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Abstract: A review of the status of fundamental research into soil genesis and development is given, together with a discussion of the outstanding problems from various perspectives, such as the geological, hydrological, and soil ecological points of view. The urgency of understanding what soil is, how it forms and evolves, relates fundamentally to its connection with the cycling of water and those elements of deep significance to biology, e.g. carbon, nitrogen, and phosphorus, as well as to the uptake and fate of the (mostly) solar energy input. The coupling is inherent in the close relationships between soil genesis and the formative process of chemical weathering, together with its abiotic drawdown of atmospheric carbon, as well as the relationship between soil evolution and the biological processes that change the soil. Each of these phases links soils to the atmospheric carbon composition and the Earth's climate system. More recently, the link between soil formation and Earth's water cycle has become clearer with the recognition that field weathering rates are more likely flux-limited (water, organic acids, and reaction products) than kinetics-limited. While a link between water and CO₂ drawdown appears explicit in the photosynthetic reaction, the relationship between plant productivity and transpiration fundamentally links water and cycling of elements such as carbon, nitrogen, and phosphorus. The summary is intended to place the works of the present book into the context of present research efforts and future goals.

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Where Are We and Where Are We Going? Pedogenesis Through Chemical Weathering, Hydrologic Fluxes, and Bioturbation

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ABSTRACT

A review of the status of fundamental research into soil genesis and development is given, together with a discussion of the outstanding problems from various perspectives, such as the geological, hydrological, and soil ecological points of view. The urgency of understanding what soil is, how it forms and evolves, relates fundamentally to its connection with the cycling of water and those elements of deep significance to biology, e.g. carbon, nitrogen, and phosphorus, as well as to the uptake and fate of the (mostly) solar energy input. The coupling is inherent in the close relationships between soil genesis and the formative process of chemical weathering, together with its abiotic drawdown of atmospheric carbon, as well as the relationship between soil evolution and the biological processes that change the soil. Each of these phases links soils to the atmospheric carbon composition and the Earth's climate system. More recently, the link between soil formation and Earth's water cycle has become clearer with the recognition that field weathering rates are more likely flux-limited (water, organic acids, and reaction products) than kinetics-limited. While a link between water and CO₂ drawdown appears explicit in the photosynthetic reaction, the relationship between plant productivity and transpiration fundamentally links water and cycling of elements such as carbon, nitrogen, and phosphorus. The summary is intended to place the works of the present book into the context of present research efforts and future goals.

14.1. WHAT AND WHERE IS SOIL PHYSICALLY, HYDROLOGICALLY, CHEMICALLY, BIOLOGICALLY, CONCEPTUALLY, AND SCIENTIFICALLY?

The need to understand soil genesis and evolution has never been higher. The soil is a center of the cycling of carbon, nitrogen, and water, and the foundation of the critical zone (CZ), (NRC, 2001), which stretches from the

bedrock to the treetops. In the soil, vegetation, microbes, and atmospheric water combine to transform bedrock from its original state into a medium that forms the basis of agriculture, foundations for our buildings, and the habitat for evolution.

Just coming up with a definition of a soil as an object, and a field of study, is not trivial. The chapter by Huggett (this volume) details the development of the modern concept of soil as an independent entity or system, starting with Hilgard (1860). Notably, Darwin (1881) referred to soil as “vegetable mould.” Early definitions were closely related to the worth of soil as a basis for agriculture (a medium for plant growth; Lyon & Buckman, 1922), and addressed its natural formation in the absence of human influence (Joffe, 1936). More in line with geomorphological applications, some viewed the soil as a mantle of loose and weathered rock (Hilgard, 1906; Coffey, 1912). Vernadsky (1926) developed the concept of the biosphere,

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of which soil is a component with ecological functions responsible for biodiversity, productivity, etc. (Bockheim et al., 2005). In the agricultural context, the zonation of the top few meters of the Earth's surface was accorded prime position and relevance. However, from what is now known as the O (organic) horizon to successive incorporations of the A (topsoil) and B (subsoil) horizons into the solum, and more recently the C horizon (variously parent material, or chemically weathered bedrock) as well (Richter & Yaalon, 2012), the concept of soil has been changing to become more compatible with an understanding of its position in Earth science between the bedrock and the atmosphere at the crown of the rock cycle. Further, although from the outset it has been the rule to regard soil formation in a context of "unchanging" conditions, such as the Holocene, it is now clear that soils may preserve a record of many changes in climate and, e.g., human influences, thus deserving the designation polygenetic (Richter & Yaalon, 2012). Over a similar time period, recognition of the importance of the suite of climatic and land-use changes imposed by human civilization has led to the suggestion that the present is no longer the Holocene, but the Anthropocene (Crutzen, 2002; Crutzen & Stoermer, 2000). These changes in our understanding of the role, position, and evolution of soil have challenged historical attributes of the study of soils as well as soil science within science itself. The soil is now seen as the "most complicated biomaterial on the planet" (Young & Crawford 2004, p. 1634), or "the crucible of life, a self-regulating, biophysical factory, acting like a composite living entity" (Hillel, 2005).

In the process of defining a soil at the interface of several complicated, interacting systems, it became necessary to define a soil not on the basis of the history of its constituents, which may move into and out of the soil, but on its position, both topographical and sequential, in the process of soil formation and erosion. In this context, the entire soil catena of a slope, located between a water channel and a ridge, is included, as is what is located between the parent material and the atmosphere, excluding to varying degrees purely organic material, such as plants or leaf litter. Most simply put, soil is the layer at the solid Earth surface, which is derived from, and distinct from, its source material, sediment, rock, or plant matter, through a wealth of chemical, biological, and physical processes, and what is not yet displaced from its catena by fluvial processes, which effectively convert the soil to sediment. The relative simplicity of this characterization of soil, like simplifications in its description or processes, hides further complexity.

From our perspective atop the soil, we are at that level where the input hydrologic flux, precipitation, is divided into four principle components: infiltration, surface runoff, transpiration, and evaporation. The topic "chemical

weathering" provides the link, as it were, between "hydrogeology" and "soil formation." Chemical weathering increases surface area, porosity, and the concentration of mineral nutrients needed for plants to grow, apparently simultaneously a precondition for growth and a result of that plant growth. As chemical weathering in the field is mostly limited by the flow of water into the soil (Maher, 2010), so is the rate of soil formation limited principally by chemical weathering (Burke et al., 2006, 2009; Dixon et al., 2009, 2012; Egli et al., 2014; Hunt & Ghanbarian, 2016; Yu & Hunt, 2017a, 2017b). Indeed, the chapter of Lyons et al. (this volume) on chemical weathering in the Antarctic's McMurdo dry valleys demonstrates the clear link to water, with weathering resulting almost exclusively from melting of subsurface ice and in the hyporheic zone of meltwater streams. However, see also the chapter by Anderson et al. (this volume; note that Anderson and Anderson, 2010, helped bring chemical processes, such as weathering, to the forefront of landscape evolution), who argue that at Gordon Gulch such chemical processes may only be limiting to the weathering of bedrock, not to the actual development of the regolith, which in steady state is controlled by surface physical processes.

The complex interplay of weathering and biota in the critical zone poses challenges for advancing research on how Earth's surface evolves in response to environmental factors (Brantley et al., 2011). In the context of hydrogeology, it is important to emphasize that soil formation and erosion processes are directly tied to two of the pathways of water encountering the surface of the Earth: surface runoff and infiltration.

To stimulate future research, we hypothesize that weathering, erosion, soil formation, and biogeochemical cycling are essentially limited by water fluxes.

14.1.1. Soil Formation, Erosion, and Burial

- Physical erosion is proportional to precipitation and thus, presumably, surface run-off (Reiners et al., 2003), while soil deepening, mineral transformation (see chapter by Egli and Mirabella, this volume), and chemical erosion processes are proportional to infiltration (run-in?).

- Soil formation joins fundamentally with the carbon cycle, as the two principle terrestrial means to draw carbon down from the atmosphere are in plant growth through photosynthesis, with an instantaneous rate proportional to a local water flux, and chemical weathering of silicate minerals in rocks, with a rate proportional to infiltration.

Formation, transport, and burial of sediment are the surface expression of the rock cycle. The burial of carbonate minerals as products of chemical weathering of silicate minerals represents by far the dominant sequestration of atmospheric carbon, with its relevance to

global temperature regulation (Berner, 1992). In the process, carbon passes through the soil in inorganic forms, such as bicarbonate, while water is buried together with the sediments, connecting to the deep-water cycle.

14.1.2. Biological Processes

Many biological processes in soil formation depend on chemical weathering for the resulting increase in mineral surface area, together with the release of mineral nutrients, such as potassium, phosphorus (Hartmann et al., 2014), and iron. Conversely, the chemical weathering process is often directly mediated by microbes. Soil fertility correlates strongly with the fixing of (predominantly) atmospheric nitrogen through interactions of soil microorganisms with plants.

- The productivity of plants is expressed in their ability to draw down carbon from the atmosphere, which is then released into the soil through metabolic activity. This productivity appears to be most strongly controlled by the water and essential nutrients drawn from the soil.

- The chemical weathering reaction itself is mostly a complex biogeochemical process that depends on the CO₂ and organic acids released by the plants within their ecosystems. The tendency for soil nitrogen and carbon components, and therefore cycles, to be linked, but that of phosphorus to vary more independently (Tian et al., 2010), as expressed in the terrestrial Redfield ratio (Redfield, 1958), is thus broadly understandable in the context of the more important influence of parent materials relative to the atmosphere in phosphorus, although the relative immobility of phosphorus is also important.

An increased understanding of the details of these interactions, including the multiple possible combinations of fungal synergisms and root types (Brantley et al., 2017a), is required for future progress in this field. Plants, their roots and associated microorganisms, and earthworms are the main soil engineers. Through their physical activities (e.g. tree uprooting) and soil aggregation they act as catalyst and provide, transform, and translocate organic matter and nutrients throughout the soil profile (as shown by Le Bayon et al., this volume).

14.2. SOIL-FORMING FACTORS AND SOIL PRODUCTION; CONNECTIONS WITH GEOMORPHOLOGY AND HYDROLOGY

Let's return to the question of what soil is, since this is currently a topic of relevance in both CZ science and geomorphology. Jenny (1941) quotes Ramann (1911; 1928): "The soil is the upper weathering layer of the solid earth crust," then continues with the inevitable criticism, "Joffe (1936), a representative of the Russian school, objects to Ramann's formulation on the grounds that it does not

distinguish between soil and loose rock material." Jenny adds that, although there will probably never be agreement between all soil scientists as to what soil is, the one characteristic that all soils appear to share is anisotropy, which at its best developed, can be classed as horizonation, while conceding that even that classification can be arbitrary. Jenny continues with the observation that the distinction between freshly fallen leaves or living grass to plant matter sufficiently decayed to be considered part of the O (organic) horizon, is artificial, as is the distinction between the lowest soil layer and parent material. Overall, he summarizes, "In the opinion of the author, the distinction between soil and environment is arbitrary; it exists only in our minds, not in nature." "Fortunately, there is no urgent need for universal agreement." These questions reappear in Cline (1961) and in Richter and Yaalon (2012), but with increasing urgency for their resolution.

Richter and Yaalon (2012) in "The Changing Model of Soil, Revisited" and Richter and Markewitz (1995) in "How Deep Is Soil?" address points made in an essay by Cline (1961). First, they propose, echoing Ramann (1911; 1928), that "the lower boundary of the soil is much deeper than the solum historically confined to O to B horizons," extending the bottom of the soil to the bottom of the C layer. Lukens and Norton's results (this volume) suggest deep weathering boundary as the bottom of the soil, meaning that the material arriving at the soil-saprolite boundary already may be substantially preweathered. This mechanism has an important impact on weathering and nutrient release. The basis for this argument is that the important effects of biogeochemical weathering throughout the column are accorded their proper due, while lending support to Cline's argument that a more holistic view of soil, divorced from its agricultural background, is achieved. Second, Richter and Markewitz (1995) state, "Cline was most impressed with how geomorphology was enriching pedology, and with the increasingly sophisticated view of soil time and of the dynamic processes of soil formation." Particularly when soil production is that process which provides the strongest limitation on the delivery of sediments from their sources on the continents and islands to their sinks in lakes and oceans, this measure of the effectiveness of the erosion process is crucial to understand. However, it is important to keep in mind that, although Gilbert (1877) made one of the first references to soil production, this reference was largely forgotten until the 1960s (Humphreys & Wilkinson, 2007), finally coming into its own starting in the 1990s (Heimsath et al., 1997). Yet, Gilbert wrote rather presciently, "Solution and frost, the chief agents of rock decay, are both retarded by the excessive accumulation of disintegrated rock. Solution gradually decreases as the zone of its activity descends and the circulation on which it depends becomes more sluggish."

In actuality, it is more often true that infiltration, as a fraction of precipitation, is higher where soil is deeper, but more likely because soil depth increases with the infiltration rate (Hunt & Ghanbarian, 2016). However, solution transport does become more sluggish with increasing time or distance (e.g., Berkowitz & Scher, 1995; Cortis & Berkowitz, 2004).

Notwithstanding, for over a century, soil formation has been addressed as a process that depends on a range of external factors (i.e. climate, organisms, relief, parent material, and time, in the line of Dokuchaev [1880/1948, translated from earlier Russian] and Jenny [1941]). As formulated by Jenny,

$$S = f(cl, o, r, p, t) \quad (1)$$

for the soil depth (or other soil property), S , as a function f of cl (climate), o (organisms), r (relief), p (parent material), and t (time). Note that the functional form of S is not, in general, given, as the equation is more intended to focus one's attention on the most important factors controlling the depth or properties of the soil. The suite of properties described by equation (1) gives the state of the soil.

If the dependence on time of individual soil variables is more naturally described in terms of discrete variability, such as associated with fairly abrupt climate change, then it may be advantageous to think of soil production in terms of an amalgamation of discrete paleoprocesses with a variety of imprints on the soil (Richter & Yaalon, 2012), leading to the term *polygenetic paleosol*. The soil functional properties are often products and witnesses of Quaternary events, natural and human induced, that occurred in the landscape. Many soils started to form under conditions that were different from the current ones (Costantini, 2018). Relict paleosols remain at the surface and continue to develop.

The posited functional relationship, equation (1), appears to place the formation or evolution of soil on a sound footing, but in actuality, without a specific functional form, its main value is its delivery of a historically connected and familiar formulation. The typical means to investigate equation (1) is to correlate statistically various of the input factors with the output factor, S . As an example, Jenny (1941) investigated California soils in distinct biomes, such as grasslands, and correlated the dependence of the C:N ratio with precipitation, P . He found that, within a specific biome, the C:N ratio slightly decreases with increasing P , but considering all biomes simultaneously led to a significant increase in C:N with P . A soil catena is believed to eliminate climatic and parent material influences from soil variability and isolate relief as a variable (Bockheim et al., 2005). Chronosequences

isolate the time variable, etc. (Jenny, 1941). This process lends scientific sophistication to a formulation that is not directly linked by mathematics to a specific process, or combination of processes, and may, moreover, hide synergisms and nonlinearities, such as threshold processes.

Consider, however, the perceived role of the soil catena in the isolation of topographic variables. According to the geomorphological perspective, this must be done by comparison between catenas, rather than within one catena (Heimsath et al., 1999), since surface translocation of soil is, under steady-state conditions, considered to be governed by the diffusion equation, a consequence of transport linear in the surface gradient and the equation of continuity. The diffusion equation thus constrains surface soil transport to be equal along the catena. Nevertheless, this approach does not yet take into account coupled effects of the variation of soil production with depth as well as infiltration (Yu et al., 2017), weakening the conclusion.

Since the advent of the 21st century, it has become increasingly evident that soil production and chemical weathering (Burke et al., 2006, 2009; Dixon et al., 2009, 2012; Egli et al., 2014; Hunt & Ghanbarian, 2016; Yu & Hunt, 2017a, 2017b) as well as denudation rates (Figure 4, DiBiase et al., 2012) are proportional to each other.

How can these results be understood? In theoretical treatments of surface reactions in porous media, the proportionality of both soil formation rates and chemical weathering rates to flow velocity arises whenever the progress of the weathering reactions is limited by the ability of flowing water to transport product solutes from the reaction front. This question is addressed using what is called the Damköhler number, Da_1 (Salehikhoo et al., 2013), a ratio between solute advection time and a reaction time. The latter time scale is calculated assuming complete mixing (Yu & Hunt, 2017c). $Da_1 \ll 1$ signifies that reaction kinetics limit (dominate), whereas $Da_1 \gg 1$ indicates that solute transport dominates (but see Bandopadhyay et al., 2017, or Reeves & Rothman, 2014, who calculate Da_1 using a ratio of diffusion to reaction times, implying that the form of transport limiting reactions is molecular diffusion). The calculation depends sensitively on both the reaction kinetics and the fluid flow rates, but Da_1 tends to increase in time (Gilbert, 1877; Cortis & Berkowitz, 2004) because the solution efficiency (velocity) diminishes over time when solute transport is non-Fickian, nowadays considered the rule, rather than the anomaly (Cushman & O'Malley, 2015). While a trend towards increasing relevance of transport with increasing time is likely universal, a crossover at about $Da_1 = 1$ can apparently occur on time scales of roughly a day and length scales of a fraction of a millimeter (Maher, 2010) up to hundreds of years (and length scales of centimeters, Egli et al., 2018). Assuming that the entirety of such

variability has not been plumbed, such time and length spans may sometimes be much larger, i.e. millennia.

Rates of physical erosion and chemical weathering are often positively correlated across diverse landscapes (Dixon et al., 2012, Dixon & von Blanckenburg, 2012). This positive relationship exists up to a certain threshold where a limit of weathering rate is reached. Soil production rates cannot be infinitely high. It is, however, still questionable where this speed limit is: some authors set it at about 320–450 t km⁻² yr⁻¹ and others at 800–2000 t km⁻² yr⁻¹ (Egli et al., 2014). However, in the New Zealand Alps, with precipitation rates 10 m yr⁻¹, Larsen et al. (2014) have measured soil production rates as high as 4000 t km⁻² yr⁻¹, a result that has been shown consistent with a linear dependence of soil production rates on precipitation over almost 4 orders of magnitude of precipitation (Hunt & Ghanbarian, 2016), from the driest place on Earth (the Atacama Desert) to among the wettest (New Zealand Alps). Other authors, e.g. West et al. (2005), noted that silicate weathering is, in principle, limited by two processes: solute transport and reaction kinetics. The supply of water, acids, and (organic) ligands relative to the supply of silicate minerals is large in transport-limited weathering regimes that are mostly found on relatively old and flat surfaces. Areas having a high erosion rate, a high uplift rate, or young surfaces also have a high supply of fresh minerals. Under such circumstances, the main control on chemical weathering depends particularly on the kinetic rate of mineral dissolution and time available for reaction. Thus, erosion rates may be so high that the associated soil production rate based on the calculation of transport-limitations may exceed the rate of reaction of a fresh mineral surface. On a soil evolutionary time-axis, Egli et al. (2018) showed that the limitations on mineral weathering imposed by reaction kinetics can affect the system until 100–200 yr of soil evolution, a result generally in accord with Damköhler number calculations of Yu and Hunt (2017b). Thereafter, solute transport seems dominant. Within regolith, faster erosion rates and shallower thicknesses mean minerals move rapidly through the weathering zone, leading to shorter residence time and hence a lower degree of weathering. For example, Ferrier and Kirchner (2008) predicted that weathering rates approach zero when denudation exceeds roughly half of the maximum soil production rate.

Both laboratory experiments (short duration, simplification) and field observations have shortcomings (lack of control of variables, changing climatic conditions, etc.). Despite the limitations associated with using either approach, it has become increasingly evident that weathering rates strongly depend on the rate at which fluid flows through the medium, be it soil (Maher, 2010) or an experimental column (Salehikhoo et al., 2013) (Figure 14.1). Here an approximately linear dependence

Figure 14.1 The dependence of weathering rate reactions on flow velocity in field measurements and lab experiments. Field results for silicate minerals are due to Maher (2010) and cover typical vertical flow rates of about 3 cm to about 2 m per year, though a few are for flow rates in the millimeters per year. Lab results on MgCO₃ were obtained by Salehikhoo et al. (2013) and span flow rates from about 30 m to 14,000 m per year. Cumulatively, the results demonstrate a 7 order-of-magnitude increase in reaction rate over 7 orders of magnitude change in flow rate.

of reaction rate on flow is demonstrated over 7 orders of magnitude of flow rate.

Note that, for the proportionality to flow rate to continue to such high flow rates as used in lab experiments, however, the parent materials must have a high intrinsic reaction rate; the source material for the Salehikhoo et al. (2013) experiments was MgCO₃, with dissolution rates orders of magnitude higher than for typical silicate minerals.

Thus, for purposes of prediction of weathering rates, a critical input is the fluid flow rate, a quantity which, in the field, is a hydrologic variable. Therefore, proportionality of weathering rates to flow rates puts soil formation squarely in the domain of hydrologic sciences, in view of the need to determine the partitioning of water at the terrestrial surface, and into soil physics as well, as a result of the relevance of the flow and transport properties of the medium. However, although the chemistry is explicitly omitted from Figure 14.1, for more slowly reacting species, the dependence of R on flow rate becomes horizontal at lower velocities (Maher, 2010), commensurate with a cross-over to $Da_1 < 1$ (Yu & Hunt, 2017b). Since employment (with success) of this sort of reductionism is counter to current trends in ecohydrology and biogeochemistry, there is a need to provide additional context for how it may work.

Specific interpretations of limitations to weathering in the field ascribe varying relevance to the roles of biota, chemistry, and physics. The possible array of processes that could be thus described is immense. Therefore, take a single example, the effects of bedrock fracturing on weathering rates. Such a topic may bring in a variety of

variables. It is clear that fracturing of bedrock promotes fluid infiltration into newly exposed rock surfaces, enhancing infiltration compared with overland flow, and thus soil formation over soil erosion. But what controls the fracturing process? Is it principally a result of freezing (physics), tree roots (biota), or chemical weathering (chemistry)? Established means of thinking favor the first two, but it has been shown that tree roots are not really capable of prying apart rock (except for relatively weak sandstone; Brantley, 2017a, and references therein), while mineral volume changes due to chemical weathering are quite capable, under sub-critical conditions, of extending fractures (Eppes & Keanini, 2017). In that case, chemical weathering is the process limiting the effectiveness of fracturing and thus soil formation. But chemical weathering is mostly controlled by water fluxes (Maher, 2010), and thus the physics of flow and transport (within the discipline of hydrology, or soil physics). Sak (this volume) nicely presents that rock weathering and the formation of weathering rinds on the surface of such rocks is governed by the rocks' composition and ambient climatic (and thus also hydrologic) conditions.

A problem often emphasized is the need to develop theory and descriptive expressions that cross scales in

time and space (Brantley, 2007). When water tends to follow paths of least resistance, the same physical basis for employing percolation theory may be invoked at all scales (Hunt & Ewing, 2016) and results for vegetation growth and soil formation over immense time scales are generated from the percolation optimal paths exponent and the fractal dimensionality of the percolation backbone, respectively (Hunt, 2017). A scaling plot (Figure 14.2) of water, earth, and biota that describes the cumulative effect of flow rates and time on soil formation and vegetation growth, demonstrates the increasing separation of time scales for, e.g., vegetation growth and soil formation, with increasing length scale, even though at scales of a few pores, these two time scales are approximately the same (and equal to the ratio of a pore size to a water flow rate), since transpiration is typically only a factor of 2 higher than infiltration. Understanding this profound separation of time scales is key to understanding the relative roles of chemistry and biology in soil development and, as it turns out, in the global carbon and water cycles.

Identifying the great slowing of chemical weathering processes relative to, e.g., biological processes with increasing length scale, lends additional theoretical

Figure 14.2 Scaling diagram of relationships limiting the growth of fertilized crops (linear in time equal to the flow rate), natural vegetation (optimal paths exponent of percolation theory and the same flow rate), and soil formation (backbone fractal dimensionality and the same flow rate). Note that the lower flow rate limit for soil formation, 2.5 cm yr^{-1} , is a bound for most of the data of Maher (2010), while the upper limit, 25 m yr^{-1} , is the quotient of the world's maximum precipitation divided by a typical porosity. The lower limit in space is $30 \text{ }\mu\text{m}$, while the shortest time scale is determined by the ratio of this length scale to the flow rate. Data sources are given in Hunt (2017); BAAD = Biometric and Allometric Database (Falster et al., 2015). (Source: Hunt, 2017).

justification to the conclusion from field work that chemical weathering is the fundamental limiting process in soil formation. The conclusion from field studies derives from the close correspondence of soil production and chemical weathering rates over long time scales. Moreover, it has been possible to use analytical formulations of the time-dependence of chemical weathering to generate an actual functional form for the soil formation function of Jenny and Dokuchaev (Yu et al., 2017).

Even though the study of chemical weathering may provide a basis to define not only the depth of the soil but also the vertical distribution of various mineralogical or chemical species, it has its own limitations. Effects of bioturbation may decouple variables that describe vertical soil structure from soil depth, necessitating additional generalization of the Dokuchaev perspective. As discussed by Johnson and Schaetzl (2015), such a revision in fundamental thinking would be a return to the concepts of Darwin (1881). Although not a primary subject of this summary, it is interesting to note that the processes that lead to vertical sorting of particles include burrowing by animals at least from the size of worms up to the size of rodents.

14.3. HUMAN IMPACTS AND RELEVANCE TO HUMAN SOCIETY

Land-use change, including the development of agriculture and the subsequent translocation of the majority of the human population to cities, has had profound impacts on soil characteristics and soil erosion, and through these, soil production (inferred from DiBiase et al., 2012). Richter and Yaalon (2012) give, as one of three fundamental changes in understanding of soils that motivate a rethinking of the discipline, the global transformation of soils from a “natural to a human-natural body.” Forman and Stinchcomb (2015) include both the critical zone (including its geologic history) and human impacts on surface processes as among their six grand challenges for Quaternary geology. Forman and Stinchcomb (2015) quote Steffen et al. (2015) to imply that “human activities continue to affect earth surface processes with non-analog responses compared to Holocene landscape dynamics.” Thus, the present time is described as the Anthropocene, in view of massive geochemical, biological, and geomorphic changes at the Earth’s surface, and their expression in sediment yield and composition. While the onset of the Anthropocene may be defined in terms of stratigraphy, geochemistry, geomorphology, or other ways (see, e.g., Edgeworth et al., 2015), it is noteworthy that the boundary as expressed in the human impacts on the soil itself has been termed the Golden Spike (Certini & Scalenghe, 2011). Here, investigations into human impacts on soils

are concentrated in the chapter of Horn and Lal (this volume) on compaction of agricultural soil due to inappropriate uses of heavy machinery; these effects include permanent changes in the stress structure of the soil, reduced air and water flow, and their impacts on agriculture as well as how to diagnose the resilience of soil ecosystems to such treatment.

The impact of humans on the soil is so large, it can no longer be neglected in any comprehensive theory of soil. The “Jinji unconformity” divides human and natural deposits (which may straddle the soil) and provides understanding of pollutant migration zones, weakness, and fracturing, as well as soil liquefaction (Edgeworth et al., 2015). Instead of emphasizing a role of human beings separate from nature, however, it may be more constructive to seek a higher order unity of principles (Haff, 2014a) that describes both human and natural processes. Some parallels include the following: The principle of superposition works in archaeology as in geology; newer cities are invariably constructed on top of older ones, and different technologies, e.g. stone, iron, and bronze, are found in superposed layers (Harris, 1979, 2014). Even subsequent reorganization of the subsurface by human activities is a form of bioturbation in soils or sediments and can invalidate superposition (Harris, 2014) in the same way as activities of other animals. Storm water removal systems can be considered artificial karst in their function and may have analogues to real karst in their architecture (Garcia-Fresca, 2007), though not in composition or rate of formation. In spite of the parallels between human and non-human natural activities, Haff (2014b) is able to list six principles that distinguish the so-called “technosphere,” an additional realm of the Earth that is an analogue to Vernadsky’s (1926) biosphere.

Practical problems with a need for timely solution include not just the loss of soil itself (Blanco & Lal, 2010; Montgomery, 2007) but the loss of soil carbon (Lal, 2004) as well as the loss of biodiversity in agricultural soils (e.g. Wilcove et al., 2013). Related problems that are only slightly further afield include the loss of land surface to productivity (through conversion of solar energy to sugar) by the replacement of permeable with impermeable surfaces, with resulting increases in sensible heat fluxes and runoff (Taha, 1997). Basic concepts are needed to guide research, whereas specific proposals are needed to lead engineering. Can the changes in energy and water partitioning be represented (Faybishenko, 2010) within traditional Budyko (1958, 1974) strategies, or do they represent fundamental deviations from theoretical guiding concepts, such as optimization of work (see Hunt, this volume)? Can we reverse the loss of carbon in soils? An important such strategy has been promoted by Taylor et al. (2016), who proposed the use of crushed basalt in agriculture, both as a means to

increase the fertility of the soil, and for its role in draw-down of atmospheric carbon.

14.4. WHERE IS SOIL AS A DISCIPLINE?

Within the evolution of the geosciences is the continued gradual movement to change its character from observational to predictive. A predictive science, by definition, must develop hypotheses, which can guide the use of mathematics to make verifiable quantitative predictions. The model or hypotheses live or die from the success or failure of these predictions. An observational science tells a story. Both sides are, of course, still represented in professional organizations such as the American Geophysical Union, as indeed both connotations are found in the term *geophysics* itself. Beyond this distinction lies a question of the applicability of models, as pointed out by Cline (1961) and reiterated by Richter and Yaalon (2012). Cline (1961) said,

Within the framework of its accumulated knowledge, every science develops a mental image of the thing with which it is concerned. This model of a science is the organized aggregate of accumulated facts, and laws and *theories based on those facts*: it is a mental picture of that which is known viewed in organized perspective through verified quantitative relationships, which we call laws, *with varying degrees of distortion by virtue of theories that attempt to explain the observed relationships*. The picture is *not the same to all who work in the science*, for it is composed of knowledge and the extensions of theory from knowledge into the unknown, and different men know, or think they know, different things. The picture is sharply in focus in those parts for which quantitative relationships have been defined; it becomes progressively more blurred as one approaches the limits of quantitative data and *progressively more distorted with increasing dependence on theory*.

We have added italics to portions of this statement that emphasize Cline's fundamental distrust of what he calls theory. Thus, Cline apparently suggests that a theoretical underpinning of a quantitative relationship would make it less reliable. In physics and chemistry, such is certainly not the case; rather, it is the lack of a theoretical explanation that should trigger suspicions.

Richter and Yaalon (2012) go on to state that Thomas Kuhn's (1962) concept of "paradigm," published in *The Structure of Scientific Revolutions*, was analogous to Cline's mental image. Kuhn suggested that science advanced through periods of utilization of recognized methods and organization of research, together with its results (that fill in the holes in the field), which build a paradigm, to discovering anomalies incompatible with that paradigm. Upon recognition of the difficulties, the cognizant scientific community reaches a crisis, which is

followed by the overthrow of the existing paradigm in a kind of revolution. Such an occurrence has come in time to be known as a paradigm shift. The physics-centricity of this picture is allegedly at odds with how other sciences change, notably biology, as Ian Hacking noted in his introductory essay to the 2012 republication of Kuhn's 1962 book. Hacking points to the immense social differences between physics and biology, as well as the loss of pre-eminence suffered by physics since 1962, at the height of the Cold War. However, soil physics, on which much of the primary analysis for flow and solute transport and diffusion is built, might be considered a branch of physics (Hunt et al., 2013). As such, the Kuhn picture may yet take precedence.

In the language of Kuhn, we should become alert when a number of problems that could be related become evident, particularly if they are repeatable and significant enough to be important. These results, inexplicable within the existing paradigm, are what Kuhn calls "anomalies."

Such anomalies have been accumulating within the discipline of soil physics since Fatt (1956a, 1956b, 1956c), together with the occasional clear criticism (Scheidegger, 1959; Berkowitz & Scher, 1995; Cushman & O'Malley, 2015) of the existing mathematical structure and its basis in a flawed mental picture. Fatt (1956a, 1956b, 1956c) pointed out that only network models could represent truthfully real porous media, while Scheidegger (1959) reported that the Advection-Dispersion Equation (ADE), the use of which was justified in the conventional "bundle of capillary tubes" picture, was not accurate. This criticism of the ADE has been continued by Berkowitz and Scher (1995), Berkowitz et al. (2002), and Benson et al. (2000a, 2000b), among others. The bundle of capillary tubes model attributes longitudinal dispersion in solute transport to the particular distribution of pore sizes relevant for each medium (in contrast to non-Gaussian transport models; Hunt & Ghanbarian, 2016), while it admits of no transverse dispersion (perpendicular to the flow direction) at all. Yu and Hunt (2017a, 2017b, 2017c) argue that impacts from reliance on the ADE are felt in the theory of solute transport through chemical weathering to soil formation. Thus, a related question, as to whether the traditional hierarchical view of soil science, with physics at the base moving up through chemistry to biology, is a valid and useful picture, may depend on whether the physical basis is flawed or not. Accordingly, the tendency of practitioners of soil science to move away from this hierarchical view towards a paradigm that considers biological matters as unconnected with physics (consider the refusal of USDA to support fundamental soil physics for the past decade), may be more a result of an unacknowledged problem.

This reasoning leads to the following important questions:

- To what extent is the conventional understanding of chemical weathering based on soil physics?
- To what extent might soil physics be in need of a paradigm shift?
- Is soil physics part of soil science or part of physics (Hunt et al., 2013)?

As a consequence, we have to ask: Do anomalies in soil science exist?

We provide an incomplete list of what turns out mostly to be related unsolved questions, or anomalies. These questions should also relate, if feasible, to some of the chapters received. Other chapters will address other unsolved problems which, however, relate more clearly to how complete our understanding is of the range of possible influences on soil formation and evolution which have not yet been incorporated fully in a single model.

1. Why does the Advection-Dispersion Equation underestimate solute arrivals at both short times (early breakthroughs) and at long times (providing the explanation for the difficulty of environmental clean-up; Cortis & Berkowitz, 2004)?

2. Why does mass conservation require scale-independent flow velocities of water under saturated conditions, but not of solute?

3. Why do field measurements of the dispersivity increase almost linearly with spatial scale (Gelhar et al., 1992; Hunt et al., 2011)?

4. Why are chemical weathering rates in the field up to 6 orders of magnitude slower than in the lab? And why does this decline not depend on mineralogy (at least for plagioclase, K-feldspar, biotite, and hornblende; White & Brantley, 2003)? According to, e.g., Hunt and Ghanbarian (2016), the distinction is between predominantly kinetic-limited reactions in the lab and the dominance of transport limitations in the field.

5. Under which conditions is mineral weathering purely related to water percolation? When is the production of organic ligands or acids the driving factor of mineral weathering and transformation? When do we have consequently a purely kinetic limitation or a kinetic control of weathering? Does weathering of different minerals depend differently on these driving factors?

6. Why do chemical reaction rates, including weathering, (appear to) decay according to a power law in time, both in laboratory experiments (Liu et al., 2008, 2009; Peng et al., 2012; Zhong et al., 2005) and the field (White & Brantley, 2003; Maher, 2010)? (It should be noted that power laws may not always be easily distinguished from exponential functions, a theme to which we return). And why are they proportional to the rate at which water flows through the medium?

7. Why do chemical weathering rates appear to decay as a different power of soil depth than they do of soil age (Hunt & Ghanbarian, 2016)?

8. Either a power law or an exponential soil production function predicts a maximum soil production rate under thin or infinitely thin soils, as well as an inverse relationship between soil thickness and soil production. The exponential form is almost universally applied. Why would soil production rates decay exponentially in depth (Heimsath et al., 1997), particularly if chemical weathering decays according to a power law (White & Brantley, 2003)?

9. Within the general exponential form of a soil production function, an alternative that has been predicted (Gilbert, 1877) and sometimes observed (Heimsath et al., 2011; Dixon & von Blanckenburg, 2012) is “humped” in form. In this case, soil is produced fastest under a critical soil thickness, and soils thinner than the critical thickness are unstable, leading to the exposure of bedrock. Can a humped soil production function exist also in the general power-law formulation? The answer is yes. If the hydraulic conductivity limiting the flow rate is that of the soil, and chemical weathering induces fracturing of the bedrock (with hydraulic conductivity no less than the soil), the relevant flow velocity will be closely related to precipitation, but if soil is very thin with little or no vegetation, then chemical weathering may be unable to produce significant fracturing and the relevant water flow velocity will be reduced by the ratio contrasting soil and bedrock hydraulic conductivities. A model of such simplicity nevertheless reproduces a humped soil production function.

10. How can one reconcile the great depth of weathered bedrock (saprolite [Richter & Yaalon, 2012], laterite, and bauxite [Yu & Hunt, 2017, and references therein]) with exponential models of soil production (Heimsath et al., 1997) that use an explicit length scale of about 0.5 m, preventing deepening of soils significantly past 1 m?

11. Why do the soil production and erosion rates in any given region tend so often to be the same (DiBiase et al., 2012)? Often criticized, the assumption of steady-state landscapes thus appears very often to hold. Soil formation rates (and also erosion rates) strongly depend on the time factor (in conditions with enough precipitation; see Egli et al., 2014). One might ask: Why are soil formation rates (of soils having the same age) worldwide in a similar range when water is not the limiting factor?

12. Given that soil production rates vary over about 4 orders of magnitude (Hunt & Ghanbarian, 2016), depending primarily on rainfall and relief, why does the solum have such a robust tendency to be about 1 m deep in temperate to boreal climates (Yu et al., 2017), with the topsoil and the typical rooting depth about one third of that (Gentine et al., 2012; although a more comprehensive statement is that virtually all roots are confined to a depth of about 2 m; Fan et al., 2017)?

13. Why is the total evapotranspiration so often just under two thirds of the precipitation (Lvovitch, 1973; Schlesinger & Jasechko, 2014; Williams et al., 2012)?

14. Can the theory of nonlinear dynamics and chaos be applied to predict processes taking place in the rhizosphere (Faybishenko & Molz, 2013)?

It is not simply the number of such anomalies that have been accumulating, but the time span, over which they have become noticeable, that appears to reveal a problem in soil physics. Given that such a crisis has been developing in soil physics since 1955 without general acknowledgment, it is not clear whether Hacking (2012) may not actually be right, in which case soil physics should be considered as a field unrelated to physics. If this “crisis” were not particularly relevant to the subject of the current book, it could be omitted here as well.

Point 14 suggests that traditional soil physics may not lack merely the unifying concepts from applying percolation theory to network models but an important component from nonlinear dynamics as well, particularly as it affects our understanding of explicit interactions in the biosphere. Here it should also be noted that still a third facet of the relatively new science of complexity is addressed in publications of Lin (e.g., Lin, 2010), who cites physicist Prigogine (Prigogine, 1980; Nicolis & Prigogine, 1989) to support the statement, “The irreversible dual-partitioning of pedogenesis, ... indicates that soils generally evolve towards increased ordering.” In this article, Lin (2010) addresses the concept of preferential flow which, however, viewed from the perspective of percolation theory, is simply the “critical path.” Further discussion of the potential advantages of applying any particular one, or all of these methods from complexity simultaneously, is beyond the present scope.

14.5. RESEARCH DIRECTIONS, NETWORKS, AND FOUNDATIONAL SUPPORT: CURRENT AND FUTURE

The production of soil *by definition* brings in, in the vertical direction, the processes of dissolved CO_2 -induced chemical weathering and thus water flow, with CO_2 contents enriched by decaying plant material and metabolism of a range of organisms. Recognition of the close relationship with plant processes and their dependence on climate has helped the community and the National Science Foundation organize a network of critical zone observatories to collect data on the primary vertical processes involved in soil formation. Three such integrative studies and their conclusions as of this time are reported here (Anderson et al., Lyons et al., Rasmussen et al., this volume). However, the story of how the CZO network came about, including persistence and

collaboration across continents and disciplines, is best told in Brantley et al. (2017b), as the proliferation of organizations and agencies is vast.

Understanding the transport of soil downslope, essential to generate a landscape understanding of soil genesis and depth, brings in the horizontal directions and thus, directly, the field of geomorphology (Gilbert, 1877; Heimsath et al., 1999; Humphreys & Wilkinson, 2007; Forman and Stinchcomb, 2015). At this point, the functional form of such transport is still uncertain, as well as its dependence on biological inputs such as tree roots, tree-throw, burrowing rodents, etc. Soil mass transport along slopes depends on several factors and occurs by gradual mechanisms such as soil creep as well as threshold (and sporadic) processes, such as landsliding. One factor of critical influence in landsliding, along with slope angle and slope shape, is the soil depth. Understanding soil depth development on steep topography is fundamental for understanding and predicting the occurrence of landsliding at threshold landscapes (Yu et al., 2019). Soils and landslides are intimately related. The weathering of bedrock into clay and the subsequent translocation of clays into subsurface horizons are the main causes of increases in the risk of landsliding (Temme, this volume). Given their mutual effects, soils and landslides form a system with feedbacks.

The dependence of soil formation on chemistry, more pronounced when reaction kinetics limits the weathering reaction (high flow rates, slowly weathering minerals), and more likely at shorter time scales (Yu & Hunt, 2017b; Egli et al., 2018), emphasizes distinctions between parent materials, rather than similarities in other soil formation factors, such as climate or relief.

The actual geochemistry is highly dependent on the symbiotic relationships between plants and fungi and microbial communities, as well as on substrate and climate. The details of these interactions are under-represented here, both in the volume generally, and in this summary.

Hydrology, by assessing critical fluxes for both the formation of soil and its removal, unifies the fields of soil science and geomorphology, including (2D) basin architecture. This relationship provided crucial motivation to establish CUAHSI (Consortium of Universities for the Advancement of Hydrologic Science), as well as a foundation for the NRC publication “Opportunities in the Hydrologic Sciences” (NRC, 1991), which underlies the establishment of the Hydrologic Sciences Program at the USA NSF. This thematic integration with soil science occurs over increasing time scales, first geomorphology, then hydrology, and finally, tectonics, biological evolution, and atmospheric changes.

In this volume, we have attempted to address a range of such questions and, here, to draw additional attention to

one possible way forward that is, perhaps, based on a stronger foundation for soil physics.

14.6. WAYS FORWARD

The fundamental question to be answered is this:

How does bedrock, as well as such unconsolidated media as landslide deposits, glacial moraines, and alluvium, become soils, of which type and what depth, with which mineralogical transformations and physical reorientations/reorganizations, associated with which ecosystems and climates? There is no one answer nor a single course of action that results.

In considering the future of research into chemical weathering and soil formation, it is helpful to see where we are and where we have come from. From Cline (1961): “At a given time, our concepts are consequences of the knowledge we have gained, which in turn depends substantially on the techniques at our disposal. Yet those concepts govern to a major degree our approach to the solution of current problems, and thus, they control developments of the immediate future.” Thus, different researchers, with their different disciplinary histories, will see different challenges, goals, and envisioned means of solution. Past thinking, with its influence on curriculum, experimental techniques, data collected, instrumentation, and archival development, has a continued influence on the present to challenge paradigm shifts. Even when a paradigm shift may be sought, a substantial divide exists across disciplines and within disciplines, between seeking solutions with a degree of universality, and those which seek to define the variability.

First, let us consider the long-standing question of whether soil should refer to the solum (A and B horizons) or also what Richter and Yaalon (2012) call the C horizon. Since this corresponds to highly weathered “saprolites” of the southeastern US, perhaps the “laterites” and “bauxites” described by other authors as due to deep tropical weathering should be incorporated as well. Yu and Hunt (2017a) already extended the percolation theory prediction of weathering depths as a function of time to deep (mostly) tropical weathering expressed as laterite or bauxite. The fundamental percolation scaling function applied was $x = x_0 (t/t_0)^{1/D_b}$ (also in Figure 14.2) with exponent $D_b = 1.87$ equal to the backbone fractal dimensionality (Hunt & Ghanbarian, 2016), x_0 the fundamental length scale, or typical grain size, and t_0 the (hydrologic) mean flow rate. In Yu and Hunt (2017a), typical values of particle diameters $x_0 = 30 \mu\text{m}$ and flow rates x_0/t_0 of 0.5 m/yr were chosen as parameters, and the prediction was compared with data from Wright (1994), Cooper (1936), Hill et al. (2000), Taylor et al. (1992), Boulange and Carvalho (1989), Freyssinet and Farah (1997), Pavich (1986), Bestland et al. (1996), and Migon

and Lidmar-Bergstro (2002). Since Richter and Yaalon (2012) explicitly mention the “saprolites” of the Atlantic piedmont, we now include together with those of Yu and Hunt (2017a), in Figure 14.3 four examples of these (Price et al., 2005; Cleaves et al., 1974, Pavitch et al., 1989; Pavitch, 1986), as well as a new example from central Europe (Felix-Henningsen, 2018). As is evident, a single reasonable prediction suffices to capture the chief variability, linking time scales of up to 150 Myr with pore-scale quantities. The same equation, but with parameter values appropriate for each particular soil, generates measured soil depths across a wide range of conditions (Yu & Hunt, 2017a, 2017b, 2017c; Egli et al., 2018).

Note that, in $x = x_0 (t/t_0)^{1/D_b}$, the soil-forming factors are represented (Yu et al., 2017) as follows: time (t) is explicit, x_0 defines the grain size of the parent porous medium (p). The flow velocity is determined by the interaction of the biota with the climate (cl and o) (Budyko, 1958, 1974) and substrate (p , depending on where the limiting hydraulic conductivity is found). Topography (r) enters when effects of erosion are considered. Implicit is that the form of the relationship is determined by transport limitations on chemical weathering (involves cl and o), while use of the transport limitation as a general result is restricted to cases for which $Da_1 > 1$.

This result is the basis for answers to most of the 13 questions in section 14.4.

Figure 14.3 Extension of depth predictions for soils to chemical weathering at great ages for what are called “laterites,” “bauxites,” or “saprolites.” Typical flow rates (roughly in the middle of Maher’s 2010 data) of about 0.5 m yr⁻¹ are assumed, along with a typical soil particle in the middle of the silt, about 30 μm and a typical porosity of 0.4. The initial predictions were tabulated in Yu and Hunt (2017b) for the data of Wright (1994), Cooper (1936), Hill et al. (2000), Taylor et al. (1992), Boulange and Carvalho (1989), Freyssinet and Farah (1997), Pavich (1986), Bestland et al. (1996), and Migon et al. (2002). New data for this synthesis include Price et al. (2005), Cleaves et al. (1974), Pavitch et al. (1989), Pavitch (1986), and Felix-Henningsen (2018). Note that these data follow the same trend as the data in the middle of the soil depths collected in Figure 14.2.

Continuing, we give some other perspectives on the study of soil evolution and chemical weathering.

First, consider geomorphology. Here soil production is inextricably linked with soil transport in shaping the landscape. The form of the soil production function, whether only decreasing with depth or humped (Gilbert, 1887; Heimsath et al., 2009), may determine the stability of soils against erosion down to bedrock. Variation in soil production rates with landscape curvature may be a consequence of the relevance of the model of soil surface transport as diffusive (Heimsath et al., 1999), rather than having anything to do with a spatially variable soil production function (Yu & Hunt, 2017c). An entire range of biologic processes related to plant (Amundson et al., 2015) and animal behavior emerges for study. These authors examined climatic influences on soil production using a ratio of mean annual precipitation (MAP) to mean annual temperature (MAT). Hunt and Ghanbarian (2016), however, found that soil production rates correlated more strongly (less scatter) to estimates of an infiltration rate using the difference between precipitation and evapotranspiration.

From the perspective of geology (e.g. Driese et al., this volume), it is essential to understand the coevolution of soil, plants, and the composition of the atmosphere through geologic time expressed in, e.g., rates of soil development and the suite of soil types found. Accordingly, these authors argue for the inclusion of a deep-time component in the Earth observatories devoted to the critical zone. Because the surface of the Earth is where humans are found, it is doubly important to trace the development of ecosystems and soil formation over geologic time and how biota adapts to and influences the evolution of the atmosphere and the terrestrial surface. The potential variety of such systems, including the soil microbiology, presents already a daunting task of classification, and even more so when the influence of extinction-triggering events, tectonic and climatic changes, and anthropogenic influences are considered. Yet, if circular inferences are avoided, the history of the Earth can, through analysis of the increasing complexity of the soil ecosystem and its geochemistry over time, reveal the impacts of various soil-forming factors individually. Such an analysis must be based on accurate forward modeling. In contrast to Amundson et al. (2015), who try to correlate the change in maximum soil production rates with the ratio of MAP/MAT, Driese et al. (this volume) extract separately MAP estimates for paleosols based on the CIA-K (chemical index of alteration less potash) geochemical proxy of Sheldon et al. (2002) and MAT estimates based on an Na/K salinization model (Driese et al., 2018; Liivamägi et al., 2014).

From the perspective of physics, what is sought are the (quasi-)universal laws or processes governing the

evolution of a geophysical system. The understanding of the history of the Earth requires the best understanding of the physical processes and physical laws that underlie the evolution of the Earth, its chemistry, and its biota. In the context of the present volume, an important part of the conventional physical understanding may be flawed. For our hydrologic science, we usually rely on laws that express local conservation of mass, charge, elemental composition, momentum, energy, etc. These laws are expressed as (partial) differential equations. In these formulations, scale effects on solute transport are essentially inexplicable; they are mysteries to be explained by non-Euclidean media, for which our imagination is the only bound. In this framework, the putative link between non-Gaussian (non-Fickian) solute transport and chemical weathering went undiscovered (note that Reeves and Rothman, 2014, attribute the link between fluid flow rates and time dependences to diffusion). In order to address these problems efficiently, it is important to abandon the continuum models of porous media and turn to network models. Then, nearly all the puzzles posed in section 14.4 appear to trace back to the single conceptual model failure of representing porous media as a bundle of capillary tubes and the mathematical inadequacy of the Advection-Dispersion Equation. The solution lies not in particular models of the medium but in the tendency for water flow through disordered media to be dominated by paths of least resistance, together with the topological description of these paths from percolation theory (Hunt & Sahimi, 2017). A particular challenge in the context of soil modeling and weathering is the consideration of a dynamic comparison of climate and soil variables instead of the traditional (and arduous) comparison of climate and (static) soil properties (Finke et al., this volume).

What about the hydrological perspective? Consider water partitioning at the Earth's surface. Since evapotranspiration (ET) removes water from being used for soil formation, while encouraging plant growth, which provides an essential contribution (CO_2) to soil formation from plant metabolism, this quantity is of interest. Arguably, the variability of ecosystems and climate, substrate and relief, should produce huge variation in the water balance. Yet there seems to be a rather high degree of consistency in the fraction of precipitation returned to the atmosphere, ET, when considered as a function of aridity index (Budyko, 1958, 1974). Moreover, for landscapes neither strongly energy limited nor water limited, there is a rather universal tendency for ET to be close to the global average, just under two thirds of precipitation (Lvovitch, 1975; Williams et al., 2012; Schlesinger & Jasechko, 2015). Hunt (this volume) shows that the tendency to constrain ET may be related to an optimization of ecosystem productivity under the constraints of

optimal horizontal water (and thus nutrient) flow paths for transpiration within the root zone, and optimal (random) solute transport paths in the vertical direction. The latter defines the soil depth as well, meaning that net primary productivity is not just a passive response to the partitioning of surface water but the primary driver of it. This result makes explicit a comment from the National Research Council (1991), “The more we learn about our desiccated, and apparently barren, neighboring planets, the more we wonder if our good fortune is not a result as well as the cause of life on the earth.” Furthermore, the variability in ET at a particular aridity index appears related to variability in actual root architecture (its mass fractal dimensionality). This work thus suggests that the relationship of hydrology with biota is so intertwined that the basic partitioning of water at the terrestrial Earth’s surface is only properly understood in biological terms, namely that evolution favors those ecosystems that maximize their productivity with respect to the available water and energy fluxes.

Even from the perspective of soil ecology and biogeochemistry, Fierer et al. (2009) cite Kuhn (1962) to emphasize the importance of fundamental unifying principles of study, compared with a simple categorization of distinctions between specific systems and processes. They note the relatively advanced states of aquatic (citing the trophic cascade theory of Carpenter et al., 1985, and ecological stoichiometry of Elser et al., 2000) and plant ecology (structuring of plant diversity and plant community dynamics across spatial scales, e.g. Grime, 1977; Tilman, 1994; Hubbell, 2001) compared with soil ecology. Yet these same authors cite Dokuchaev (1880/1948) and Jenny (1941) as authors helping to provide a basis for the study of soil ecology. They also suggest that there are similarities across ecosystems that may warrant formulation of more general principles: “Even where disturbances such as agricultural conversion or plant invasions have altered soil properties, the underlying processes often remain remarkably similar (Haas et al., 1957; Mann, 1986; Lauber et al., 2008).” They report that the observation that “all compounds that get metabolized in soil must pass through the same physiological ‘funnel’ that constrains decomposition to a shared set of biochemical pathways (McGill, 2007) ... may partially explain why parameters such as litter C:N ratio and lignin:N ratio can often predict decomposition rates across a range of ecosystem types.”

In conclusion, it is suggested that a combination of techniques should be utilized, involving everything from advances in fundamental research in physics to experimental techniques in measurement and interpretation, classification, and generalization. Advances in one relevant discipline must be communicated to the other related disciplines. Understanding of the relationships between

micro- and macrobiota will be essential, and how the soil constrains these relationships. In this process, both universal tendencies and specific distinctions must be accounted for. Presumably only then will it be possible to disentangle the effects of the multiple influences on ecosystem stability, adaptability, and vulnerability, together with their interactions with solar variability (early weak sun paradox), astronomical events (possible bolide collisions), tectonic developments, and volcanism (e.g. development of supercontinents, or release of CO₂ by the Siberian traps).

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