In Defense of Metanarratives:
Extremal Principles, Optimality and Selection in Earth Surface Systems

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Preface

This paper was originally written in early 2015 and revised in April 2015, as an invited paper for a special issue of a geography journal. By mutual agreement with the guest editors, I withdrew the paper after deciding that I was unwilling/unable to satisfy the demands of one reviewer. The major, but by no means only, issues were that the referee and guest editors felt I should more fully address history and philosophy of science issues and parse the definitions of principles, theories, narratives, etc. I felt that I could say what I was trying to say without getting into that stuff, which would have taken a lot of work on my part that would have seriously inhibited my studies on the (to me) far more interesting and important topics of how Earth surface systems actually work. After sitting on it for two years, and publishing bits and pieces of the ideas on optimality and selection in other contexts (but not the metanarratives part) I concluded that I am unlikely to ever resubmit it anywhere. But I did put a lot of work into writing the damn thing, so I am posting it online, for what it is worth. I have not changed it, other than a bit of formatting (embedding figures and tables in the document and an added note or two) and correcting a few errors I missed the first time around.

Abstract

Metanarratives are critiqued and even rejected by many geographers and geoscientists. Yet, despite the inescapable role of geographical and historical contingency in physical geography, metanarratives are helpful, perhaps even necessary, in part because equifinality is common in Earth surface systems (ESS). Similarity of forms and patterns implies a possible single underlying cause. However, by definition the similar outcomes of equifinality are not the result of the same underlying processes, indicating that any encompassing construct must be in the form of a metanarrative. An effective metanarrative need not be strictly true, but should be useful in explanation, and its implications subject to empirical verification. Metanarratives should also be simplifying rather than complexifying. An example proposed here is the principle of efficiency selection: the most efficient pathways and modes of mass and energy flux are preferentially preserved and enhanced. This explains and unifies optimality principles proposed for a variety of ESS. Efficiency selection is testable based on observations and simplifying in that it encompasses a number of situations with a single concise proposition. According to the principle of efficiency selection, apparent optimality in ESS is neither teleological nor deterministically inevitable, but rather an emergent property.

Keywords: metanarrative, equifinality, extremal principles, optimality, Earth surface systems, efficiency selection

Introduction

Physical geography and geosciences have, sometimes grudgingly, accepted that no matter how much data and detail we achieve, explanation cannot be reduced to universal laws of physics and chemistry. We have also recognized the flaws and hazards of overarching “theories of everything”, and accepted the irreducible geographical and historical contingency in Earth surface systems (ESS). Conversely, there remains a need to synthesize, contextualize, compare, and contrast case studies. Though global laws and generalities can, in combination with local and contingent factors, explain ESS, we need conceptual frameworks that tie together phenomena and patterns, not just process mechanics--that is, we need metanarratives. This paper argues for the utility of metanarratives, via an example based on optimality principles.

Metanarratives

A narrative is an account or story of events, experiences, or observations. A metanarrative is, essentially, a narrative about narratives. More complex, specific, and nuanced definitions of metanarrative are deployed in various social science and humanities fields (e.g., Nunning, 2001). Here I use the most general of the two definitions from the Oxford dictionary: an overaching account or interpretation of events and circumstances that provides a pattern or structure for people’s beliefs and gives meaning to their experiences (substitute “conceptual frameworks” and “observations” to make the definition more geoscience-friendly). A narrative about stream channel morphology or ecosystem structure, for example, might be based on principles of energy dissipation. A metanarrative might encompass energy dissipation, and also other narratives/principles based on, e.g., least work, maximum efficiency, minimum entropy, etc.

I use the term metanarrative here because I focus on the role and importance of overarching, integrative explanatory or interpretive frameworks. Because these may conceivably take the form of theories, hypotheses, conceptual models, principles, laws, or paradigms, metanarrative is used here as a broad, general term that may include all of these forms. This paper will not parse the definitions of theories, paradigms, etc., or seek to classify explanatory frameworks--partly due to space limitations, but also because such categories are overlapping and contested (note: this was my attempt to bypass what the editors wanted me to do. They didn't buy it). Nor does space allow exploration of the philosophical implications touched upon here. Following a general discussion of the role of metanarratives, the paper turns to the phenomenon of equifinality, a key motivation for seeking overarching explanations. It then proposes a metanarrative to encompass the phenomenological equifinality associated with a broad class of “optimality” theories, and proceeds to a discussion of the characteristics of effective metanarratives in geoscience.

Some scientists have perpetually sought all-encompassing theories that explain, well, everything. “Everything” may be confined to a domain, such as landscape evolution; sometimes the goal is to explain all of nature. Geoscientists have become cynical with respect to theories of everything, partly due to recognition that explanation in the field-based sciences has irreducible elements of geographical and historical contingency, and thus of local idiosyncrasy (see, e.g., Turner et al., 2013; Wilcock et al., 2013; Furlani and Ninfo, 2015; Cullum et al., 2016; Van Dyke, 2016). A somewhat jaded view of grand theory also results from the fact that constructs promoted as universally applicable have fallen well short, be they domain-specific theories such as the cycle of erosion or plate tectonics, or broader constructs such as self-organized criticality, chaos theory, constructal laws, or catastrophe theory (these notions have not been shown to be incorrect; just incomplete). Because metanarratives include or may resemble grand theories of everything, geoscientists may be skeptical of metanarratives in general.

Many social critics and postmodernists are strongly critical of metanarratives. In social sciences and humanities, metanarratives are represented as claiming to be above local or "ordinary" accounts. These metanarratives, typically designated as such by their critics rather than their proponents (Marxist political economy is an often-cited example), are characterized as claiming to capture universal properties of human experience and thereby supposedly superior to more idiosyncratic, grounded accounts. Postmodern social critics have argued for rejection of metanarratives in favor of the local, and acknowledgement of the social and political nature of all narratives. Pednyowsky (2003), for example, shows how critical scholars have constructed a metanarrative of science to contrast with alternative social construction of nature narratives. Ironically, Pednyowsky (2003) also reveals how treating science as a single metanarrative obscures the great variety of scientific practices.

Though the term is applied almost exclusively in social sciences and humanities, the concept of metanarrative is applicable to the geosciences. Evolution by means of natural selection, ecological succession, plate tectonics, Gaia theory, Milankovitch cycles, steady-state equilibrium, and others are examples of overarching constructs that have influenced physical geography and can legitimately be termed metanarratives. Succession, for instance, subsumes more specific narratives or theories based on, e.g., facilitation, niche-assembly, and cycles, and is thus a metanarrative by the broad definition used here.

Critiques of metanarratives as a class are generally based on: (1) A tendency to obscure or distort important local factors (not necessarily just details); and (2) Failure to be universally applicable within their domains. The first critique is often true, though this does not necessarily invalidate the metanarratives. The second, even when true, is not a good reason (by itself) for rejecting explanations. For example, the conservation laws for energy and mass are universally operable, but even in problems of say, sediment transport or fluid dynamics they do not always explain everything and are not applicable, in a practical sense, to all problems. That does not invalidate the use of the conservation laws.

Even sound, useful metanarratives can impede scholarship if used uncritically, and allowed to indeed obscure local factors. However, we cannot possibly observe all ESS, or make sense of them, without some simplifying framework. We must organize a potentially infinite amount of information, but we also need to tell stories, and to leverage what we learn from the cases observed to the many more that we cannot. Some kind of broader construct is required.

Metanarratives need not be universal deterministic laws. They may be probabilistic rather than deterministic--not necessarily in a strict statistical sense, but describing likelihoods and tendencies rather than inexorable outcomes. Effective metanarratives need not be reductionist (they do not have to be atomistic or applicable bottom-up); they can operate at any relevant spatial and temporal scale, or a range of scales. And, they should simplify interpretation of case studies.

One reason that metanarratives are called for is the presence of equifinality, explored below.

Equifinality

Equifinality occurs when different processes, environmental controls, or histories lead to similar outcomes. This causal convergence is common in Earth system and geographic phenomena (e.g., Haines-Young and Petch, 1983; Culling, 1987; Beven, 2006; Savenjie, 2001; Schulz et al., 2001; Bunting and Middleton, 2009; Cruslock et al., 2010; Nicholas and Quine, 2010; Paik and Kumar, 2010; Patterson and Hoalst-Pullen, 2011; Tett et al., 2013). Equifinality is both a real-world phenomenon (e.g., a variety of processes in varied settings create vertical texture-contrast soils, Phillips and Lorz, 2008), and a property of some classes of models, whereby models based on different processes, assumptions, or theories produce similar results (c.f. Beven, 2006). In some cases both forms of equifinality exist—for example, channel networks formed in quite different environmental settings with different dominant processes often show topological and statistical similarities nonetheless, and these structures have been successfully reproduced using models based on quite different assumptions (e.g., Abrahams, 1984; Zanardo et al., 2013).

Equifinality is directly linked to metanarratives for two reasons. First, the similarity of forms, patterns and behaviors implies the possibility of some common cause. Second, by definition the similar outcomes of equifinality are not the result of the same fundamental processes, indicating that any common cause is best described by an overarching construct that subsumes multiple underlying processes. The role of metanarratives will be further explored below via an exploration of optimality in ESS, one manifestation of phenomenological equifinality in physical geography.

Optimality principles

Environmental sciences abound with explanations based on principles positing that development of ESS is governed or characterized by a tendency to maximize or minimize some aspect of energy or mass flux or organizational characteristics. Because these are often thought to enhance the function of ESS by increasing efficiency or stability, and for brevity, these are referred to here as optimal principles. And because they either propose or seek to explain similar phenomena arising in a variety of systems, and may be based on different models or assumptions, optimality-based explanations are an example of equifinality.

Case studies and field observations provide empirical support, to varying degrees, for optimality principles discussed here—all, in some senses, “work.” But ESS have no intentionality, and no one has ever explained why an ESS should maximize, minimize, or optimize anything (see, e.g., Phillips, 2011; Quijano and Lin, 2014). Without intent or governing laws, how do we explain the widespread (though hardly universal) success of optimality principles in describing, predicting, and modeling ESS? Is there a potential metanarrative that can explain this? If so, it could not only address the question of why the principles (often) work, but also potentially tie them together in a way that facilitates expansion to new phenomena and new cases.

ESS are controlled and influenced by a set of general factors—laws, principles, relationships that apply to any air mass, ecosystem, karst landscape, etc., any time, anywhere. They are also controlled and influenced by geographically and historically contingent factors that are not necessarily applicable in all cases, and are sometimes unique. Metanarratives can be a tool for identifying commonalities among ESS influenced by different sets of general factors, or when those global controls are inadequate for explanation. Here a metanarrative is developed that identifies commonalities among optimality principles derived from different mechanistic underpinnings, and for different ESS phenomena.

Optimal principles have been proposed in ecology, geomorphology, climatology, and fluid dynamics (see supplemental material). While these use different terminology and methods, and stress different aspects of ESS, many are consistent with each other, if not equivalent. For instance, optimal principles of ecosystem development based on exergy, emergy, power, and ascendency are formally related, and the metrics highly correlated (Patten 1995; Ulanowicz et al. 2006). Fath et al. (2001) and Yen et al. (2014) showed that in the context of ecological networks, most optimal principles are mutually consistent. Ozawa et al. (2003) showed the equivalency of optimal principles related to atmospheric heat flux, global climate, fluid convection, and turbulent dissipation. Extremal principles related to hydraulic geometry (interrelationships between fluvial channels and the flows within them) have been shown to be consistent with respect to their fundamental hydrological and geomorphological implications, and Huang and Nanson (2000; Nanson and Huang, 2008) indicate that all can be subsumed under a more general principle of least action (i.e., geomorphic work is performed with the minimum possible energy).

The least action principle (LAP) in physics states that the motion between any two points in a conservative dynamical system is such that the action has a minimum value with respect to all paths between the points that correspond to the same energy. In essence, the LAP suggests that nature always finds the most efficient path. In ESS, this means accomplishing work (e.g., productivity in ecosystems, heat flux in fluids, sediment transport in rivers) with as little energy as possible (Levchenko, 1999; Huang and Nanson, 2000). For a given input of energy, maximum efficiency in accomplishing work, coupled with conservation laws, dictates maximization of energy dissipation via entropy (Maximum Entropy Production; MEP)—thus the general consistency of optimality principles based on energy, power, and entropy. Confusion sometimes arises as to exactly what is being optimized—extremal principles applied to fluvial channels do not, for instance, propose that sediment transport is minimized, but rather that the energy used per unit of sediment transport is minimized.

Some optimal principles (see supplemental material) are directly linked to the LAP, by proposing maximum efficiency in energy use and/or mass fluxes. Others are either directly based on MEP, or propose maximum energy throughput, which also implies MEP (Fath et al. 2001; Ozawa et al. 2003; Dewar, 2005; Kleidon et al. 2010). A third group is based on preferential utilization, preservation, or replication of the most efficient flux gradients, and is thus based on a principle of gradient selection (GS; Phillips 2010a; 2011). Table 1 lists optimal principles according to their framing with respect to LAP, MEP, or GS.

Table 1. Optimal principles (see supplemental material) linked to overarching principles of least action (LAP), maximum entropy production (MEP), and gradient selection (GS). Source references are given in the supplemental material.

Principle	Source	Principle
Maximum energy efficiency	Kropotkin 1902	LAP
Maximum power	Lotka 1922; Odum 1991	MEP
Maximum generation of available potential energy	Lorenz 1960	MEP
Minimum stream power	e.g., Brebner & Wilson 1967; Yang 1971	LAP, GS
Maximum energy cycling	Morowitz 1968	MEP
Minimum entropy exchange	Paltridge, 1975	MEP
Maximum exergy storage; maximum emergy	Jørgensen & Mejer 1979; Odum 1991; Jørgensen 1997	MEP
Maximum energy residence time	Cheslak & Lamarra 1981	MEP
Maximum flow efficiency	e.g. Davies & Sutherland, 1980; Yang et al., 1981; Jia 1990	LAP, GS
Increasing ascendency	Ulanowicz 1986; 1997	LAP
Maximum energy dissipation	Schneider & Kay 1994	MEP
Minimum empower/exergy ratio	Bastianoni & Marchettini 1997	GS
Increasing energy flow	Levchenko, 1999; Levchenko et al., 2012	MEP; LAP
Least action	Huang & Nanson 2000; Nanson & Huang 2008	LAP, GS
Maximum energy flux	Eagleson 2002	MEP
Biogeochemical selection	Lapenis, 2002	GS
Maximum entropy production (MEP)	Ozawa et al., 2003; Dewar 2005	MEP
MEP	Dewar 2010	MEP
MEP	Kleidon et al. 2010	MEP
Gradient selection	Phillips 2010; 2011	GS
MEP	del Jesus et al. 2012	MEP
Maximum power	Kleidon et al. 2013	MEP
MEP	Lin, 2015	MEP

Equivalence of optimal principles does not imply redundancy. With different domains of origin and application, and various metrics and criteria, most are of interest independently of their commonalities. The key question is *why* these principles seem to work. ESS cannot plan or desire any particular pathway or outcome. At least three possible explanations exist for this phenomenological equifinality that do not require goal functions: Pathways and outcomes associated with the LAP, MEP, and GS are more probable than other outcomes; positive feedbacks reinforce LAP/MEP/GS trends; and/or features and evolutionary pathways associated with LAP/MEP/GS are preferentially preserved and enhanced by selection processes. As shown below, all three apply and are interrelated.

Probability and Feedback

Many extremal principles are based on optimal outcomes as tendencies or probabilities and make no claims of determinism or inevitability (e.g., Smith 1986; Lapenis 2002; Nanson and Huang, 2008; Dewar 2010; Kleidon et al., 2010; 2013; Lin 2015). The *mechanisms*, however, are generally based on feedbacks that reinforce some outcomes and/or inhibit others. Optimal behavior is related to feedbacks when they either reinforce optimal phenomena that happen to occur, or mitigate against suboptimal trends. For example, when more rapid or efficient material use or cycling in ecological systems confers a survival or reproductive advantage, this positively reinforces the trend toward maximizing cycling rates (e.g. Kropotkin 1902; Lapenis 2002; del Jesus et al. 2012). Ozawa et al. (2003) proposed feedback mechanisms as an explanation for MEP in fluid dynamics and climate.

With respect to morphologies resulting from turbulent flows, Nanson and Huang (2008) considered feedbacks of slope in river channels. These feedback effects, through a series of iterative adjustments, nudge the fluvial system toward a steady state defined by transport capacity ≈ imposed water and sediment load. These configurations are more stable (and thus optimal in a loose sense) than alternatives, and thus tend to persist (Nanson and Huang 2008).

Nanson and Huang (2008) used the term “survival of the most stable” to describe the iterative adjustments, and others have also invoked a process of hydraulic selection (more efficient flow paths are preferentially formed and enhanced) in the formation of fluvial channels (Leopold 1994; Twidale 2004; Phillips 2010a). Ulanowicz (1997) presented similar arguments (i.e., stability is positively related to persistence) for ecological systems. To the extent optimal patterns are based on probability or feedback considerations, both imply selection in the sense that the optimal patterns are more likely be preserved, reinforced, or replicated. With respect to how optimal pathways and configurations arise, probability implies feedbacks and feedbacks imply selection.

Selection

Feedbacks increase the probability of optimal configurations, and these are manifest via selection. In ecological systems, for example, all that is necessary to produce a trend toward maximum mass and energy fluxes or entropy is that ecological systems become saturated (all niches become occupied; all resource space is ultimately used), and that higher productivity rates confer advantages to the organisms involved and are thus selected for (Lapenis 2002; Phillips, 2008). The general logic applies to other hypotheses regarding ecological systems in Table 1. These hypotheses can all be related to the notion that phenomena that increase, e.g., energy or mass flux or storage, or otherwise nudge the system toward the optimum involve advantages in survival, competitive abilities, mutualism, or reproduction.

Gradient Selection. The principle of gradient selection in geomorphology and hydrology is simply that the most efficient flow paths are dominant, and that these tend to persist and grow over time (Phillips 2011). For the specific case of stream channels, Huang and

Nanson (2000; 2007; Nanson and Huang 2008; Huang et al. 2014) showed that the principle of maximum flow efficiency is a product of the LAP. Phillips (2010a) proposed a similar but more general principle of hydraulic selection, and Smith (2010) invoked selection of the most efficient pathways, and positive reinforcement of these, in his theory for the emergence of channelized drainage.

Using surface water flow (Q) as an example, standard flow resistance relationships (in this case the D'Arcy-Weisbach equation) give

$$Q = A\ (8g\ R\ S/f\ )^{0.5} \qquad (1)$$

where A is cross-sectional area (product of width w and mean depth d), g is the gravity constant, R is hydraulic radius, S is energy grade slope, and f a friction factor.
The relative flow of two competing flow paths *1, 2* is given by

$$Q_1/Q_2 = (w_1/w_2)\ (d_1/d_2)\ (R_1/R_2)^{0.5}\ (S_1/S_2)^{0.5}(f_1/f_2)^{-0.5} \qquad (2)$$

For sheet flows, and most channel flows where $w >> d$, hydraulic radius is approximated by mean depth ($R \approx d$). Substituting d for R in eq. (1),

$$Q \propto (w^1,\ d^{1.5},\ S^{0.5},\ f^{-0.5}). \qquad (3)$$

Thus pathways allowing for deeper flow are the single most important influence on the efficiency of alternative pathways. An increase in *S,* however, or an opportunity (e.g., via a river cutoff or avulsion) to access a steeper path with no decrease in *Q, d,* or velocity (*V)* (or decreases that are proportionately less than the increased slope) results in increased mean boundary shear stress (τ), cross-sectional stream power (Ω), and stream power per unit weight of water (ψ):

$$\tau = \gamma\ R\ S \approx \gamma\ d\ S \qquad (4)$$

$$\Omega = \gamma\ Q\ S \qquad (5)$$

$$\psi = V\ S \qquad (6)$$

where γ is specific gravity of water.

The increased shear stress and stream power may result in channel erosion, thus increasing *A*, *R, d.* This creates a more efficient flow path (⇑Q). This may have further positive feedbacks to shear stress and stream power, up to the point where water availability and structural limits on slope gradients or channel size become limiting. This sequence, visualized in Figure 1, is consistent with the LAP, and maximizes energy dissipation and entropy. The underlying process mechanisms, including adjustments of channel and flow geometry, result in a configuration that happens to produce characteristics of the system conforming to optimality. Optimality conditions are the result, not the cause, of the of the system characteristics. The same phenomena occur when an established channel is able to access a more efficient route, as in the case of an avulsion or cutoff (Figure 2).

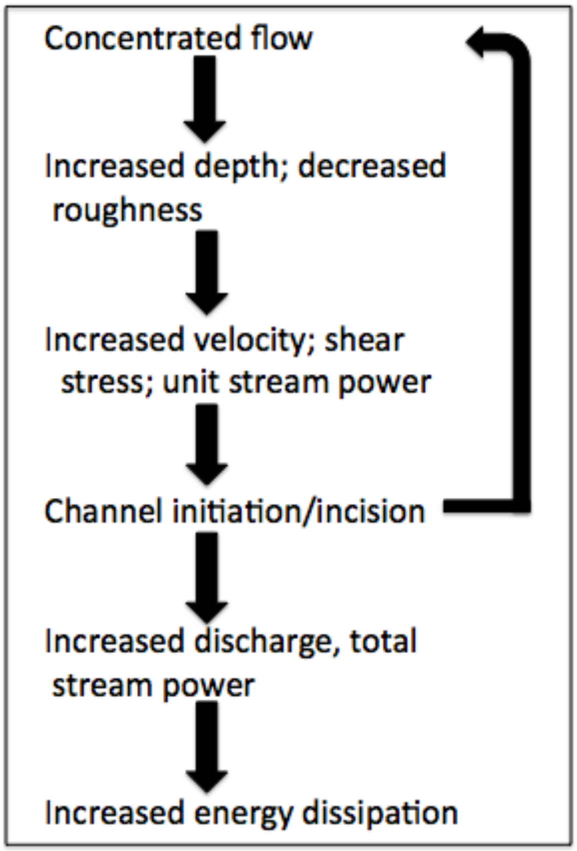

Figure 1. Relationships between positive feedback, gradient selection, and energy dissipation in surface runoff.

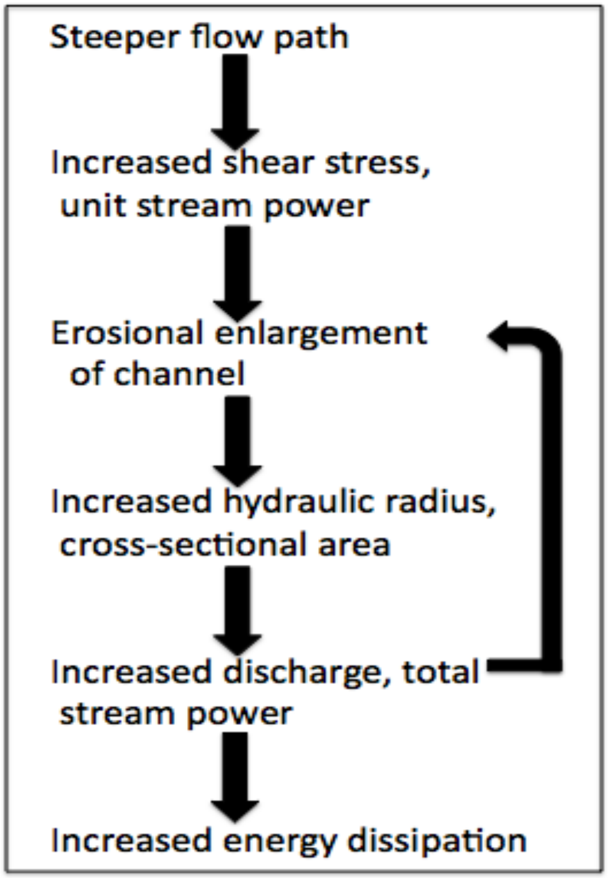

Figure 2. Relationships between gradient selection, positive feedback, and energy dissipation for the case of stream flow access to a steeper flow path.

Similar reasoning applies to subsurface flows, or a combination of potential surface and subsurface flow paths, at least if subsurface fluxes exhibit positive feedback whereby favored flow paths are self-enhancing due to effects of saturation on hydraulic conductivity, pipe or solutional erosion, or other factors. A number of studies indicate that this is indeed often the case (e.g. Liu et al. 1994; Price 1994; Gabrovsek and Dreybrodt 2001; Filipponi et al. 2009).

Principle of Efficiency Selection

The metanarrative emerging from this analysis is *efficiency selection*: Pathways and configurations that are most efficient in obtaining and using energy are selected for, in the sense of being more likely to occur and persist. Like biological selection, efficiency selection is not deterministic -- not all of the fittest individuals or more efficient features survive, grow, and replicate, but they do so in greater proportion than less fit or efficient ones. Thus there is a tendency over time toward configurations with greater efficiency. These are not dictated by any law; nor do they require any goal function within an ESS; they are emergent phenomena. Specific examples of more efficient configurations being more likely to occur and/or be preserved or perpetuated are given by, e.g., Ozawa et al. (2003) for climate, Lapenis (2002) for biosphere development, Smith (2010) for surface hydrologic flows, and Hunt (2016) for subsurface flows. In general, however, more efficient configurations are selected for because (1) they are more likely to occur in the first place; (2) positive feedbacks often reinforce them; and (3) in many cases they are more stable and thus more likely to persist.

In Defense of Metanarratives

Useful metanarratives need not be reductionist, or "grand theories of everything." Good metanarratives simplify disparate phenomena, and are subject to empirical evaluation. These criteria are discussed below, both in general terms and with respect to efficiency selection.

Truth and pragmatism

Acceptance of metanarratives because they work is consistent with Baker's (1996) view that geoscientists are philosophically pragmatic. Despite occasional nods to logical positivism, critical realism, etc., and common philosophical apathy, geoscientists in general are receptive to whatever approaches achieve research goals. A model or metanarrative does not have to be strictly true to be pragmatically useful. Many effective metanarratives, even more so than scientific theories in general, are based on probabilities and tendencies (as is efficiency selection), and are thereby tacitly acknowledged to occasionally be false.

Moreover, a metanarrative may be useful even when known to be false. For instance, the assumption of steady-state soil thickness often employed in soil and landscape evolution models and underlying some dating methods is often violated, and is not an accurate representation of soil and regolith processes and evolution. However, the fact that steady-state thickness is not a truth statement about soils or regolith may have little or no effect on the efficacy and utility of some models and methods based on the assumption (Phillips, 2010b).

Similarly, subsurface water flux is often satisfactorily described and modeled based on assumptions of flow through a porous medium described by D'Arcy's law. This is done even in some cases where flow is known to be non-Darcian and characterized by preferential flowpaths, because in many cases the preferential pathways are numerous and scattered enough so that, in the aggregate, moisture fluxes approximate flow through a porous medium (e.g., Weyman, 1973; Beven and Germann, 1982). The status of Darcian flow and steady-state soil thickness as metanarratives can be debated, but they show that an explanatory construct need not be strictly correct to be useful.

Testability and evaluation

Efficiency selection, like Darwinian natural selection, is not testable for individual cases. As selection is non-deterministic, falsification in individual cases does not falsify the principle. Because testing must involve numerous cases, selection principles apply in the aggregate, not to individual ESS. However, a candidate metanarrative must be shown to be true (with respect to its implications for ESS) in at least some cases, and an accepted one should be verified in the majority of the cases empirically examined. It should also meet the criterion of parsimony (Occam's Razor); it must be simpler than competing narratives that also conform to empirical observations. Thus, while a physical geography metanarrative need not be experimentally falsifiable, its implications about ESS (as opposed to its internal assumptions) do have to be ground-truthed.

Simplification

W.M. Davis's cycle of erosion was a dominant metanarrative in geology and physical geography from the late 19th through the mid-20th century. This construct was an effective metanarrative for a number of reasons, one of which was that it simplified interpretations of landscapes and landforms. The supplanting of the Cycle by other paradigms is a well-known story in geomorphology (Chorley et al., 1973; Orme, 2007), but it can be argued that one reason for its fall from grace was that it was complexified, at least with respect to explanation of individual landscapes. When the original cyclic theory could not be applied to, e.g., karst or arid landscapes, new versions of the cycle were proposed. When key assumptions such as episodic uplift followed by long tectonic quiescence were questioned or refuted, the cycle could have been simplified as a construct applying to specific situations of dominantly fluvially-eroded landscapes where uplift is followed by a period of tectonic stability hold. In such cases, Davis' original model indeed accurately describes landscape evolution. However, adherents of the cycle instead developed more complicated stories to attempt to fit field evidence into the cyclic theory.

The steady-state and Darcian flow concepts mentioned earlier have in common that they are convenient fictions, but also that they are simplifications. This is a hallmark of a good metanarrative. The Cycle of Erosion fell out of favor because the way it was deployed ultimately complicated rather than simplified the study of landscape evolution. Other metanarratives based on comparing rates or intensity of "competing" processes (uplift vs. denudation; force vs. resistance; etc.) simplified things (Orme, 2007).

A counter example is the soil-landscape paradigm or so-called "clorpt" model, describing geographical variations in soils as the result of the combined influences of climate (cl), biota or organisms (o), topography or relief (r), geology or parent material (p), and time (t). Thus *Soil = f(cl, o, r, p, t).* This approach has also been generalized to ESS of all types (Johnson and Hole, 1994; Huggett, 1995). The soil factor framework comes originally from Dokuchaev (1883); the "clorpt" form was popularized by Jenny (1941). Though the factorial model has been critiqued, the general soil-landscape paradigm remains the chief metanarrative underlying pedology, soil geography, and practical soil surveying and mapping.

One reason for the longstanding vitality of this metanarrative is that it simplifies soil geography. The basic premise is quite simple: soils are products of the environment. Second, it provides a handy tool; a checklist of environmental factors. Third, it is general enough (and also acknowledges the possibility of locally important environmental controls) to accommodate observed soils without having to complicate the concept or models based on it. On account of these traits, it cannot be falsified, only (in)validated based on its utility in explaining soils.

The mass and energy flux dynamics underlying many of the optimality principles proposed for ESS are sometimes quite complex, and differ between, say, fluid convection, biogeochemical cycles, and sediment transport. However, a simplifying construct such as efficiency selection is able to explain and unify the optimality notions.

Goal functions and teleology

(Note: reviews were also particularly critical of this section).

An appropriate geoscience metanarrative should not imply intentionality of nonliving entities or the necessity of an external designer. With respect to optimality, for instance, it has never been clear why ESS would maximize or minimize any particular quantity or flux. This form of teleological implication (noting that teleology is broadly and variously defined and does not always imply intentionality or a guiding hand) are one reason that an increasing number of physical geographers are skeptical of metanarratives based on “balance of nature” ideas whereby ESS are supposed to seek some form of balance or equilibrium (e.g., Gibson and Brown, 1985; Perry, 2002; Nanson and Huang, 2008; Smith, 2010). These explanations become much more attractive when they can be framed in terms of, e.g., emergent behavior rather than purported goals of environmental systems, as emergence is independent of any teleological implications and is simpler than postulating goal functions.

Rather than a universal physical or geographical principle dictating optimality, efficiency selection is a simplifying metanarrative that identifies a common phenomenology that is emergent and probabilistic rather than deterministic. Higher probabilities of optimal behavior are associated with positive feedbacks, and these optimal developmental pathways are manifest via selection, whereby the more efficient structures, relationships, and interactions are more likely to be preserved and replicated than other possibilities. Therefore optimal-like behavior in ESS does not require, or necessarily imply, any goal functions. It also does not require that LAP, MEP, or GS have status as deterministic laws (Kleidon et al., 2010; 2013). Rather, all that is required is that the maximization or minimization involved increases the likelihood of survival and replication of the responsible entity. Optimality in ESS is therefore neither teleological, nor deterministically inevitable. Rather, it is an emergent property arising from selection.

Concluding comments

Metanarratives are useful, but they need not be “theories of everything,” atomistic, reductionist, or teleological. Effective metanarratives need not even be strictly true, though they must either reveal or reflect empirically verifiable truths, or serve a pragmatic role in doing so. Useful metanarratives in geosciences must be empirically verifiable, and lead to simplification rather than complexification of interpretations. The principle of efficiency selection is proposed as an example of a useful metanarrative, and suggests that others based on emergent properties may also be useful.

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SUPPLEMENTAL MATERIAL

Table S1. Examples of extremal (optimal) principles in Earth surface systems.

Principle	**Domain**	**Summary**	**Comments**	**Source**
Maximum energy efficiency	Biological systems	Evolution selects for most energy efficient combination of organisms	Focuses on mutual aid in evolution rather than competition	Kropotkin 1902
Maximum power	Ecological systems	Systems organize to maximize energy throughput	Equivalent to maximization of energy throughflow	Lotka 1922; Odum 1991
Maximum generation of available potential energy	Atmosphere	Atmosphere heat flux operates to maximize rate of potential energy production	Equivalent to maximum entropy production	Lorenz 1960
Minimum stream power	Fluvial channels	Channels adjust so as to transport sediment with minimum possible expenditure of work	Phrased in various forms	e.g., Brebner & Wilson 1967; Yang 1971; reviews: Griffiths 1984; Paik & Kumar, 2010
Maximum energy cycling	Biological systems	Systems organize to maximize mass & energy cycling		Morowitz 1968
Minimum entropy exchange	Climate	Ocean-atmosphere heat flux minimizes entropy exchange with external environment	Equivalent to maximum entropy export to external environment	Paltridge, 1975

Maximum exergy storage; maximum emergy	Ecological systems	Systems maximize storage of useful energy (emergy)	Accumulation of mass & energy; exergy = maximum possible useful work	Jørgensen & Mejer 1979; Odum 1991; Jørgensen 1997
Maximum energy residence time	Ecological systems	Systems organize to maximize energy residence time	Equivalent to maximum exergy storage & maximum emergy	Cheslak & Lamarra 1981
Maximum flow efficiency	Fluvial channels	Channels adjust to maximize flow efficiency & minimize energy expenditure	Phrased in various forms	e.g., Davies & Sutherland, 1980; Yang et al., 1981; Jia 1990 reviews: Molnar & Ramirez 1998; Paik & Kumar, 2010
Increasing ascendency	Ecosystems	Ecosystem development characterized by increasing ascendency	Ascendency = f(total mass/energy flux, specificity of each flow)	Ulanowicz 1980; 1997
Maximum energy dissipation	Biological systems	Systems increase order at the expense of disorder (entropy) in surrounding systems	Generally equivalent to maximum entropy production	Schneider & Kay 1994
Minimize empower/exergy ratio	Ecological systems	Efficiency enhanced by maximizing empower relative to exergy	Empower = rate of emergy acquisition;	Bastianoni & Marchettini 1997
Increasing	Biosphere	Biosphere has	Self-	Levchenko

energy flow	evolution	evolved by maximizing energy flow	organizing mechanisms promote maximum energy efficiency	1999; Levchenko et al. 2012
Least action	Fluvial channels	Channels tend to adjust so as to transport sediment with the minimum possible work	Consistent with maximum flow efficiency	Huang & Nanson 2000; Nanson & Huang 2008
Maximum energy flux	Vegetation	Natural selection favors maximum energy flux	Maximum equated with optimum	Eagleson 2002
Biogeochemical selection	Biosphere, ecosystems	Selection favors faster & more efficient energy & nutrient cycling	Tendency toward maximum productivity & recycling	Lapenis, 2002
Maximum entropy production (MEP)	Fluid convection	At steady state, convection maximizes heat flux and thus entropy export		Ozawa et al., 2003
MEP	Turbulent flows	At steady state, entropy export maximized by turbulent energy dissipation		Ozawa et al., 2003; Dewar 2005
MEP	Plant physiology	Optimization theories unified by MEP	"Survival of the likeliest"	Dewar 2010
MEP	Environmental & ecological systems	Nonequilibrium thermodynamic systems organized in steady state such that entropy production is maximized		Kleidon et al. 2010
Gradient	Geomorphic	Steeper, more	Also:	Phillips

selection	systems	efficient flux paths tend to persist & grow	resistance selection—preferential preservation of more resistant features	2010; 2011
MEP	Vegetation & carbon assimilation	Vegetation evolves toward maximum productivity, associated with MEP		del Jesus et al. 2012
Maximum power	Drainage basin evolution	Maximization of sediment transport to deplete topographic gradients	Based on tendency of ESS to deplete driving gradients as rapidly as possible	Kleidon et al. 2013
MEP	Ecological succession	Rate of entropy production increases during succession	Ecosystem net energy budget must export entropy	Lin, 2015

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