Gaia: Complex Systems Prediction for Time to Adapt to Climate Shocks

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Abstract

A proposal, called “Gaia”, that life regulates Earth’s climate to its advantage, is partially supported by Earth’s climate history, wherein temperature fluctuations over the past ca. half billion years have mostly been small enough to protect life from extremes of climatic fluctuations, while global temperatures overall cooled during the 3.8 Ga when life was present, in spite of increased solar irradiance. Kirchner states that the simultaneous existence of bi-directional and uni-directional responses is inconsistent with the understanding of the effects of a single organism. Further, the counterargument that plant life creates climate crises endangering life’s survival has been advanced. These two objections require a more nuanced understanding of the biosphere as interacting, nested, ecosystems. It has also been asserted that chemical weathering provides negative feedback to climate fluctuations due to its strong temperature dependence, making it a global thermostat. However, this suggestion is based on the failure to recognize that chemical weathering rates in situ, unlike the lab, are limited by water fluxes. Since warmer temperatures need not support increased precipitation, particularly at times corresponding to the assembly of supercontinents, weathering is unsuited as a thermostat. Here, we present quantitative predictions of the time required, 80 Ma, for a synergistic system of plants/bacteria/fungi to reach continental size. Although the prediction was originally applied to the wrong biosphere adaptation, we now show that 80 Ma exceeds by only 33% the time required (60 Ma) for Earth to return to homeostasis after biological innovations of land plants ultimately plunged Earth into Paleozoic ice ages. This alternate understanding provides a rationale to examine further the potential for soil ecosystem adaptation to deliver the homeostatic response implied in the Gaia “hypothesis.”

INTRODUCTION

With *Gaia: A New Look at Life on Earth* [1], James Lovelock proposed that Earth's biosphere is a global-scale self-regulating organism. Evidence that Earth is life-supporting ("Homeostasis by and for the biosphere") include the concentrations of CH_4, O_2, and CO_2 in Earth's atmosphere, which are more than 30 orders of magnitude out of their equilibrium values, in contrast to the atmospheric chemistry of Earth's nearest-neighbor planets which obey chemical equilibrium [2]. Kleidon (2002) and Lenton (2002) refer to bounded fluctuations in Earth's mean temperature over the past ca. half billion years, and to models indicating that atmospheric and soil moisture conditions produced by life increase plant productivity by 250%. The original Gaia hypothesis has, however been mostly abandoned (with reasons summarized in Schneider, 1986, 2002), even though the concept that the biosphere is composed of interacting complex systems exhibiting emergent behavior Margulis (1999), is rather generally accepted. Indeed, the history of Earth's climate system is taught within the discipline of Earth system science.

The need to cast Gaia as a planetary-scale organism traced originally to a result from biology, in which organisms profit only from regulating their internal environment, whereas the external environment predominantly influences the organism [5]. In this way, however, the concept of homeostasis as a biosphere characteristic was questioned also for smaller scales associated with elements of the biosphere. [6] also pointed out the lack of testable predictions, as well as the difficulty to reconcile a directional regulator for reducing temperatures and atmospheric CO_2, from an early hot Earth that can also stabilize CO_2 at an optimal value for life [5]. Still, the "Gaia hypothesis" has contributed to progress in thinking about Earth [7,8]. Moreover, we suggest here that it may be possible to verify the success of a previously made holistic prediction.

From Lovelock's perspective [9], the biosphere's ability to regulate Earth's climate to its advantage is not a coincidence [10], as is also reflected by a steadily increasing body of evidence connecting the biosphere and the physical planet Earth (see a bibliography compiled by Brig Klyce [11]).

The research evaluated here applied statistical mechanics of heterogeneous media (a branch of complex systems research) to predict a time scale for the formation of a continental-scale "organism" [12]. Although already obtained; the potential relevance of this result to Paleozoic ice ages is only now proposed. The subsequent discussion resolves some criticisms of the "Gaia hypothesis."

In our perspective, biological innovations based on photosynthesis (bacteria and plants) that allow better exploitation of the atmosphere's carbon pool are viewed as (cooling) shocks to the system, leading to storage of energy derived from the sun [3], while the overall soil ecosystem, including bacteria, animals, and fungi can, by consuming some of that energy, respond so as to promote homeostasis [13]. Global temperature is then regulated not solely by the rate of injection of oxygen into the atmosphere through photosynthesis, but in tandem with the rate at which it is removed through metabolism. Since soil-based bacterial and fungal adaptation to new plant strategies, if given by the fundamental scaling functions here, are slower than the relatively rapid spread of plants across the land through release of spores through the atmosphere, achievement of homeostasis is delayed.

Our analysis is based on an existing scaling relationship for plant growth (and fungal hyphae) [12], which was tested on pines (eucalypts) along a precipitation gradient of factor 4 (20) [14] and over time scales [12] from minutes to 100,000 years, while being used to "extrapolate to a time scale when an 'organism' with an optimal, hierarchical, structure would reach continental size (about 5,000 km, if growing from the center). That time scale is less than 100 Ma (about 80 Ma).” Our application to Earth’s history was not appropriate: “We will find that the time scales are adequate [short enough] if a symbiotic combination of plants and bacteria are envisioned. However, utilizing land plants in such a symbiosis would postpone the time of the development of a global ‘organism’ to a date billions of years after the far-from-equilibrium composition of the atmosphere was obtained.” We show here that 80Ma is very nearly an appropriate time span in a different context. We consider restoration of the Earth to higher temperatures subsequent to Paleozoic ice ages triggered by colonization of the land by plants.

RESULTS AND DISCUSSION

Originally, $x_0 \approx 1\mu\text{m}$ [12] was estimated roughly as a fundamental pore scale, while the time scale t_0 was taken to be the time for water to flow across a 1µm pore at a typical subsurface flow rate [15], 1µm/s ($t_0 = 1\mu\text{m} / 1\mu\text{m s}^{-1} = 1\text{s}$). This prediction is given by the dashed red line in Figure 1 and compared with actual woody plant data [12]. For lengths centimeters or less, the data reflect laboratory root tip or fungal hyphae extension rates [12,16]. On scales exceeding 120 m, data reflect the RLS of single organisms (clones) with multiple subaerial stems, both plants and fungi [16], while at intermediate length scales, the data are for vegetation height, which is known to be nearly equivalent to RLS on length scales between about 0.5 meters and 40 meters [12]. For $x > 10$ km, neither the fundamental character of what could be called an “organism,” nor its form of communication, were specified.

Figure 1 indicates near conformance of Eq. (4) with the upper bounds of the RLS data on time scales ranging from minutes to 100ka, and length scales from 100 µm to 10 km. Using the same line, the time for a continental scale (5000 km) “organism” to develop was estimated at 80

Ma [12]. Although the slope of the line is universal, the value of the time scale required for an "organism" of 5000km changes, if the parameter values for Eq. (4) are different. In later publications [16,17], x_0 was defined explicitly as a median particle size or plant xylem diameter. Then, if x_0 is not known explicitly, a better fundamental length scale is 10 µm - 30 µm, because this range is both near the middle of the silt particle size range and a geometric mean plant xylem diameter [18]. Since most variability in tree heights at a given time relates to their actual transpiration rates [14], more slowly growing vegetation requires much less water. The earliest establishment of an "organism" of continental size would then be associated with the fastest growth rates (along the solid red line).

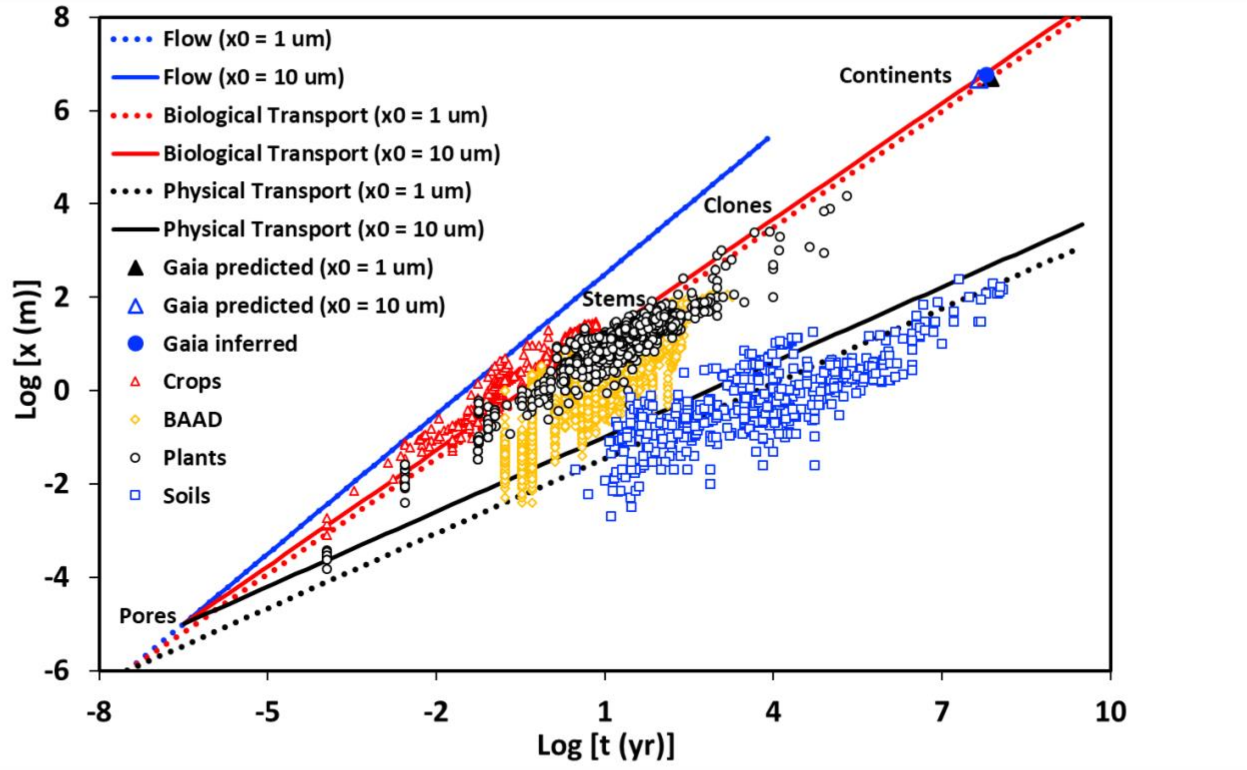

Fig. 1. Application of scaling relationships to biological and physical transport processes, assuming a flow speed independent of scale (blue) with value taken from a summary [15]. Root growth rates (red) decline over time according to the two-dimensional optimal paths exponent

from percolation theory (Eq. (4)), soil formation rates (black) decline over time according to the scaling of solute transport using the fractal dimension of the percolation backbone. “BAAD” refers to the biometric and allometric database for plant heights [19], “plants” were from many sources, selected for faster growth, and “soils” are soil depths (data compilation**Error! Reference source not found.**) Dashed lines reflect predicted times for biological organisms to reach a given RLS, and soil to reach a given depth using the originally suggested length scale of 1 µm, while solid lines indicate the changes resulting from choice of 10 µm as the fundamental length scale. Gaia predicted uses the time scale required for Eq. (4) to generate 5000 km, in accord with the original prediction. “Gaia inferred” pairs a physical extent of ca. 6,200 km, obtained either as half the square root of the area of all the continents today, or the area of Pangaea, with the time for emergence from an ice age (60 Ma).

Hunt and Manzoni (2016) proposed that a continental-scale “organism” could consist of a synergistically operating system of plant roots and associated bacteria. Given that fungi follow the same growth model as plants and act to decompose wood [12], they may be included as well. Bacteria have recently been shown to act collectively, e.g., by deferring consumption until better food sources are located, communicating at relatively short length scales through chemical “quorum sensing,” and at longer length scales through electrical signaling along ion channels [20]. Perhaps horizontal gene transfer serves at yet larger scales. We propose the possibility that a soil ecosystem that can produce a negative climatic feedback of continental size can indeed be predicted through the scaling Eq. (4) that we tested at smaller length scales. Consider that the span 10µm to 10km tests explicitly 9 of the necessary 11-12 decades of length scale. In Eq. (4) the time t required for length scale x to reach continental size is required.

Since the initial test of Eq. (4) addressed the time required for drawdown of sufficient CO_2 to produce the great oxygenation crisis [21], Eq. (4) was judged irrelevant, as land plants arrived over a billion years too late. Producing an ice age through biological innovation, however, is better viewed as a climate crisis generated by a component of the ecosystem, namely the plants, which robustly overproduce, whereas achievement of homeostasis afterwards would be consistent with establishment of a global-scale, adaptive "organism," or a nested system of ecosystems comprising a "symbiotic planet" [22].

Thus, we test Eq. (4) by applying it to the lifting of the climate shocks (ice ages) brought on by colonization of the land by plants. It has now become clear that the early colonization of land was by rooted plants [23,24], though fossil evidence suggests quite short root systems. Initiated near 500 Ma [23,25], the effects of the dramatic increase in photosynthesis on atmospheric CO_2 content appear to have led to large-scale glaciation by 488 Ma [26]. The end of the glacial episode is estimated to be at 440 Ma [26], 60 million years after initial colonization. Given such a climate shock, return to equilibrium could roughly coincide with development of a "symbiotic planet." The prediction, that it requires 80 Ma for adaptation to new conditions according to scaling relationship, Eq. (4), is only 33% larger than the actual value.

Later colonization of the land by significantly rooted vascular plants at 420 Ma [23,24] was followed by cooling and a glacial episode lasting approximately from 372 Ma to 359 Ma [27]. The time required for reestablishment of ideal environmental temperatures for life was approximately 60 million years since initial colonization, only 25% less than the prediction of Eq. (4).

Although we do not here assert that our test constitutes a proof that Earth's biosphere may be identified with a global "organism," the predicted and verified time scales were, nonetheless, developed specifically from a strong Gaia hypothesis. Thus, we posit that any Gaia perspective, together with scaling relationships from complexity, may provide added tools for analysis of the biosphere's past, or projected future.

That the scaling relationship in Eq. (4) for plant growth could be extended to planetary scales as a means for understanding Gaia-like adaptation to land colonization by plants would be in accord with Lovelock's comment in a relatively recent interview [9] by *Nature*: "I'm very intrigued by the latest attempt to resuscitate the idea that all of climate regulation is done by rock weathering. The geologists keep on ignoring the bacteria." The research of Hunt and Manzoni (2016) discussed here and elsewhere [28,29] is entirely consistent with Lovelock's implication. First, the primary dependence of rock weathering rates is on moisture fluxes, rather than temperature, which restricts the efficacy of the rock weathering thermostat to periods of time when the atmospheric moisture and temperature are in phase. One epoch when high temperatures and atmospheric CO_2 content appear not to have been in phase with greater precipitation, was during the great Permian extinction, a likely result of unification of Earth's land masses in Pangaea under relatively arid conditions [29]. Absent higher rates of rock weathering, removal of CO_2 from the atmosphere would have been slow indeed. Second, although the solid inorganic carbon reservoir volume is much larger than the organic carbon reservoir, Figure 1 demonstrates clearly that, particularly changes in its rate of storage, are much slower. Specifically, at 100 ka, the predicted and observed soil/weathering depth is at most a few meters, while the predicted and observed laterally integrated biological dimension reaches 10 km. Any pore-scale horizontal advection driven by plants is of a similar magnitude to the vertical advection driven by gravity [30]; thus spread of, and communication between, bacteria in the subsurface can be considerably enhanced in the horizontal directions (relative to vertical) through coupling with plant processes. Also, consistent with the original suggestion that the required global "organism" could be a plant/bacteria soil ecosystem (in which plant matter breakdown and production are in steady-state), homeostasis occurs when a global balance in CO_2 drawdown and emission is achieved at the right atmospheric composition that a moderation of temperature is achieved. Here such homeostasis emphasizes the key roles of bacteria and fungi, but allows their spread and adaptation to be controlled by the underground spreading rates of plant roots and fungal hyphae. The scaling relationships, on which this manuscript is based, thus tend to emphasize the relevance of biota, including bacteria, in developing a large scale, restorative response, to climate perturbations, in comparison to the abiotic response, which is not even necessarily identified as a negative feedback. However, this negative feedback develops on time scales of approximately 60 Ma, much longer than the time scales at which biosphere feedbacks have been found to be positive.

The same scaling relationships used here also form the basis for an accurate (within 1.5%) prediction of the global fraction of precipitation returned to the atmosphere through terrestrial evapotranspiration [30]. The result is based on maximization of plant productivity using a thin root layer defined by the soil depth, and a global-scale assumption of neither energy nor water limitations [30]. Thus, although a soil ecosystem may promote homeostasis, plants by themselves fit a model of "greed" with respect to CO_2, taking as much as they can, in order to exploit solar and soil resources as possible to most effectively cover Earth's surface with plant matter. Taken together, our results imply that negative feedback for climate change is not generated through plant interaction with atmospheric chemistry, in accord with cited evidence [5] that a modern 25% increase in atmospheric CO_2 content led to only a 2% increase in productivity. Productivity is more directly tied to (evapo-) transpiration. Therefore, an additional criticism[Error! Reference source not found.] of the homeostasis hypothesis is removed.

The question of whether life on our planet tends to promote climate and chemical homeostasis (Gaia), or to cause fluctuations that endanger life (Medea), is of fundamental importance to understanding Earth's history as well as the future of our species. However, the question appears to be, as yet, unanswerable. The innovation of photosynthesis was deadly to a great deal of life but promoted an environment which led to the explosion of multi-cellular life in the Cambrian, together with further crises along the way, from snowball Earth to Paleozoic ice ages. We looked at two of these major climate swings, arising from the conquering of the land by plants, and showed that a theoretical narrative already begun, which had produced an explicit prediction for achievement of homeostasis through the linking of ecosystems up to the continental scale, is remarkably accurate. The same theoretical framework has also recently been applied to generate an accurate, parameter-free, prediction of the global water cycle through application of an ecological hypothesis that plant ecosystems, which are most successful at reproducing themselves (in terms of volume of CO_2 drawn down from the atmosphere) will dominate. Thus, through a kind of conceptual division and synthesis, of ecosystems into their parts and their reassembly, we can identify the component - "greedy" photosynthesizers - that has led to climate shocks, and the whole that has restored equilibrium. Especially, we believe that the result reported here, regarding recovery from the Paleozoic ice ages, can help point the way to a future in which the opposite sides of the Gaia hypothesis can coexist meaningfully and usefully. Thus, whether the biosphere as a whole is Gaia-like or Medea-like (or neutral) is not put to the test, but a potentially important result and associated perspective are introduced.

METHODS

Theory

In any integrative sense, the existence of a global-, or at least continental-scale "organism" (think interacting ecosystems [22]) requires some means of communication over such a scale [12]. If this communication is tied to the growth of plants and fungi, the assessment of controlled homeostasis should relate to the prediction for increase in root lateral spread (RLS) l of plants/fungi as a function of time and water flow rates in the subsurface. Within the soil, roots were proposed to follow paths of minimal cumulative resistance [12,16,28]. In a disordered network, such as soil, where local (pore-scale) resistances to movement or flow are broadly distributed, such a path becomes long and tortuous and may be described using fractal geometry [28,31]. Then the RLS relates to root length L, through a non-linear power-law, $L \approx l^{\delta}$. The exponent δ is known as the fractal dimension of the optimal paths in heterogeneous media, that reflects confinement of plant root ecosystems globally to a very thin soil layer, with a universal value of 1.21 [28,31].

Predictions for the RLS ("biological transport") of plants were made using the equation [12,14]

$$x = x_0 \left(\frac{t}{t_0}\right)^{\frac{1}{D_{opt}}} \tag{1}$$

where D_{opt} in two dimensions (2D) = 1.21 is the optimal paths exponent from percolation theory [28], valid when the paths are confined to a 2D layer, such as the soil layer.

For soil depth predictions ("physical transport"), however, one may use the equation [12,32–34]

$$x = x_0 \left(\frac{t}{t_0}\right)^{\frac{1}{D_b}} \tag{2}$$

with D_{b} in three dimensions, (3D) = 1.87 the fractal dimensionality of the percolation backbone in 3D [28].

Although the flow, which supports soil development is mainly vertical, the connectivity of the dominant flow paths is three dimensional. Solute transport limits chemical weathering and soil depths under nearly all natural conditions. Predictions for flow and for crop heights can be made using [12]

$$x = x_0 \left(\frac{t}{t_0}\right) \tag{3}$$

which represents a scale-independent flow velocity. Here, water and nutrients are brought to the plants, eliminating constraints on root growth from the need to search for nutrients that are heterogeneously distributed within the soil.

In order to make proportionality useful for predicting plant growth as a function of time t, note that such scaling relationships require a fundamental length scale x_0 and a related time scale t_0,

$$t = t_0\,(x/x_0)^{1.21} \tag{4}$$

while identifying the RLS, l, with the length, x, and the ratio t/t_0 as the number of pores the root has grown through, which corresponds to root length L in multiples of x_0.

Experimental data

Our work utilizes exclusively experimental data reported by other authors, we did not perform experiments ourselves. Individual sources of data reported here were named in previous publications [12,32–34]. Data were reported for three categories, crop height, plant height (or root lateral spread), and soil depth. Since natural vegetation growth characteristics were postulated to be governed by the need to find nutrients and/or water within the heterogeneous soil medium, plants which were heavily fertilized and watered were considered separately and called “crops.” Crop heights apply mostly to annual crops, such as beans, peas, corn, hemp, tomatoes, sunflowers, tobacco, wheat, and amaranth. However, when trees in plantations are heavily nourished, such as in *Eucalyptus* plantations, these were also treated as crops. In the case of short-term laboratory measurements of root tip extension rates, distinctions between crops and natural vegetation were made on the basis of the descriptions of the environment. When the environment tested had either too little water or too much salt, for example, such experiments were included within natural vegetation. Plants grown under conditions described as ideal were considered again as crops. The BAAD database [19] with over 6000 entries for plant height was also divided in this fashion, with the relatively small database for fertilized *Eucalyptus* plantations added into the crops category, extending that data set to more than two years. Climate, rather than temporal, effects on growth rates were, e.g., inferred from dominant tree heights of *Eucalyptus regnans* along a climate gradient in Australia [14], which ranged from 4 m to 88 m. The depth to the bottom of the B (or Bw) horizon was considered to be the bottom of the soil [12,35]. Egli et al. (2018) incorporated also the BC-horizon, by adding ½ of its thickness to the total soil thickness. Soil depth data from deep time (10 Ma and up) was described in original publications [32,34] as "deep tropical weathering," with specific labels such as "laterite" and "saprolite," although climate regimes for some sources were humid temperate continental.

For the maximum crop height, natural vegetation RLS, and soil depth the same values of x_0 and t_0 were used, which are given in the text. Thus, the same network structure and flow properties were considered to govern all three scaling relationships and the exponents chosen were universal, generated from percolation theory [28]. The assumption throughout is that the association of local pores into dominant transport paths is described using percolation theory for finding the paths of lowest resistance. The results are predictions without use of unknown/adjustable parameters.

Data Availability

Data are available in the supplementary table.

References

1. Lovelock, J. E. *Gaia: A New Look at Life on Earth. Oxford University Press.* (1972).
2. Lovelock, J. E. & Margulis, L. Atmospheric homeostasis by and for the biosphere: The Gaia hypothesis. *Tellus* **26**, 1–9 (1974).
3. Kleidon, A. Testing the effect of life on Earth's functioning: how Gaian is the Earth system? *Clim. Change* **52**, 383–389 (2002).
4. Lenton, T. M. Testing Gaia: the effect of life on Earth's habitability and regulation. *Clim. Change* **52**, 409–422 (2002).
5. Kirchner, J. W. The Gaia hypothesis: fact, theory, and wishful thinking. *Clim. Change* **52**, 391–408 (2002).
6. Kirchner, J. W. The Gaia hypothesis: Can it be tested? *Rev. Geophys.* **27**, 223–235 (1989).
7. Gillon, J. Feedback on Gaia. *Nature* **406**, 685–686 (2000).
8. Grinspoon, D. It's Time to Take the Gaia Hypothesis Seriously. *Nautilus* (2017). Available at: https://nautil.us/its-time-to-take-the-gaia-hypothesis-seriously-5935/.
9. Ball, P. James Lovelock reflects on Gaia's legacy. *Nature* (2014). doi:10.1038/nature.2014.15017
10. Waltham, D. *Lucky Planet: Why Earth is Exceptional – and What that Means for Life in the Universe. Icon Books*. (2014).
11. Klyce, B. Gaia, What's new since 1998? (2021). Available at: https://panspermia.org/gaia.htm.
12. Hunt, A. G. & Manzoni, S. *Networks on Networks: The Physics of Geobiology and Geochemistry*. (Morgan & Claypool Publishers, 2016).
13. Bromhall, N. Role of fungi in the world ecology. Encylopedia Brittanica. (2019).

Available at: https://www.britannica.com/video/81498/fungi-matter-molecules-soil-atmosphere.

14. Hunt, A. G., Faybishenko, B. A. & Powell, T. A new phenomenological model to describe root-soil interactions based on percolation theory. *Ecol. Modell.* **433**, 109205 (2020).
15. Blöschl, G. & Sivapalan, M. Scale issues in hydrological modelling: A review. *Hydrol. Process.* **9**, 251–290 (1995).
16. Hunt, A. G. Spatiotemporal scaling of vegetation growth and soil formation: Explicit predictions. *Vadose Zo. J.* (2017). doi:10.2136/vzj2016.06.0055
17. Egli, M. *et al.* Prediction of soil formation as a function of age using the percolation theory approach. *Front. Environ. Sci.* **28**, 1–21 (2018).
18. Watt, M., Silk, W. K. & Passioura, J. B. Rates of root and organism growth, soil conditions and temporal and spatial development of the rhizosphere. *Ann. Bot.* **97**, 839–855 (2006).
19. Falster, D. S. *et al.* BAAD: A biomass and allometry database for woody plants. *Ecology* **96**, 1445 (2015).
20. Lyon, P., Keijzer, F., Arendt, D. & Levin, M. Basal cognition: Multicellularity, neurons, and the cognitive lens. *Philos. Trans. R. Soc. B Biol. Sci.* **376**, 132 (2021).
21. Kopp, R. E., Kirschvink, J. L., Hilburn, I. A. & Nash, C. Z. The Paleoproterozoic snowball Earth: A climate disaster triggered by the development of oxygenic photosynthesis. *Proc. Natl. Acad. Sci. U. S. A.* **102**, 11131–11136 (2005).
22. Margulis, L. *Symbiotic Planet: A New Look At Evolution. Houston: Basic Book*. (1999).
23. Morris, J. L. *et al.* The time scale of early land plant evolution. *Proc. Natl. Acad. Sci.* **115**, E2274–E2283 (2018).

24. Kenrick, P. *et al.* The interrelationship of land plants and the nature of the ancestral embryophyte. *Curr. Biol.* **28**, 733–745 (2018).

25. Pennisi, E. Land plants arose earlier than thought, and may have had a bigger impact on animals. (2018). Available at: https://www.science.org/content/article/land-plants-arose-earlier-thought-and-may-have-had-bigger-impact-evolution-animals#:~:text=All the analyses indicate that,multicellular animal species took off.

26. Lenton, T. M., Crouch, M., Johnson, M., Pires, N. & Dolan, L. First plants cooled the Ordovician. *Nat. Geosci.* **5**, 86–89 (2012).

27. Streel, M., Caputo, M. V., Loboziak, S. & Melo, J. H. G. Late Frasnian–Famennian climates based on palynomorph analyses and the question of the Late Devonian glaciations. *Earth Sci. Rev.* **52**, 121–173 (2000).

28. Hunt, A. G. & Sahimi, M. Transport and Reaction in Porous Media: Percolation Scaling, Critical-Path Analysis, and Effective-Medium Approximation. *Rev. Geophys.* (2017). doi:10.1002/2017RG000558

29. Hunt, A. G. & Sahimi, M. The spaces in between. *Eos 98* (2017).

30. Hunt, A. G., Faybishenko, B. A. & Ghanbarian, B. Predicting characteristics of the water cycle from scaling relationships. *Water Resour. Res.* **57**, e2021WR030808 (2021).

31. Porto, M., Havlin, S., Roman, H. E. & Bunde, A. Probability distribution of the shortest path on the percolation cluster, its backbone, and skeleton. *Phys. Rev. E* **58**, R5205 (1998).

32. Hunt, A., Faybishenko, B. & Ghanbarian, B. Non-linear hydrologic organization. *Nonlinear Process. Geophys.* **28**, 599–614 (2021).

33. Yu, F., Hunt, A., Egli, M. & Raab, G. Comparison and contrast in soil depth evolution for steady state and stochastic erosion processes: Possible implications for landslide

prediction. *Geochemistry, Geophys. Geosystems* **20**, 2886–2906 (2019).

34. Yu, F. & Hunt, A. G. An examination of the steady-state assumption in soil development models with application to landscape evolution. *Earth Surf. Process. Landforms* **42***,* 2599–2610 (2017).

35. Yu, F. & Hunt, A. G. Predicting soil formation on the basis of transport-limited chemical weathering. *Geomorphology* **301**, 21–27 (2017).

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Author contributions

A.H.: Data curation, Conceptualization, Methodology, Formal analysis, Validation, Roles/Writing - original draft; Writing - review & editing. M.S.: Conceptualization, Methodology, Validation, Roles/Writing - original draft; Writing - review & editing. B.F.: Conceptualization, Validation, Roles/Writing - original draft; Writing - review & editing. M.E.: Methodology, Validation, Roles/Writing - original draft; Writing - review & editing. Z.J.K.: Methodology, Validation, Roles/Writing - original draft; Writing - review & editing. B.G.: Data curation, Formal analysis, Validation, Roles/Writing - original draft; Writing - review & editing. F.Y.: Methodology, Validation, Roles/Writing - original draft; Writing - review & editing.

Competing Interests

The authors declare no competing interests.