network or graph with N components or nodes and m links or edges connecting them. We will consider here only connected graphs, where

each node is connected to at least one other. We also consider only simple graphs, where any two components are either connected or not, regardless of the direction of the connections and the number of connections—for instance, soil and plants may be connected via water, carbon, nutrients, and minerals. Under these conditions a graph has a maximum of $(2N - 2)/2$ links and a minimum m of $N - 1$.

Associated with the graph is an $N \times N$ adjacency matrix A , whose elements are 1 if the row and column components are connected, and 0 otherwise, with zeros on the diagonal. Algebraic (or spectral) graph theory is based on analysis of A , particularly its N eigenvalues $\lambda_1, \lambda_2, \lambda_3, \dots, \lambda_N$.

The largest eigenvalue λ_1 is called the spectral radius. The maximum spectral radius for a graph of a given N, m is

$$\lambda_{1, \max} = [2m(N-1)/N]^{0.5} \quad (1)$$

For a fully connected graph, where every node is directly linked to every other, this reduces to $\lambda_1 = N - 1$. For a graph with the minimal connectivity,

$$\lambda_{1, \min} = [(2N - 2)/N]^{0.5} \quad (2)$$

The mean number of links per node for any graph is m/N , so the upper bound can also be expressed as

$$\lambda_{1, \max} = [(mN-m)/N]^{0.5} \quad (3)$$

Spectral radius has been widely used in algebraic graph theory as an indicator of complexity. It is inversely related to graph coherence in networks of interacting time-varying systems (Restrepo et al., 2006), and varies directly with N and m . The largest eigenvalue is also sensitive to the number of cycles in the network. Though in a simple, undirected graph λ_1 is always positive, in a directed graph the real part of the largest eigenvalue is equivalent to the Lyapunov exponent, and therefore $\lambda_1 > 0$ signifies dynamical instability. Fath (2007) used spectral radius as an indicator of complexity of ecological food webs, and Phillips (2011a;b; 2012; 2014; 2018) to measure complexity in soil, geomorphological, and ecological state-and-transition models. Renaud et al. (2020) applied spectral radius to study properties of plant-pollinator networks. Spectral radius is closely related to singular value decomposition entropy of ecological networks (Strydom et al., 2021), and is more directly related to some other measures of graph entropy (Geller et al., 2012; Mowshowitz and Dehmer, 2012).

The concept and term graph energy ($E(g)$) originated in physical chemistry, where it is used to approximate the total π -electron energy of molecules. Graph energy is the sum of the absolute values of the eigenvalues of A :

$$E(g) = \sum |\lambda_i| \quad (4)$$

A more general interpretation of graph energy is as a representation of the total strength of feedbacks in the network, which can be thought of as reverberations in the system. In a simple undirected graph,

$$(2N - 2)^{0.5} \leq E(g) \leq (2N - 2), \quad (5)$$

so that the ratio of maximum to minimum possible graph energy for a given N is $(2N - 2)^{0.5}$.

$E(g)$ is directly related to the spectral radius:

$$E(g) = 2\lambda_1 \quad (6)$$

Graph energy has not been widely applied in Earth and environmental sciences. Exceptions include Phillips (2017), where $E(g)$ was applied to assess the intensity of interactions among hydraulic units in a river, and Phillips (2019), where it was used as an indicator of the intensity of feedback in ecosystems in the context of responses to climate change. In addition to chemistry, graph energy has been used in network analyses in a number of other scientific and engineering applications (Jimenez-Aparacio et al., 2021).

Synchronization of the network represented by the graph is measured by algebraic connectivity α , which is equal to the second smallest eigenvalue (largest positive eigenvalue) of the Laplacian of the graph adjacency matrix:

$$\alpha = \lambda(L)_{N-1} \quad (7)$$

The Laplacian is

$$L = D - A \quad (8)$$

where D is the degree matrix of A .

Algebraic connectivity is constrained by

$$4/ND \leq \alpha \leq \kappa(G) \quad (9)$$

D is graph diameter (the minimum longest path between any pair of nodes) and $\kappa(G)$ is vertex connectivity, the minimum number of nodes which could be removed to disconnect the graph. Maximum possible algebraic connectivity is associated with a fully connected graph, where $\alpha = N - 1$. Jeon et al. (2010) and Song and Lee (2018) used algebraic connectivity to assess the connectivity of tunnel networks of subterranean termites in studies of the efficiency of foraging strategies and tunnel excavation. Algebraic connectivity was applied by Kim and Phillips (2013) to state-and-transition models of wetland vegetation, and by Hembry et al. (2018) in a study of how biological mutualism affects ecological networks. Yazdani and Jeffrey (2012) and Phan et al. (2018; 2021) used it to assess robustness and redundancy of water distribution networks.

Networks, connections, and selection

For a network or system with a given number of components, an everything-is-connected-to-everything-else structure represented by a fully connected graph gives the highest possible spectral radius, graph energy, and algebraic connectivity. This implies the EICTEE configuration has the greatest complexity (though definitions, aspects, and measures of complexity are many), the highest degree of total network feedback, and the greatest synchronization. A fully connected system, compared to other system structures, can respond to change or disturbance with greater rapidity, synchronization, intensity, and with more degrees of freedom (Figure 4). To the extent that this confers advantages to network survival, growth, and perhaps propagation—and at least intuitively, it seems that this must be the case for many ESS—it will be selected for. Connections that arise as ESS components go about their functions are likely to be preserved, moving the network closer to full connectivity.



Figure 4. Swamp forest along the Waccamaw River, South Carolina. Complex interconnections among hydrology, geomorphology, soils, vegetation, fauna, and microbes provide numerous degrees of freedom for absorbing and recovering from change. This site, for instance, photographed in 2021, experienced the three largest floods of record (estimated recurrence intervals of up to >500 years) in 2018, 2015, and 2016, as well as saltwater intrusion from storm surge in the 2016 and 2018 events.

From the perspective of an individual ESS component, we assume it is advantageous to be directly linked to every other component, to provide or receive energy, mass, or information or to facilitate quicker responses to change. The most efficient way for a component to collection information (etc.) from multiple nodes is a convergent radiation pattern (a single key node connected to every other node, which are connected only to the key node). The most efficient way for a component to distribute or transmit information is a divergent radiation pattern. For an undirected graph, these structures are identical. For any radiation type graph, regardless of N , $\lambda_1 = \sqrt{2} \approx 1.414$.

If we consider a fully connected graph as a collection of radiation subgraphs G_i ($i = 1, 2, \dots, N$) of the fully connected graph G , a standard relation from algebraic graph theory is that

$$\lambda_i < \sum \lambda_i G(i) \quad (10)$$

If the radiation subgraphs are all have N nodes,

$$\Lambda = \sum \lambda_i G(i) = 1.414 N \quad (11)$$

When the ESS network is viewed as a single integrated graph the reduction in spectral radius is

$$\lambda_i/\Lambda = (N-1)/1.414 N \quad (12)$$

For $N = 10$, for instance, $\lambda_i/\Lambda = 0.636$, indicating that the spectral radius of the single fully connected graph is <64% of that of the collected radiation subgraphs.

The fully connected structure can therefore be interpreted as one that maximizes connectivity for both individual components and for the network as a whole, while containing subnetworks for each individual that minimize complexity (as indicated by λ_i) and minimize complexity for the system as a whole compared to the summed spectral radii of the collection of subgraphs.

Network synchronization also increases as m increases relative to N . Though the addition of a single link might leave graph diameter D unchanged, it cannot reduce it, and continued adding of links must lower D by reducing the maximum shortest path between any two nodes, thereby increasing the lower bound of algebraic connectivity ($4/ND$; eq. 9). At the same time, larger m must also increase the vertex connectivity, which provides the upper limit for α .

Discussion

Connectivity in ESS emerges and increases because:

1. Hydrological, geomorphological, pedological, biological, and climatological processes operate continuously in landscapes, transporting and transforming mass, energy, and information. Their zones of operation inevitably encroach on each other, and the transport pathways intersect. This creates connections among the elements or components involved.
2. Connections are often preserved and reinforced. This may be due to positive feedbacks (e.g., enlargement and maintenance of preferential flow paths), mutually beneficial effects on interacting components (e.g., soil-plant interactions), the irreversible nature of some processes and pathways (e.g., weathering, slope movements), and efficiency advantages of using already-established pathways.

3. As a rule, connectivity between ESS components has net benefits to the individual components.

4. Increased connectivity of the ESS confers advantages of more intense and rapid energy and material cycling, more degrees of freedom for adapting to change, and greater synchronization of evolution and responses. Any disadvantages of increased complexity are offset by these benefits and the simultaneous achievement of maximum network efficiency for individual components and reduced cumulative complexity for the whole system. These phenomena are indicated by the spectral radius, graph energy, and algebraic connectivity properties.

As TFL is a premise of this work, there exists no need to test or demonstrate it. The existence of TFL is sufficient to support crowded landscape concept, which is nearly, if not fully, axiomatic. What remains to be evaluated is the assertion that higher connectivity confers advantages to an ESS network, and that it can be selected for.

Advantages

Biota cannot exist independently of their ecosystems, so connectivity within biological communities and their abiotic environments is well established. In recent years the tight connectivity of biota has become even more apparent, as organisms of both the same and different species can communicate with each other directly or via other biological intermediaries. This involves flora, fauna, and microbes. Several accessible syntheses of the research in this area for the general public have been published recently (Tudge, 2006; Wohlleneben, 2016; 2019; Sheldrake, 2020; Simard, 2021; Seifert, 2022).

With respect to abiotic components of ecosystems and biotic-abiotic interactions, a general advantage to more rapid and intense biogeochemical cycling has been recognized as least as far back as Lotka (1922; see also Lapenis, 2002; Lekevicius, 2002; 2006; Wilkinson, 2003). There are two lines of reasoning supporting this. First, for individuals, greater rates of use of water, nutrients, and food is associated with, and supports, more rapid rates of growth and general health and thus favors survival and reproduction. Second, the more rapidly a fixed amount of matter and energy is cycled among ecosystem components, the greater the total availability, akin to the economic advantages of keeping money in circulation.

In hydrology the evolution of highly connected systems—including not only channel and preferential flow networks, but also storage and slow-flow areas—produces “store and pour” configurations (Phillips, 2022). These configurations enhance the stability of both surface and subsurface hydrological systems by allowing them to better handle both low and high input (dry and wet) episodes. Ecohydrological feedbacks, especially via plants, provide positive feedback to store-and-pour structures. More rapid use and cycling of water has also been shown to confer ecological advantages (Eagleson, 2002; del Jesus et al., 2012; Cong et al., 2017; Zhang et al., 2021).

The study of plant-soil reciprocal interactions (as opposed to edaphic properties of soils with respect to plant growth) has focused on the mutual interactions of plants and soils (including the microbial, fungal, and faunal components of soil) with respect to ecosystem engineering and niche construction. However, these interactions also benefit

soils by increasing their resistance and resilience (and thus their likelihood of preservation) via, e.g., erosion protection, aggregate formation, and role in store-and-pour soil hydrology.

The importance of interconnections of geomorphological and geological components of ESS is clear enough, but how these benefit the survival and enhance of the landforms and geological features is less clear. Indeed, the breakdown of parent rock by weathering is necessary for the formation of regolith and soil. Erosion, sediment transport, and deposition may have positive effects on ESS, but often these are negative for preservation of both geomorphic and other components. However, it can be argued that the connections with biota, soil, and hydrology both enhance the preservation of landforms (as described above with respect to soil), and are necessary for geomorphic recovery from disturbances.

Selection

Given that connectivity is advantageous for ESS networks, (how) does selection preserve and enhance them? With respect to hydrological and geomorphological phenomena, this often occurs due to gradient, resistance, and efficiency selection. Pathways with the steepest flux gradients, landscape elements with the highest resistance, and configurations with the greatest efficiency for work (consistent with the least action principle) preferentially occur, recur, grow, and survive (Hunt, 1998; 2017; Huang and Nanson, 2000; Phillips, 2010; 2011; Smith, 2010; Nanson and Huang, 2017; 2018).

With respect to ecosystems, biogeochemical cycling, and abiotic-biotic interconnections, Darwinian natural selection selects for connections that advantage individual biota (Smith, 1986; Lapenis, 2002; Phillips, 2008). Further, a number of authors have presented evidence that (as organisms cannot survive independently of their ecosystems), the ecosystem is the primary unit of selection (e.g., Smith, 1986; Rowe, 2001; Lekevicius, 2002; 2006; van Nuland et al., 2016; Ware et al., 2019). A supraorganic perspective emphasizing connectivity among organisms, soils, and abiotic factors also enhances the stability and function of agroecological systems (e.g., Jackson, 2010; Brunetti, 2014). Phillips (2019) showed that ecosystems respond to climate change as integrated units, not as a collection of individual elements, which increases the odds of preservation of ecosystems.

Conclusions

In Earth surface systems, everything is connected to everything else. These linkages are not always direct and unmediated, but many ESS, represented as networks of interacting components, attain or approach full, direct connectivity among components. The question is how (in the broadest sense) and why this happens at the system or network scale.

The crowded landscape concept dictates that linkages and connections among ESS components are inevitable. The connection selection concept holds that the linkages among components are advantageous to the network and are thus selected for and thereby preserved and enhanced.

These network advantages are illustrated via algebraic graph theory. For a given number of components in an ESS, as the number of links or connections increases, spectral radius, graph energy, and algebraic connectivity increase. While the advantages (if any) of increased complexity are unclear, higher spectral radii are directly correlated with higher graph energy. The greater $E(g)$ is associated with more intense feedback in the system, and tighter coupling among components. This in turn reflects advantageous properties of more intense cycling of water, nutrients, and minerals, as well as multiple potential degrees of freedom for individual components to respond to changes. The increase of algebraic connectivity reflects a greater ability or tendency for the network to respond in concert to changes.

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