Evolutionary Pathways in Soil-Geomorphic Systems

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ABSTRACT:
Understanding evolution of soils and landforms (and other Earth surface systems) has itself evolved from concepts of single-path, single-outcome development to those that recognize multiple possible developmental trajectories and different maturely developed states. Soil geomorphology and pedology should now move beyond showing that multiple trajectories are possible to investigating why some evolutionary pathways (EPs) are common and persistent, whereas others are rare and transient. A typology of EPs is developed and applied to soil formation in the North Carolina coastal plain. Some EPs are impossible because of violation of generally applicable laws or absence of necessary conditions; others are currently impossible, having occurred in the past but requiring conditions that no longer exist. Improbable paths are possible but rare, because necessary circumstances involve rare events or boundary conditions. Inhibited EPs are also possible but rare because of resistance factors or feedbacks that prevent or inhibit them. Transient paths may be common but are not long-lived or well preserved and are thus rarely observed. Recurring but nonrepeating EPs occur in different locations but are irreversible in any given location and cannot recur except in the case of system-resetting disturbance or new inputs. Recurring EPs are not inhibited or self-limited, occur in different locations, and may be repeated because of ongoing or recurrent processes or conditions. Selected path types occur in multiple situations, but with increased probability due to feedbacks or responses that encourage or enhance recurrence and/or persistence. The case study shows examples of all possible EP types.

Key Words: Earth surface systems, evolutionary pathways, multiple pathways, pedogenesis, soil geomorphology

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The development and change over time (evolution) of geomorphic, soil, hydrological, and ecosystems (Earth surface systems [ESSs]) are often, perhaps mostly, characterized by multiple potential developmental trajectories. That is, rather than an inevitable monotonic progression toward a single stable state, climax, or mature form, there exist multiple stable states or potentially unstable outcomes and multiple possible developmental pathways. Until late in the 20th century, basic tenets of geosciences, ecology, and pedology emphasized single-path, single-outcome conceptual models such as classical vegetation succession; development of mature, climax, or zonal soils; or attainment of steady-state or some other form of stable equilibrium (see reviews by Osterkamp and Hupp, 1996; Gregory and Lewin, 2014; Schaetzl and Thompson, 2015). As evidence accumulated of ESS evolution with, for example, nonequilibrium dynamics, alternative stable states, divergent evolution, and path dependency, the emphasis was on the existence of two or more potential pathways, contesting and contrasting with the single-path frameworks. Now it is appropriate to address the question of why the number of actually observed pathways is relatively small, with some evolutionary pathways (EPs) being common and persistent, whereas others are rare and transient.

The ideas developed below are based on the fact that developmental pathways vary in terms of their probability and frequency of occurrence. This is well known to pedologists and geomorphologists. However, there are advantages to considering these in a systematic framework of different path types. Broad, synthetic considerations of EPs of ESS will become increasingly important and useful as issues regarding responses to, for example, climate and land use change continue to emerge.

The purpose of this article is to explore why some developmental sequences are rare versus common, why some are nonrecurring, and some are reinforced. After developing a typology of ESS evolutionary paths, focusing on soils and landforms, the empirical example of formation of coastal plain soils in eastern North Carolina will be examined.

BACKGROUND

Reviews and syntheses contrasting single-path convergent conceptual models of soil and geomorphic systems with multiple-path, potentially divergent trends are given elsewhere (e.g., Phillips, 2006, 2017; Bestelmeyer et al., 2009; Raab et al., 2012; Samonil et al., 2014; Phillips and Van Dyke, 2017) and are only briefly summarized here.

Table 1 shows various conceptual models and theoretical frameworks that either directly stipulate or indirectly imply the possibility of multiple evolutionary or developmental pathways for ESS. These contrast with single-path frameworks, based on a progression toward some single endpoint. Well-known single-path examples include classical single-climax ecological succession; various "equilibrium" theories in geomorphology and ecology; soil development toward a mature, zonal, or climax soil; and cyclical theories of landscape evolution. The terms "end state" and "outcome" are used here as a shorthand for observed states following a period of development and do not imply that evolution ceases or has a true final outcome. Multipath theories generally involve the possibility of divergent evolution, but some convergent phenomena also involve multiple pathways, as when development from multiple starting points, along multiple trajectories, leads to similar outcomes (see equifinality and polygenesis in Table 1). Table 2 gives specific examples of the concepts shown in Table 1.

The examples in Tables 1 and 2 reflect the consensus that multiple evolutionary paths (EPs) are at least possible in ESS and arguably likely. Given that some of the phenomena are related to sensitivity to minor variations and disturbances, and others to historical and geographical contingency, one might suspect a vast number of possible developmental trajectories. Yet, some EPs are repeatedly observed (accounting for the emergence of the single-path, single-outcome concepts), whereas others are rare. Still others, at least theoretically imaginable or plausible EPs, are not observed at all. Thus, the question shifts from "Are there multiple pathways?" of the late 20th century to "Why are there not even more observed

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TABLE 1. Theories and Conceptual Frameworks for ESS Evolution That Stipulate or Imply Multiple EPs

Concept	Abbreviated Definition	Most Common Domain of Usage
Alternative stable states	Stable attractors exist, but >1	Ecology Geomorphology
Configuration and immanence	ESS include immanent elements (common to all systems of a given type) and configurational elements that are geographically and historically contingent	Geology Geomorphology
Divergent evolution	Increasing variability or dissimilarity over time; initially similar states become (on average) more different	Pedology Geomorphology
Dynamical instability; deterministic chaos	Sensitivity to minor, even miniscule, variations in initial conditions and/or to disturbances. Effects of disturbances or initial variations disproportionately large and long-lived	All
Equifinality	Multiple processes or historical sequences produce very similar results or outcomes	Geomorphology Hydrology
Historical or geographical contingency	Outcomes depend in part on idiosyncratic characteristics of history or place	All
Multiple developmental pathways	>1 Possible EP	All
Nonequilibrium	EPs do not necessarily converge toward stable equilibrium attractors; multiple stable or unstable attractors may exist	All
Perfection	All ESSs have elements of uniqueness due to geographical and historical contingency, and improbability of replication of specific sets of environment controls	Geomorphology
Polyclimax	EPs trend toward (presumably stable) attractors, but >1	Ecology
Polygenesis	Outcomes may be attributable to multiple processes or historical sequences. May be equivalent to equifinality, or simply imply multiple causality	Pedology

"All" in the last column refers to all major (sub)disciplines of Earth and environmental sciences.

TABLE 2. Examples of Multipath Phenomena in Soil and Geomorphic Systems

Concept	Objects or Phenomena	References
Alternative stable states	Barrier island geomorphology	Stallins, 2005
Alternative stable states	Lakes	Jannsen et al., 2014
Configuration and immanence	Geological and geomorphic systems	Simpson, 1963; Lane and Richards, 1997
Divergence	Topography, soils and vegetation of dollnes	Bárány-Kevei, 1998
Divergence	Fluviokarst landscape evolution	Phillips, 2004; 2018
Divergence	Pedogenesis	Šamonil et al., 2014; Phillips, 2017
Divergence; dynamical instability; chaos	Landforms; geomorphic systems	Phillips, 2006
Dynamical instability	Geomorphic systems	Scheidegger, 1983
Equifinality	Biophysical landscapes	Culling, 1987
Equifinality	Hydrological modeling	Beven, 2006
Geographical and historical contingency	ESSs	Harrison, 2001; Van Dyke, 2015
Multiple pathways	Pedogenesis	Johnson and Watson-Stegner, 1987; Stolbovoy, 1992
Multiple pathways	Coastal landscapes	Payo et al., 2016
Multiple pathways	Fluvial systems	Van Dyke, 2016; Fryirs, 2017
Multiple pathways; nonequilibrium	Fluvial systems	Grant et al., 2017
Multiple pathways; path dependence	Mountain permafrost systems	Verleysdonk et al., 2011
Nonequilibrium	Geomorphic (fluvial) systems	Renwick, 1992
Perfection	Geomorphic and pedologic systems	Phillips, 2007a,b; 2010

References are illustrative only, not comprehensive. Where available, synthetic or review references were selected.

trajectories?" A classification of EPs is proposed below as a starting point for addressing this question.

A TYPOLOGY OF EVOLUTIONARY PATHWAYS

Overview

At least eight different types of pathways can be envisioned. These are summarized in Table 3 and discussed below. These EPs can be conceived as trajectories of system development, historical sequences of system evolution, or time-dependent relationships between processes and responses. They may be perceived at a variety of spatial and temporal scales, and the nature and classification of pathways are necessarily context dependent.

Impossible paths are those that can be ruled out because they would violate generally applicable laws or where necessary conditions do not occur. Examples include net nonlocal upslope mass transport or water fluxes and energy transformations that violate matter and energy conservation laws. A currently impossible path denotes an EP that occurred in the past, but requires conditions that no longer exist. For instance, there exist types of paleosols that do not have even an approximate modern analog, because their genesis was influenced by, for example, an atmospheric composition that no longer exists and/or by extinct biota with no modern analogs (Retallack, 2001). Over shorter time scales, landscape evolution, pedogenesis, or succession patterns linked to, for example, a glacial climate cannot recur in currently unglaciated zones until a new glaciation occurs.

Improbable paths are possible but infrequent because the necessary circumstances involve rare events or combinations of boundary conditions. Examples include the formation and subsequent modification of extraterrestrial impact craters or responses to extremely rare flood or storm events. Inhibited paths are also possible but rare. In this case, however, rather than a dependence on infrequent events or conditions, resistance factors or feedback mechanisms prevent or retard development along the pathway. For instance, while deterioration of argillic horizons can occur, once formed, these clay-rich subsoil layers are highly resistant and persistent. Thus, their resistance makes pathways involving destruction of argillic horizons uncommon. Similarly, strongly eroded patches may resist pathways of recovery of soil and vegetation cover due to exposure of low-permeability, infertile substrate (cf., Garcia-Fayos and Cerda, 1997; Puigdefabregas et al., 1999).

TABLE 3. Types of Evolutionary Paths in Geomorphological and Pedological Systems

1. *Impossible:* Path would violate generally applicable laws, or necessary conditions do not occur.
2. *Currently impossible:* Developmental paths that occurred in the past, but require conditions that no longer exist.
3. *Improbable:* Possible but rare, because necessary circumstances for the path involve rare events or conditions.
4. *Inhibited:* Possible but rare, because resistance factors or feedback mechanisms prevent or inhibit development.
5. *Transient:* Pathway is not long-lived or well preserved. Possible, perhaps even common, but rarely observed due to short duration and lack of preservation.
6. *Recurring but nonrepeating:* Path may occur in different locations, but in any given location is irreversible and self-limiting (and thus cannot recur except in the case of system-resetting disturbance or new inputs).
7. *Recurring:* Path occurs in different locations and may be repeated due to ongoing or recurrent processes or conditions. Not inhibited or self-limited.
8. *Selected:* Path type occurs in multiple situations, but with increased probability due to feedbacks or responses that encourage or enhance its recurrence and/or persistence.

See text for examples.

Transient paths are short-lived (the definition of this may depend on the time scale of interest) and poorly preserved. Whether rare or more common, their short duration and limited persistence mean that they are rarely observed. Depressions left by rotted stumps may fill with organic matter, for example, but because of decomposition, deposition of mineral sediment, and slumping of adjacent soil, these organic-rich depressions generally do not persist as such (Pawlik, 2013). Hillslope development trends that lead to gradients exceeding the angle of repose also cannot last long (Selby, 1993). These transient evolutionary trajectories are relatively rapid and also lead to outcomes that are fragile, unstable, or prone to reversal by offsetting processes.

Some pathways occur in different locations but are irreversible and self-limiting in any given location and thus cannot recur except in the case of system-resetting disturbance or new inputs (the former are disturbances that effectively obliterate the existing soil cover, as, for example, by erosional stripping or sedimentary burial). These are recurring but nonrepeating paths. Fluvial erosion to base level and depletion of weatherable minerals by chemical weathering are both examples. Both are widely observed but involve inherently self-limited development and irreversible processes. By contrast, recurring paths occur in different locations and may be repeated because of ongoing or recurrent processes or conditions. These pathways are not inhibited or self-limited. Some of these may be cyclical, as in episodic floodplain stripping followed by new alluvial accretion, which leads to another stripping episode (e.g., Nanson, 1986; Dean and Schmidt, 2013). Cyclic and seasonal beach responses (Nordstrom, 1980) and coastal dune blowout evolution (Gares and Nordstrom, 1995) are other examples.

Selected paths are recurrent and are preferentially developed, enhanced, or preserved by feedbacks. Principles of gradient, resistance, and efficiency selection operate in geomorphic systems to make certain flux patterns more probable and to reinforce them once developed. These occur, for instance, in the development of fluvial channels and channel networks, karst conduits, and soil water preferential flow paths (Leopold, 1994; Nanson and Huang, 2008, 2017; Kauffman, 2009; Phillips, 2011; Twidale, 2004; Smith, 2010; Hunt, 2016). Selected paths are assumed to be subsets of both types of recurring EP.

As with virtually any typology involving Earth surface phenomena, there undoubtedly exist EPs that do not readily fit. Certainly, there are those that may overlap categories. For instance, EPs involving organic litter inputs, decomposition, and humus formation are both recurring and, over typical pedological and soil geomorphological time scales, transient. Selected paths, for another example, are also recurring.

Using P_N, P_o to designate the number of imaginable trajectories and the number of observed pathways, $P_o < P_N$, and often $P_o < < P_N$. With respect to a specific ESS at a particular time, $P_o = 1$, that is, only one historical sequence or chain of events led to the observed system state. However, when contemplating future development, $P_o = 0$, but the number of potential future pathways $1 \leq P_f \leq P_N$. Likewise, when attempting to reconstruct unobserved past pathways, the number of possible historical trajectories $P_h \leq P_N$. The number of observed pathways in an aggregated sense (e.g., historical trajectories of sandy dune soils or boreal forest hillslopes rather than a particular soil or hillslope at a specific time) typically yields $1 < P_o \leq P_N$.

$P_1, P_2, \ldots, P_8$ denote the number of pathways of each type noted above, as numbered in Table 3. Immediately, the reduction in the number of observed versus imaginable EPs is evident in that $P_o \leq P_N - (P_1 + P_2)$ or $P_o \leq P_N - P_1$ if a longer-term perspective is taken. Similarly, $P_o \geq P_6 + P_7$ (assuming P_8, selected pathways, are also counted among P_6 and P_7). Given the finite time and space available for evolution of any ESS, the recurrence of selected EPs must itself limit the occurrence of nonselected paths as well as of improbable and inhibited EPs.

While multiple EPs are possible in pedological and geomorphological systems, the number of actually observed paths is relatively small because some paths are impossible, whereas others are rare, improbable, or transient. Other pathways are actively selected for, increasing their probability and persistence, at the expense of other potential pathways.

Impossible, currently impossible, and improbable path types are assumed to be self-evident and certainly less relevant to observed evolutionary trends. The other path types are examined in more detail below.

Inhibited Paths

Negative feedbacks that work so as to maintain or restore some system states may operate to prevent or retard some possible pathways. In the subhumid tropics of the southeastern United States, for example, removal of forest vegetation by humans, fire, or pest infestations can result in a pathway toward severe erosion, exposing clayey argillic horizons, and sometimes extensive gullying, as shown by historical soil erosion on areas where revegetation was inhibited by land use practices (Trimble, 1974; Yoho, 1980; Daniels, 1987; Phillips et al., 1993). If plant regrowth is not inhibited, however, vegetation cover is usually quickly reestablished, and accelerated runoff and soil erosion following forest clearance are short-lived (Yoho, 1980; Trimble et al., 1987; Anderson and Lockaby, 2011). This vegetation response in these cases prevents the pathway toward a severely eroded state.

In some situations, critical thresholds may control whether development is inhibited or not. Muhs (1984) gives several examples in pedogenesis. These include presence of carbonates that inhibit clay development and clay mineral compositions that impede bioturbation. Note, however, that when thresholds of carbonate leaching and clay mineral ratios are exceeded, the impediments no longer occur.

Sometimes pathways are limited by resistance factors. In some bedrock-controlled streams, for example, high bank resistance prevents any significant lateral migration, so that fluvial adjustments are primarily in the vertical dimension (e.g., Whipple et al., 2000; Chin and Phillips, 2007).

Transient Paths

The example of oversteepened slopes mentioned above is one of the clearest illustrations of transient pathways. The angle of repose is defined as the steepest angle that can be maintained in a given material. When processes such as mass movements, erosion, sedimentation, or anthropic cut-and-fill lead to steeper slopes, the latter are unstable, leading to mass movements and recovery to the angle of repose (Selby, 1993). Another example is soil or rock weathering in humid environments that produces highly soluble salts, which are rapidly leached out (Doehne, 2002).

Transient pathways are also common in inherently dynamic, rapidly changing environments such as unconsolidated coastlines. Rapid response to storms and other high-energy events and multiple daily tidal cycles result in development—and rapid destruction—of, for example, beach ripples, longshore bars and troughs, beach cusps, mud lumps and mud boils, and so on (Davidson-Arnott, 2010).

Again, note that transience, recurrence, and repeatability may depend on the time scale of interest.

Recurring, Nonrepeating Paths

Some EPs occur frequently in time and space but at a given location or in a particular system cannot repeat because of irreversible processes or self-limiting aspects (although this situation can change in the case of new inputs to the system or a major disturbance that initiates new developmental trends). Weathering processes are often irreversible, and chemical weathering may depend on the availability of weatherable minerals. Thus, while pathways involving chemical weathering and depletion of weatherable minerals are common, they cannot normally be repeated with a given weathering system (e.g., Ollier and Pain, 1996; Taylor and Eggleton, 2001). Various forms of hillslope denudation involve irreversible processes and are thus nonrepeatable. These are examples of situations where, at least over many time scales, some paths may be unrepeatable because of material limitations. A trajectory involving the weathering of a granitic rock mass, for instance, cannot be repeated, nor can one involving the leaching of salts and carbonates from parent materials in a humid climate.

Other recurring paths are nonrepeating because they proceed to some sort of ultimate limit. Fluvial erosion is limited by base level, for instance, and a downcutting pathway cannot recur unless there is some lowering of relative base level or rejuvenation upstream. There also exists evidence that the thickness of regoliths and weathering profiles (or the depth of weathering) may be limited by landscape relief (Linton, 1955; Goodfellow et al., 2014; Rempe and Dietrich, 2014). Thus, while erosion or thickening of regolith to base level may occur elsewhere within the same landscape, it cannot recur in the same channel system or weathering profile in the absence of rejuvenation.

Recurring Paths

These also occur in different locations and are not inherently irreversible, nonrepeatable, or self-limited. In addition to examples given above, pathways involving meander growth, evolution, and cutoff in laterally migrating alluvial rivers are repeatable, at least with respect to phenomenology if not local details (Guneralp and Marston, 2012). In some cases, soil erosion may stimulate soil production via weathering by bringing the bedrock weathering front closer to meteoric waters and biological influences at the surface. This pattern is potentially repeatable (e.g., Penck, 1924; Humphreys and Wilkinson, 2007). Phenomena linked to cyclical or ongoing inputs such as litterfall, organic matter decomposition, and humification are also recurring (although at some time scales these may be transient).

Selected Paths

The most fundamental phenomenon in path reinforcement is selection, which applies to both types of recurring pathways above. This includes not only Darwinian natural selection, but also a variety of other selection processes. Fluxes of mass and energy in ESS preferentially select and reinforce the most efficient pathways. In doing so, they also tend to selectively preserve the most stable and resistant materials and structures and remove the weaker and unstable ones. Numerous theories, hypotheses, and conceptual frameworks exist in geosciences that predict or seek to explain the development of flow paths in ESS. These include so-called “extremal” principles and the least action principle (LAP) in hydrology and fluvial geomorphology, principles of preferential flow in hydrology, constructal theory, and various optimality principles in geophysics and ecology.

Extremal principles related to hydraulic geometry (interrelationships between fluvial channels and the flows within them) have commonalities with respect to their fundamental hydrological and geomorphological implications, and Huang and Nanson (2000; Nanson and Huang, 2008; 2017) argue that all can be subsumed under a more general principle of least action (i.e., geomorphic work is performed with the minimum possible energy). Phillips (2010) generalized this even further, contending that water flow will be more prevalent along more efficient rather than less efficient pathways and that emergent feedbacks cause these paths to be preferentially preserved and enhanced.

The 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, that nature always finds the most efficient path. The general applicability and utility of the LAP in physics are not contested, although debate persists as whether the LAP is a true physical law. In ESS, the LAP is manifested by accomplishing work (e.g., fluvial sediment transport, ecosystem productivity, heat flux in fluids) with as little energy as possible.

With a given energy input, conservation laws coupled with maximum efficiency in accomplishing work dictate that energy dissipation via entropy must be maximized (maximum entropy production). Thus, there exists a general consistency among optimality principles based on energy, power, and entropy. This phenomenon also clarifies the superficial contradiction between extrema based on minimization and maximization, as minimization of energy to perform work implies maximization of dissipation and entropy. Note also that work itself is not necessarily minimized, only the energy deployed to perform that work. In stream channels, for instance, extremal principles do not suggest that sediment transport is minimized, but rather minimization of the energy used to accomplish a given amount of transport.

The concept of preferential flow has been principally associated with soil hydrology and soil physics, but Uhlenbrook (2006) noted that preferential flow applies to all hydrological phenomena at all scales. Preferential flow may be predetermined or influenced by preexisting structures and spatial variability, but even in homogeneous materials preferential flows develop because of dynamical instabilities, with reinforcement of incipient preferential paths (Liu et al., 1994). Hunt (2016) linked subsurface water and solute flows to nutrient uptake and plant growth using critical path analysis and percolation theory, showing that similar phenomenologies exist among these processes.

Woldenberg (1969) developed a theory explaining how and why channelized flow systems evolve toward more efficient networks. A similar general principle was formalized by Bejan (2007) as the "constructal law": "For a flow system to persist in time (to survive) it must evolve in such a way that it provides easier and easier access to the currents that flow through it." Prevalence of preferential flow at a broad range of scales was reviewed by Lin (2010), who discussed the tendency for these to either develop into, or be controlled by, morphological features in soils and landscapes. Constructal-type behavior arises from traditional path-of-least-resistance reasoning if selection results in persistence of the preferring flow paths, although, in contrast to constructal theory, flow patterns in ESS are often strongly influenced by factors other than the flow itself.

CASE STUDY: COASTAL PLAIN SOILS

To illustrate these ideas in a real-world context, we turn to the example of developmental sequences of soil on sand and loamy sand parent materials on uplands of the Atlantic coastal plain physiographic province of eastern North Carolina, USA (Fig. 1). This example was chosen because it has previously been examined with respect to the characteristics of the overall network of soil transitions (Phillips 2015). Here we unpack the individual developmental pathways within the overall network of transitions with respect to the path types described above.

The network of soil transitions is shown in Fig. 2 and is derived from three lines of evidence. First, differences in soils between

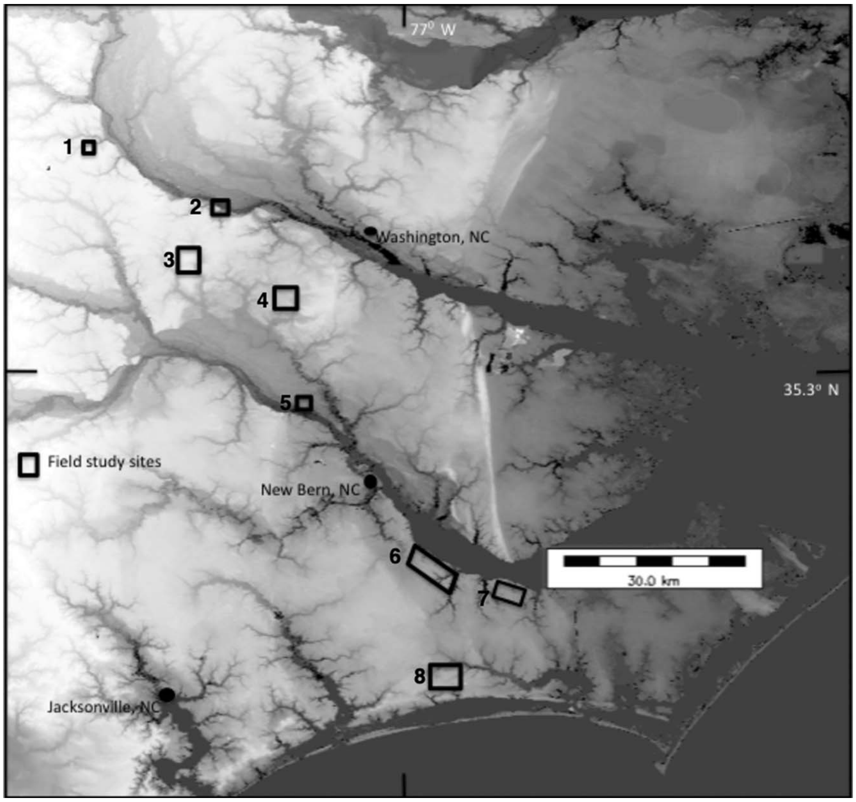

FIGURE 1. North Carolina coastal plain study sites. Base map is shaded relief (modified from Phillips, 2015). Numbered sites are as follows, with reference to previously published studies: (1) Otter Creek Natural Area near Falkland (Phillips et al., 1994); (2) Lower Tar River valley near Grimesland (Phillips, 2007b); (3) Littlefield (Phillips et al., 1999a; Phillips, 2000, 2013); (4) Clayroot (Phillips et al., 1999b; Phillips, 2013); (5) Lower Neuse River valley near Fort Barnwell (Phillips, 2007b); (6) Fishers Landing, Flanner Beach, and Slocum Creek near Neuse Forest and Croatan (Phillips, 2001, 2004, 2007b); (7) Pinecliffs, Cherry Branch and Siddie Fields (Redneck Beach) near Cherry Point (Phillips 1993, 2001, 2004, 2007b); (8) Patsy Pond near Bogue (Phillips et al., 1996).

adjacent members of a chronosequence suggest that transitions occur from the soils on the younger to those on the older member. In this case, soil series on two adjacent Pleistocene marine terraces were compared, as described elsewhere (Phillips, 1993, 2001). The younger surface is less than 80 Ka; the older, approximately 250 Ka. In Phillips (1993), soil richness was compared based on profiles within 10 km of either side of a Pleistocene paleobarrier ridge that marks the boundary. The later study used a broader area of the same terraces to explore divergent pedogenesis (Phillips, 2001), also based on soil richness and morphology.

The second line of argument is based on identifying soil transitions using soil morphological and stratigraphic indicators to identify past and ongoing changes in soil morphology (Phillips et al., 1999a, 1999b; Phillips, 2000, 2007b). The most common indicators found are (1) erosional truncation of A-horizons, based on horizon thickness relative to undisturbed pedons and exposure of B-horizon material at the surface; (2) surface deposition, indicated by cumulic surface horizons (and occasional buried A horizons); (3) "fingers" of translocated clay and other materials extending into C horizons, suggesting increasing solum thickness; (4) buried E and Bt horizons overlain by incipient podzolized sequences (A, E, and Bw, Bs, or Bh sequences), resulting from burial by aeolian sand and secondary podzolization; (5) AE, A&E, or E&A horizons signifying leaching and eluviation in the lower A horizon; and (6) changes in water table height or drainage indicated by the type and location of redoximorphic features.

The third general basis for establishing soil transitions is spatial patterns of soil adjacency. The logic is that if soil types repeatedly occur adjacent to each other along gradients representing systematic variations in, for example, slope curvature, or water table elevation or soil drainage, then transitions between those soil types are possible. Earlier work relied on standard catena sequences (Phillips et al., 1999a), whereas later studies (Phillips, 2013) used methods similar to those of Grzebyk and Dubrucq (1994) to establish evolutionary sequences. These three lines of reasoning were combined to produce the network of pathways of soil development shown in Fig. 2.

Parent materials for pedogenesis are sandy coastal plain sediments (finer parent materials also occur but produce different soils and temporal sequences). Minimally developed soils are classified as Udipsamments or Quartzipsamments in the U.S. Soil Taxonomy, depending on the amount of finer material within the sand. As incipient spodic features develop or fine laminae form, a transition occurs to Spodic or Lamellic Quartzipsamments in the purer sands. Where more fines are present or added by deposition, pedogenesis may result in evolution to Hapludults.

Sandier soils on a podzolization-dominated pathway on the left of Fig. 2 can develop spodic horizons. Subsequently, if there is significant clay input, these can evolve to Ultic subgroups. Fine sediment inputs can occur because of long-distance transport of dust to the Atlantic coastal plain (Goudie and Middleton, 2001; Prospero et al., 2001) and the local redistribution of fines via wind erosion (Pease et al., 2002; Gares et al., 2006).

Clay also occurs in the parent sediments underlying the sandier surface layers, as part of transgressive coastal sedimentary sequences (Daniels et al., 1978; Markewich et al., 1986; Mixon, 1986), and in thin lenses within sandy parent material (Fig. 3) and can be brought to the surface via bioturbation. Insects such as ants, for example, preferentially use finer material for their surface mounds, which is then redistributed by lessivage (Phillips, 2007b). Lessivage and continued weathering may convert Hapludults to more highly developed Ultisols.

Aeolian sand deposition can partially bury the Ultisols, with secondary podzolization in the surficial deposits producing Spodic Paleudults and Paleaquults (Phillips et al., 1999a, 1999b). At the study sites supporting this work, this primarily occurs at agricultural field edges. Vertical redistribution of finer material, assuming continued inputs (or fines from subsurface layers brought to the surface by soil fauna), can result in the development of argillic horizons (Phillips, 2004). This is the basis for the pathway from the Ultic Alaquods to the Spodic Ultisols. More commonly, secondary podzolization in thick sandy surficial deposits converts Paleudults and Paleaquults to Spodic versions.

Pedogenetic Pathways

In this section, the transitions identified above are interpreted in terms of the pathways involved. These are in turn linked to the path types described earlier.

On recently deposited sands and loamy sands or those with minimal pedogenetic development, both podzolization and lessivage

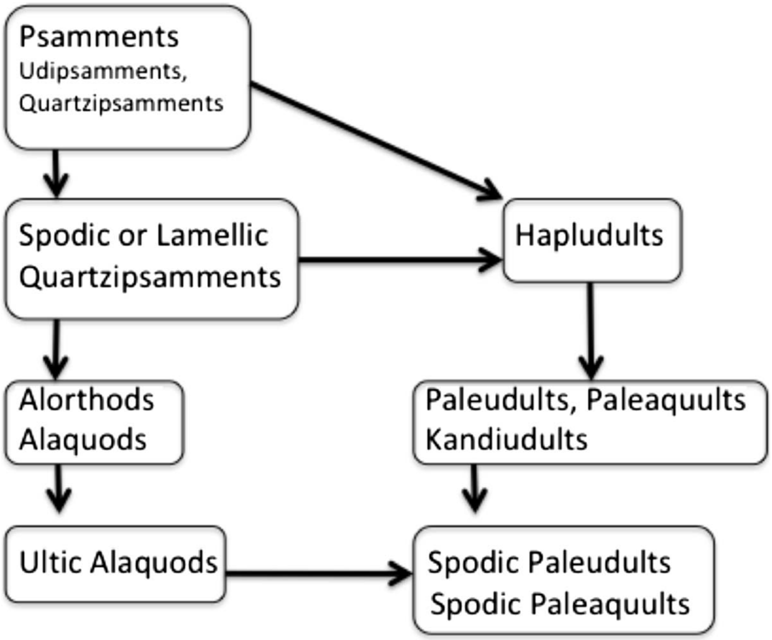

FIGURE 2. Network of transitions among soil taxa in the study area. This network was analyzed using graph theory by Phillips (2015).

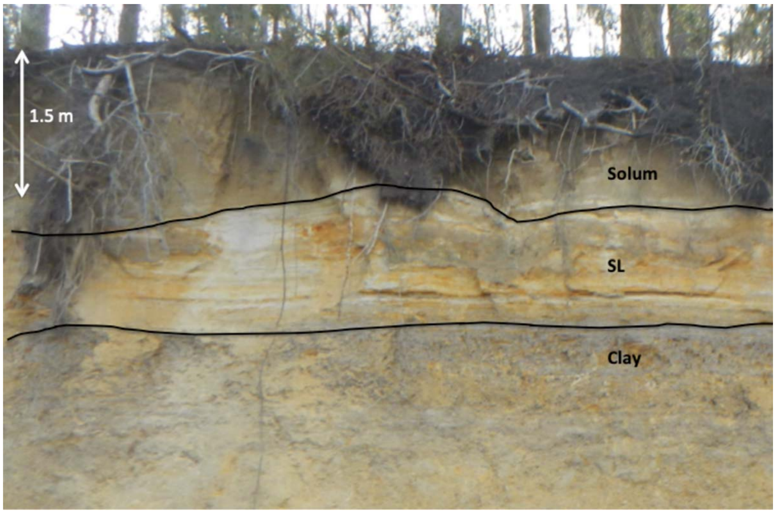

FIGURE 3. Soil exposed on eroding cliff along the Neuse River estuary. Solum (above the stratified material) is about 1.5 m thick. Sandy loam parent material (labeled SL) underneath has thin layers of fine material. At the bottom of the section (although partially obscured by slope processes), clayey sediments occur. A color version of this figure is available in the online version of this article. full color online

pathways occur, and both are recurring types. Soils of Holocene (and even historic) dunes indicate that podzolization, involving translocation of Fe compounds and organic matter, can occur very rapidly, resulting in formation of Spodic Quartzipsamments such as the Kureb series. Continued podzolization leads to development of Spodosols (Table 4). Some of these (e.g., Leon, Mandarin) may be bisequal.

Lessivage is also commonly observed, redistributing clay to subsoils. This can turn Psamments into Lamellic Quartzipsamments, although some sandy parent materials have fine laminae that may be of sedimentary origin. The Alpin series, with several E&Bt horizons, is the only series of this suborder commonly mapped in the region, but lamellae can be observed in other sandy Entisols. In some upland depressions, Humaquepts may also form, with Bg horizons. Lessivage can ultimately result in development of Hapludults (Table 4). Continued lessivage, clay formation, and weatherable mineral depletion (including gradual domination of argillic horizons by low-activity clay minerals) result in development of Kandiudults and Paleudults. In areas with higher water tables, Paleaquults occur.

As is often the case, lessivage and podzolization pathways may occur contemporaneously. Lessivage typically becomes dominant, but some soils with argillic horizons retain some spodic features such as Bh horizons. Some Arenic and Grossarenic Paleaquults and Paleudults also have Bh or Bs features. Secondary podzolization is common in thick sandy surficial deposits, although only one recognized Ultisol series (Onslow, Table 4) is in a Spodic subgroup.

Pathways involving lessivage and podzolization are of the recurring type. The podzolized sands retain high hydraulic conductivity, and thus translocation of humic acids and iron is not inhibited as these accumulate in B-horizons. Clay accumulation due to lessivage does impede drainage and translocation somewhat, but bioturbation and the presence of root channels and faunal burrows allow clay translocation to continue. Melanization (darkening of the surface layer due to organic matter) also generally occurs in these pathways and is recurring. Haploidization due to bioturbation (mainly tree uprooting and faunalturbation by burrowing mammals) is also common and recurring. Also, some forest environments in the region are naturally fire-prone or are currently managed using frequent controlled burns. In these settings, a recurring cycle of litter accumulation, fire, and ash additions to soil is common.

A recurring but nonrepeated path important in the development of the more highly weathered Ultisols is weatherable mineral depletion. Leaching of bases and formation of sesquioxides are also recurring but irreversible and thus nonrepeating.

Another common pathway is depodzolization (see Barrett and Schaetzl, 1998) associated with plowing of croplands and disturbance of surface layers by heavy machinery during timber harvesting. This is a recurring path on croplands, which are regularly disturbed. However, in forest stands, depodzolization is an inhibited pathway. Unless the surface is regularly disturbed, the rapid podzolization quickly resumes, as observed on abandoned cropland and on logged sites.

Another inhibited path is the complete or near-complete destruction of Bt horizons, which is inhibited by the concentration of sesquioxides and other low-activity clays and the resistance of these subsoils to erosion. Cady and Daniels (1968), based on evidence from North Carolina sites, argued that Bt horizons develop to a point and begin to degrade as the upper solum becomes increasingly acidic and leached. Clay lost from the upper Bt may be destroyed by chemical weathering or moved in suspension to the lower Bt. The latter seems more likely in the study area, because of the presence of eluvial bodies in B-horizons of Ultisols (Daniels et al., 1968), and the role of roots and tunneling insects in preventing the perching of water tables and retarding of percolation (Phillips, 2007b). However, some top-down degradation of Bt horizons does occur (Daniels et al., 1968), although the horizons are rarely entirely degraded,

Occasionally observed pathways include sandy surface deposition accompanied by secondary podzolization and/or argilluviation. This occurs mainly on the downwind side of croplands (typically northern and eastern boundaries, given the prevailing southwesterly winds during bare-field conditions in late winter and early spring). It can also occur along the estuarine shorelines of the area as storm overwash deposits beach sand on soils just inland. The podzolization and lessivage aspects are recurring. Repeated episodes of sand deposition certainly occur in the shoreline settings and probably also in the field-edge environments (Phillips et al. 1999a, 1999b; Pease et al., 2002; Gares et al., 2006).

Other pathways not readily evident from Fig. 2 also occur in the region. Occasionally observed, but more spatially localized, are pathways involving partial or full inversion of the usual coarser-over-finer vertical textural contrast. These occur because of tree uprooting and excavation. These pathways are transient because of the event-based nature of the disturbance and the fact that percolating water apparently restores the original textural contrast relatively rapidly. Figure 4, for instance, shows a cross section of a tree-uprooting pit-mound pair.

TABLE 4. Specific Examples of Common Soil Series (U.S. Soil Taxonomy) Associated With the Soil Types Shown in Fig. 2

Taxa Shown in Fig. 2	Examples
Udipsamments	Typic: Tarboro Aquic: Seabrook
Quartzipsamments	Typic: Newhan Aquic: Chipley
Spodic Quartzipsamments	Kureb
Lamellic Quartzipsamments	Alpin
Alorthods	Entic Grossarenic: Centenary Oxyaquic: Echaw
Alaquods	Typic: Lynn Haven Aeric: Leon
Ultic Alaquods	Olustee
Hapludults	Typic: State, Wickham Arenic: Conetoe Aquic: Altavista, Suffolk
Paleudults	Typic: Norfolk† Aquic: Goldsboro Arenic: Autryville, Wagram† Grossarenic: Troup,† Blanton
Kandiudults	Typic: Norfolk† Arenic: Wagram† Grossarenic: Troup†
Paleaquults	Typic: Rains Aeric: Lynchburg Arenic,‡ Grossarenic‡
Spodic Paleudults	Onslow
Spodic Paleaquults‡	
Other common taxa	
Typic Humaquepts	Torhunta
Umbric Edoaquods	Murville

†In 1988, these series were reclassified from Paleudults to Kandiudults. However, some pedons on the lower coastal plain may not meet the low-activity clay criterion.

‡These taxa recorded in fieldwork (Phillips et al., 1999a) but are associated with no officially recognized series.

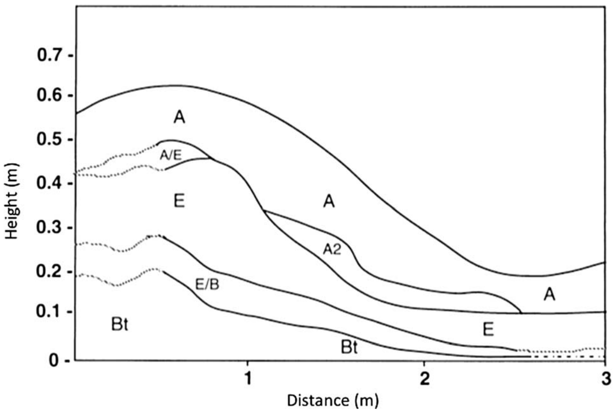

FIGURE 4. Cross section through a tree uproot pit-mound system, Otter Creek Natural area (OCNA) near Falkland, North Carolina (adapted from Phillips et al., 1994). A and E horizons range from sand to sandy loam in texture; Bt horizons are sandy clay loam. Depth from the surface to the Bt horizon at non-uproot sites at OCNA ranges from 30 to 95 cm (Phillips et al., 1994). Note that on both the mound and pit the A-E-B and associated coarser-over-fine textures are present.

The age of the feature is unknown, but the general coarse-over-fine contrast was restored in less time than it takes to obscure the pit mound topography. At Fisher's Landing near New Bern, North Carolina, earthworks constructed in 1862 in the U.S. Civil War have horizon sequences and thicknesses indistinguishable from adjacent soils undisturbed by excavation.

At forested sites, standing (i.e., not uprooted) tree death eventually results in a hole associated with the rotted (or occasionally, burned) stump. These depressions often fill first and, most rapidly, with organic litter (including litterfall and coarse debris from living trees as well as remnants of the stump; Fig. 5). However, because of rapid decomposition of organic matter in the subtropical climate and infilling by (especially) slumping of the surrounding soil and deposited mineral sediment, the pathway leading to a persisting organic-rich pit is transient, and I have not observed such a feature in a fully infilled stump hole.

With respect to currently impossible pathways, parent materials and geomorphic surfaces on the lower coastal plain are no older than late Pleistocene (Daniels et al., 1978), so I am aware of no evidence of paleosols associated with extinct organisms or soil-forming factors. However, there are exposed paleosols associated with, for example, higher Pleistocene sea levels and drainage conditions that no longer exist (Fig. 6). Thus, while there are no known EPs in the currently impossible category regionally, they certainly exist at a more local level.

Portions of the coastal plain feature Carolina Bays—elliptical depressions with poorly drained interiors, asymmetric sandy rims, and consistent orientations. The origin of these unique topographic features is uncertain, but they appear to have been formed in a single contemporaneous episode, and strong evidence exists for extraterrestrial impacts (Zamora, 2017). From a landform perspective, they are an example of an improbable pathway. Pedologically, however, this is not the case. While Carolina Bays have distinctive spatial patterns of soils, soil types in the poorly drained interiors and on the surrounding sand rims do not have any unique characteristics (i.e., they are also found on other poorly drained sites or sand ridges in the region not associated with Carolina Bays).

On a shorter time scale, it could be argued that pathways associated with tree uprooting are rare and improbable on managed pine

FIGURE 5. Stump hole near Fishers Landing, North Carolina (outlined by snow), infilling with organic matter. Depression is about 45 cm wide.

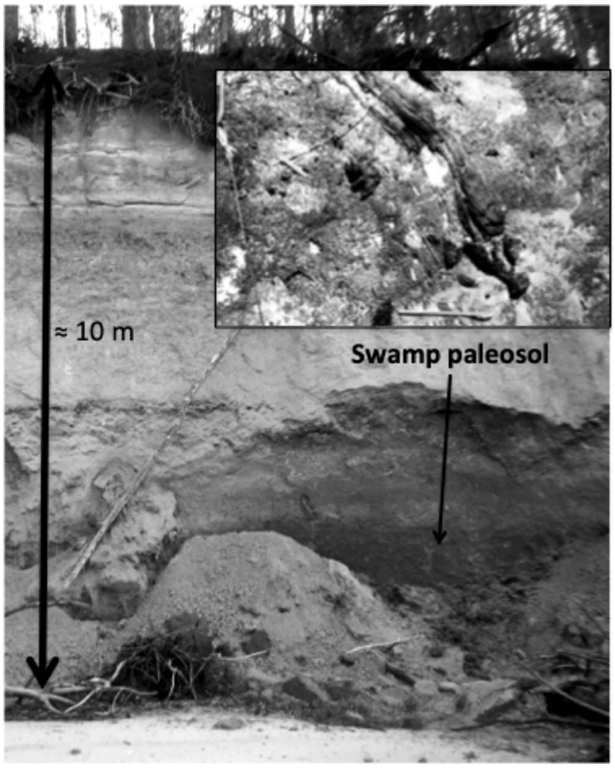

FIGURE 6. A swamp paleosol formed during higher Pleistocene sea level, exposed near Neuse Forest, North Carolina. Inset (about 40 × 50 cm) shows bald cypress (*Taxodium distichum*) roots within paleosol. Exposure shows the Pleistocene Flanner Beach formation, described in detail by Mixon (1986).

forests, as (1) the region's pine species have deep taproots and rarely uproot; (2) in managed forests, harvesting typically occurs before trees reach the larger size classes typically associated with uprooting; and (3) salvage logging is conducted when blowdown events do occur, so that rootwads often settle back into the pit when downed trunks are removed.

The most obvious examples of selected pathways are the development and maintenance of preferential flow paths during podzolization (Phillips et al., 1996; Montagne et al., 2013) and several cases of resistance selection, resulting in the persistence of low solubility, physically durable, and chemically stable substances. This is evident in the formation of sandy A- and E-horizons, where more soluble constituents and weathering products are preferentially translocated, and the accumulation of sesquioxides.

Figure 7 shows the common and recurring EPs described above; note that these correspond exactly to the soil transitions shown in Fig. 2. Figure 8 depicts the rare, inhibited, and transient EPs.

DISCUSSION

Soil geomorphology and pedology have moved beyond the notion that pedogenesis proceeds inexorably in most cases toward a predetermined mature climax or zonal soil. Pedogenesis may be regressive or progressive, divergent or convergent, and characterized by numerous possible trajectories and state changes. Certain attractor states certainly exist, but these are regionally variable and environmentally and historically contingent. Further, at scales ranging from soil regions to hillslope catenas, regularities in the soil cover are overprinted in many cases by extensive local variability. Predictions based on single-path, single-outcome concepts may indeed be valid in a general, aggregate sense, but exceptions are not only common, but by now also expected.

Given the many possibilities, the question is now why some EPs are common and recurring, and others rare. Some pathways that could be reasonably hypothesized are not observed at all. In much of the 20th century, the focus was on identifying monotonic developmental sequences, with variations therefrom treated as exceptions to a normative trajectory. Now the task is more akin to identifying a state space in which multiple pedogenetic paths may occur, with some parts of the state space densely occupied by similar, recurring EPs, and others sparsely occupied.

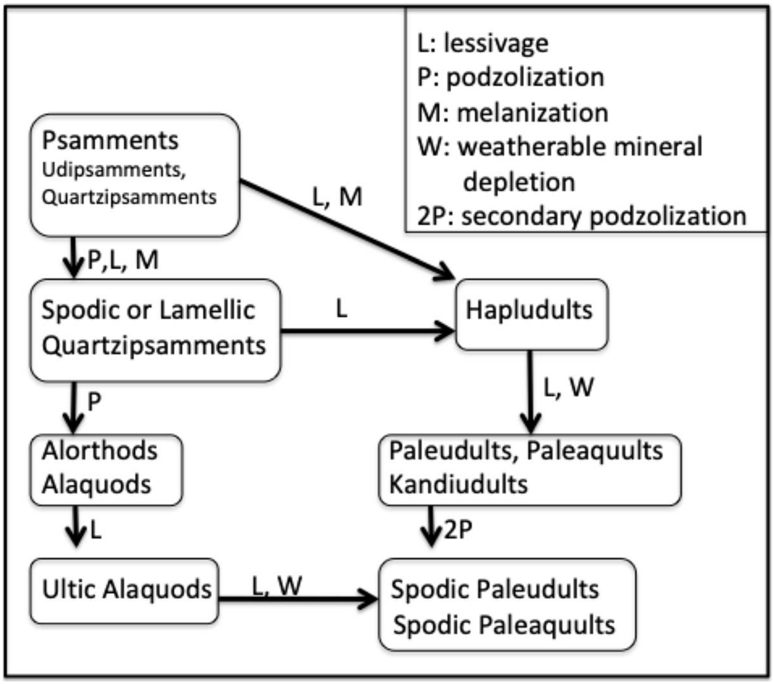

FIGURE 7. Common, recurring, and selected pedogenetic pathways.

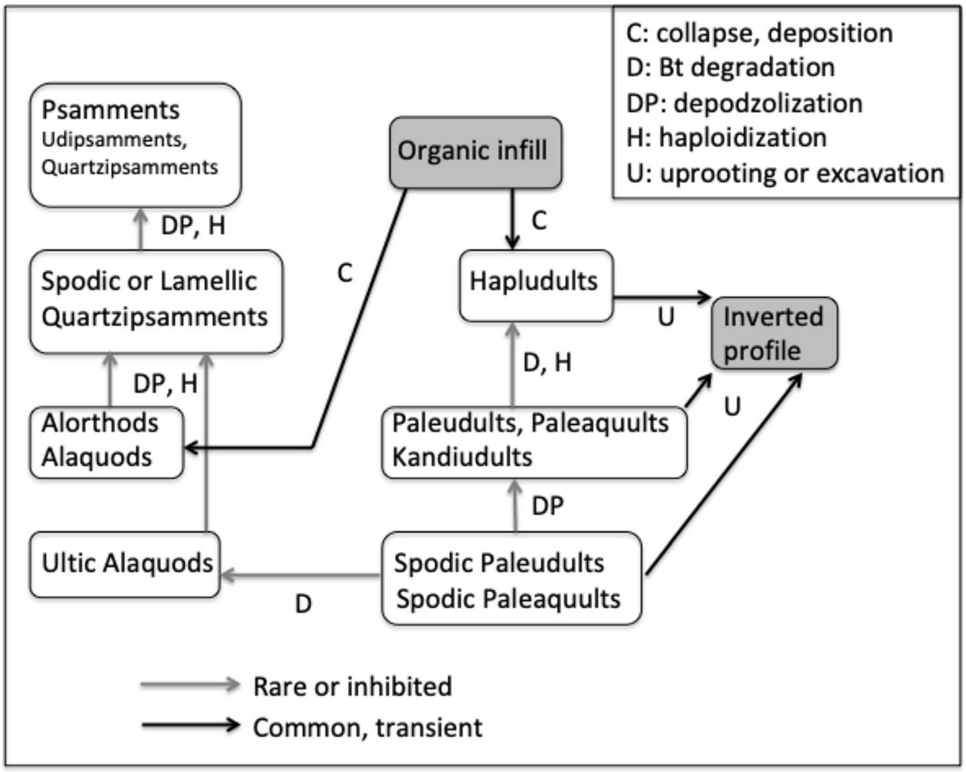

FIGURE 8. Rare, inhibited, and transient pedogenetic pathways.

The approach taken here is not based on any identified, assumed, or hypothesized normative pathways. Nor is it based on any systems-theory or mathematical notions of evolutionary trajectories. Rather, it is based on developing a typology of observed EPs, based on well-known phenomena in pedogenesis, as a step toward understanding their relative frequency of observation or manifestation.

CONCLUSIONS

As understanding of the evolution of soils and landforms has transformed from concepts of single-path, single-outcome development to those that recognize multiple developmental trajectories and outcomes, soil geomorphology and pedology should address why some EPs are common and persistent, whereas others are rare and transient. A typology of EPs includes those that are impossible, currently impossible, improbable, inhibited, and transient and thus either do not occur, seldom occur, or are rarely observed. Recurring, nonrepeating EPs are irreversible at a specific site, but occur in different locations, and recurring EPs may be repeated because of ongoing or recurrent processes or conditions. Some of both recurring path types may be selected because of feedbacks or responses that encourage or enhance recurrence and/or persistence. The case study of North Carolina coastal plain upland soils shows examples of all possible EP types.

Soil and other ESS changes are ongoing and, in some cases, accelerating (in the study area, for instance, in locations directly affected by rising sea levels and increasingly severe tropical cyclones). These transformations are occurring on what are often already complex and strongly interconnected spatial mosaics of soils and other factors. Thus, it will become increasingly important to synthesize and evaluate site-specific studies in a broader context of potential responses and trajectories. The concept of EPs and their relative likelihoods and longevity is a step toward accomplishing this.

REFERENCES

Anderson C. J., and B. G. Lockaby. 2011. The effectiveness of forestry best management practices in the southeastern United States: A literature review. South. J. Appl. Forestry. 35:170–177.

Bárány-Kevei I. 1998. Geoecological system of karst. Acta. Carsol. 27:13–25.

Barrett L. R., and R. J. Schaetzl. 1998. Regressive pedogenesis following a century of deforestation: Evidence for depodzolization. Soil Sci. 163: 482–497.

Bejan A. 2007. Constructal theory of pattern formation. Hydrol. Earth Syst. Sci. 11:753–768.

Bestelmeyer B. T., A. J. Tugel, G. L. Peacock, D. G. Robinett, P. L. Shaver, J. R. Brown, J. E. Herrick, H. Sanchez, and K. M. Havstad. 2009. State-and-transition models for heterogeneous landscapes: A strategy for development and application. Rangel. Ecol. Manage. 62:1–15.

Beven K. 2006. A manifesto for the equifinality thesis. J. Hydrol. 320:18–36.

Cady J. G., and R. B. Daniels. 1968. Genesis of some very old soils: The Paleudults. Trans. 9th Int. Cong. Soil Sci. 4:103–112.

Chin A., and J. D. Phillips. 2007. The self-organization of step-pools in mountain streams. Geomorphology. 83:346–358.

Culling W. E. H. 1987. Equifinality: Modern approaches to dynamical systems and their potential for geographical thought. Trans. Inst. Br. Geogr. 12:57–72.

Daniels R. B. 1987. Soil erosion and degradation in the Southern Piedmont. *In:* Land Transformation in Agriculture. Wolman M. G., and E. Fournier (eds.). Wiley, New York, pp. 407–428.

Daniels R. B., E. E. Gamble, and W. H. Wheeler. 1978. Age of soil landscapes in coastal plain of North Carolina. Soil Sci. Soc. Am. J. 42:98–105.

Daniels R. B., E. E. Gamble, and L. J. Bartelli. 1968. Eluvial bodies in B horizons of some Ultisols. Soil Sci. 106:200–206.

Davidson-Arnott R. 2010. Introduction to Coastal Processes and Geomorphology. Cambridge University Press.

Doehne E. 2002. Salt weathering. A selective review. Geological Society of London, Special Publications. 205:51–64.

Garcia-Fayos P., and A. Cerda. 1997. Seed losses by surface wash in degraded Mediterranean environments. Catena. 29:75–83.

Dean D. J., and J. C. Schmidt. 2013. The geomorphic effectiveness of a large flood on the Rio Grande in the Big Bend region: Insights on geomorphic controls and post-flood geomorphic response. Geomorphology. 201:183–198.

Fryirs K. A. 2017. River sensitivity: A lost foundation concept in fluvial geomorphology. Earth Surf. Process. Landf. 42:55–70.

Gares P. A., and K. F. Nordstrom. 1995. A cyclic model of foredune blowout evolution for a leeward coast: Island Beach, New Jersey. Ann. Assoc. Am. Geogr. 85:1–20.

Gares P. A., M. C. Slattery, P. Pease, and J. D. Phillips. 2006. Eolian sediment transport on North Carolina coastal plain agricultural fields. Soil Sci. 171:784–799.

Goodfellow B. W., O. A. Chadwick, and G. E. Hille. 2014. Depth and character of rock weathering across a basaltic-hosted climosequence on Hawai'i. Earth Surf. Process. Landf. 39:381–398.

Goudie A. S., and N. J. Middleton. 2001. Saharan dust storms: Nature and consequences. Earth Sci. Rev. 56:179–204.

Grant G.E., J. O'Connor, and E. Safran. 2017. Excursions in fluvial (dis)continuity. Geomorph. 277:145–153.

Gregory K. J., and J. Lewin. 2014. The Basics of Geomorphology. Sage, London.

Grzebyk M., and D. Dubrucq. 1994. Quantitative analysis of distribution of soil types: Existence of an evolutionary sequence in Amazonia. Geoderma. 62:285–298.

Guneralp I., and R. A. Marston. 2012. Process-form linkages in meander morphodynamics: Bridging theoretical modeling and real world complexity. Prog. Phys. Geogr. 36:718–746.

Harrison S. 2001. On reduction and emergence in geomorphology. Trans. Inst. Br. Geogr. 26:327–339.

Huang H. Q., and G. C. Nanson. 2000. Hydraulic geometry and maximum flow efficiency as products of the principle of least action. Earth Surf. Process. Landf. 25:1–16.

Humphreys G. S., and M. T. Wilkinson. 2007. The soil production function: A brief history and its rediscovery. Geoderma. 139:73–78.

Hunt A. G. 2016. Spatio-temporal scaling of vegetation growth and soil formation from percolation theory. Vadose Zone J. 15, doi:10.2136/vzj2015.01.0013.

Jannsen A. B. G., S. Teurlincx, S. An, J. H. Janse, H. W. Paerl, and W. M. Mooij. 2014. Alternative stable states in large shallow lakes? J. Great Lakes Res. 40:813–826.

Johnson D. L., and D. Watson-Stegner. 1987. Evolution model of pedogenesis. Soil Sci. 143:349–366.

Kauffman G. 2009. Modelling karst geomorphology on different time scales. Geomorphology. 106:62–77.

Leopold L. B. 1994. A View of the River. Harvard University Press, Boston, MA.

Lane S. N., and K. S. Richards. 1997. Linking river channel form and process: Time, space and causality revisited. Earth Surf. Process. Landf. 22:249–260.

Lin H. 2010. Linking principles of soil formation and flow regimes. J. Hydrol. 393:3–19.

Linton D. L. 1955. The problem of tors. Geogr. J. 121:470–487.

Liu Y., T. S. Steenhuis, and Y.-S. Parlange. 1994. Formation and persistence of fingered flow fields in coarse grained soils under different moisture contents. J. Hydrol. 159:187–195.

Markewich H. W., M. J. Pavich, M. J. Mausbach, B. N. Stuckey, R. G. Johnson, and V. Gonzalez. 1986. Soil development and its relation to the ages of morphostratigraphic units in Horry County, South Carolina. U.S. Geol. Surv. Bull, vol. 1589B. U.S. Geological Survey, Washington, DC.

Mixon R. B. 1986. Depositional Environments and Paleogeography of the Interglacial Flanner Beach Formation, Cape Lookout Area, North Carolina. Neatherly T. L. (ed.). *In*: Geological Society of America Centennial Field Guide, Vol. 6, Southeastern Section, Geological Society of America, Boulder, CO, pp. 315–320.

Montagne D., I. Cousin, O. Josiere, and S. Cornu. 2013. Agricultural drainage-induced Albeluvisol evolution: A source of deterministic chaos. Geoderma. 193:109–116.

Muhs D. R. 1984. Intrinsic thresholds in soil systems. Phys. Geogr. 5:99–110.

Nanson G. C. 1986. Episodes of vertical accretion and catastrophic stripping: A model of disequilibrium flood-plain development. Geol. Soc. Am. Bull. 97:1467–1475.

Nanson G. C., and H. Q. Huang. 2008. Least action principle, equilibrium states, iterative adjustment and the stability of alluvial channels. Earth Surf. Process. Landf. 33:923–942.

Nanson G. C., and H. Q. Huang. 2017. Self-adjustment in rivers: Evidence for least action as the primary control of alluvial-channel form and process. Earth Surf. Process. Landf. 42:575–594.

Nordstrom K. F. 1980. Cyclic and seasonal beach response: A comparison of oceanside and bayside beaches. Phys. Geogr. 1:177–192.

Ollier C., and C. Pain. 1996. Regolith, Soils, and Landforms. John Wiley, Chichester, UK.

Pawlik L. 2013. The role of trees in the geomorphic system of forested hillslopes—A review. Earth Sci. Rev. 126:250–265.

Penck W. 1924. Morphological Analysis of Landforms. Macmillan, London, English translation by H. Czech and K. C. Boswell, 1953.

Payo A., J. W. Hall, J. French, J. Sutherland, B. van Maanen, R. J. Nicholls, and D. E. Reeve. 2016. Causal loop analysis of coastal geomorphological systems. Geomorphology. 256:36–48.

Pease P. P., P. A. Gares, and S. A. Lecce. 2002. Eolian dust erosion from an agricultural field on the North Carolina coastal plain. Phys. Geogr. 23:381–400.

Phillips J. D. 1993. Chaotic evolution of some coastal plain soils. Phys. Geogr. 14:566–580.

Phillips J. D. 2000. Signatures of divergence and self-organization in soils and weathering profiles. J. Geol. 108:91–102.

Phillips J. D. 2001. Divergent evolution and the spatial structure of soil landscape variability. Catena. 43:101–113.

Phillips J. D. 2004. Geogenesis, pedogenesis and multiple causality in the formation of texture-contrast soils. Catena. 58:275–295.

Phillips J. D. 2006. Deterministic chaos and historical geomorphology: A review and look forward. Geomorphology. 76:109–121.

Phillips J. D. 2007a. The perfect landscape. Geomorphology. 84:159–169.

Phillips J. D. 2007b. Formation of texture contrast soils by a combination of bioturbation and translocation. Catena. 70:92–104.

Phillips J. D. 2010. The Perfect Soil. Proceedings of the 19th World Congress of Soil Science, pp. 59–61.

Phillips J. D. 2011. Emergence and pseudo-equilibrium in geomorphology. Geomorphology. 132:319–326.

Phillips J. D. 2013. Sources of spatial complexity in two coastal plain soil landscapes. Catena. 111:98–103.

Phillips J. D. 2015. The robustness of chronosequences. Ecol. Model. 298:16–23.

Phillips J. D. 2017. Soil complexity and pedogenesis. Soil Sci. 182:117–127.

Phillips J. D. 2018. Historical contingency in fluviokarst landscape evolution. Geomorphology. 303:41–52.

Phillips J. D., H. Golden, K. Cappiella, B. Andrews, T. Middleton, D. Downer, D. Kelli, and L. Padrick. 1999a. Soil redistribution and pedologic transformations on coastal plain croplands. Earth Surf. Process. Landf. 24:23–39.

Phillips J. D., J. Gosweiler, M. Tollinger, S. Mayeux, R. Gordon, T. Altieri, and M. Wittmeyer. 1994. Edge effects and spatial variability in coastal plain Ultisols. South. Geogr. 34:125–137.

Phillips J. D., D. Perry, K. Carey, A. R. Garbee, D. Stein, M. B. Morde, and J. Sheehy. 1996. Deterministic uncertainty and complex pedogenesis in some Pleistocene dune soils. Geoderma. 73:147–164.

Phillips J. D., M. C. Slattery, and P. A. Gares. 1999b. Truncation and accretion of soil profiles on coastal plain croplands: Implications for sediment redistribution. Geomorphology. 28:119–140.

Phillips J. D., M. Wyrick, G. Robbins, and M. Flynn. 1993. Accelerated erosion on the North Carolina coastal plain. Phys. Geogr. 14:114–130.

Prospero J. M., I. Olmez, and M. Ames. 2001. Al and Fe in PM 10 suspended particles in south-central Florida: The impact of the long range transport of African mineral dust. Water Air Soil Pollut. 125:291–317.

Puigdefabregas J., A. Sole, L. Gutierrez, G. del Barrio, and M. Boer. 1999. Scales and processes of water and sediment redistribution in drylands: Results from the Rambla Honda field site in southeast Spain. Earth Sci. Rev. 48:39–70.

Raab T., J. Krummelbein, A. Schneider, W. Gerwin, T. Maurer, and M. A. Naeth. 2012. Initial ecosystem processes as key factors of landscape development—A review. Phys. Geogr. 33:305–343.

Rempe D. M., and W. E. Dietrich. 2014. A bottom-up control on fresh-bedrock topography under landscapes. Proc. Natl. Acad. Sci. U. S. A. 111:6576–6581.

Renwick W. H. 1992. Equilibrium, disequilibrium, and nonequilibrium landforms in the landscape. Geomorphology. 5:265–276.

Retallack G. J. 2001. Soils of the Past. *In:* An Introduction to Paleopedology (2nd ed). Blackwell, Oxford, UK.

Šamonil P., I. Vasickova, P. Daněk, D. Janik, and D. Adam. 2014. Disturbances can control fine-scale pedodiversity in old-growth forests: Is the soil evolution theory disturbed as well? Biogeosciences. 11:5889–5905.

Schaetzl R. J., and M. I. Thompson. 2015. Soils—Genesis and Geomorphology (2nd ed). Cambridge University Press, New York.

Scheidegger A. E. 1983. The instability principle in geomorphic equilibrium. Zeitschr. Geomorphol. 27:1–19.

Selby M. J. 1993. Hillslope Materials and Processes (2nd ed). Oxford University Press, Oxford, UK.

Simpson G. G. 1963. Historical science. In: Albritton C. C. (ed.) The Fabric of Geology. Stanford, CA: Freeman, Cooper & Co., 24–48.

Smith T. R. 2010. A theory for the emergence of channelized drainage. J. Geophys. Res. Earth Surface. 115:F02023.

Stallins J. A. 2005. Stability domains in barrier island dune systems. Ecol. Complex. 2:410–430.

Stolbovoy V. S. 1992. Current problems in the study of tropical soils. Soviet Soil Sci. 24:1–15.

Taylor G., and R. A. Eggleton. 2001. Regolith Geology and Geomorphology. John Wiley, Chichester, UK.

Trimble S. W. 1974. Man-Induced Soil Erosion in the Southern Piedmont, 1700–1970. Soil Conservation Society of America, Ankeny, IA.

Trimble S. W., F. H. Weirich, and B. Hoag. 1987. Reforestation and the reduction of water yield on the Southern Piedmont since circa 1940. Water Resour. Res. 23:425–437.

Twidale C. R. 2004. River patterns and their meaning. Earth Sci. Rev. 67:159–218.

Uhlenbrook S. 2006. Catchment hydrology—a science in which all processes are preferential. Hydrol. Process. 20:3581–3585.

Van Dyke C. 2015. Boxing daze—using state-and-transition models to explore the evolution of socio-biophysical landscapes. Prog. Phys. Geogr. 39:594–621.

Van Dyke C. 2016. Nature's complex flume—using a diagnostic state-and-transition framework to understand post-restoration channel adjustment of the Clark Fork River, Montana. Geomorphology. 254:1–15.

Verleysdonk S., M. Krautblatter, and R. Dikau. 2011. Sensitivity and path dependence of mountain permafrost systems. Geogr. Ann. A. 93:113–135.

Whipple K. X., G. S. Hancock, and R. S. Anderson. 2000. River incision into bedrock: Mechanics and relative efficacy of plucking, abrasion, and cavitation. Geol. Soc. Am. Bull. 112:490–503.

Woldenberg M. J. 1969. Spatial order in fluvial systems: Horton's laws derived from mixed hexagonal hierarchies of drainage basin areas. Geol. Soc. Am. Bull. 80:97–112.

Yoho N. S. 1980. Forest management and sediment production in the South—A review. South. J. Appl. Forestry. 4:27–36.

Zamora A. 2017. A model for the geomorphology of the Carolina Bays. Geomorphology. 282:209–216.