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Forest ecosystems create pedogenic patchworks through woody debris, trees, and disturbance

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ABSTRACT

Forest ecosystems are highly diverse and heterogeneous in organisms, soils, litter such as woody debris, and disturbance regimes. Nonetheless, the causes, intensity, self-organization, and functioning of forest soil heterogeneity within single stands have received little attention. The concept “pedogenic patches” is introduced to integrate ecology and soil formation into a holistic view of forest soil heterogeneity. We define “pedogenic patches” as spatially limited and temporally defined locations that have at least one soil-forming factor which differs enough from their surroundings to cause differing intensities of soil processes and thus divergent pedogenic processes. Per this definition, discrete components of soil-forming factors such as woody debris, trees, canopy gaps, boulders, and creek banks can create pedogenic patches if pedogenic process rates lead to different soil morphology compared to their surroundings. A pedogenic patch’s quantitative intensity depends on the size, age, number, and distinctness of soil-forming factors and processes. Furthermore, pedogenic patches are the quanta of soil formation: Point-wise pedogenic patches with a degree of intense, persistent, and resilient pedogenesis can move in forest ecosystems to create patchwork soilscapes of various heterogeneity. Forest ecosystem studies could identify pedogenic patches to measure soil formation and evaluate forest soil heterogeneity through various diversity indices. Doing so would provide new insights into forest floor functioning, soil-regulated biodiversity, evolution of forests through disturbance, and ecological trade-offs of self-organizing ecosystems.

1. Introduction

A heterogeneous environment facilitates the establishment of species-rich ecosystems, and vice versa. Soils are the quintessential example of the former relation, where a breadth of mineral surfaces, pore space, solution chemistry, and organic matter contain niches for organisms (Birkhofer et al., 2012). But soils are also the product of organisms and their alterations to their environment (Hartemink et al., 2019; Amundson, 2021). Forest soils are a case in point: Compared to blocky fields of agricultural soils or grassy plains of rangeland soils, forest soils within single stands exhibit higher spatial and temporal heterogeneity in soil properties, horizons, and profiles (Mader, 1963; Phillips and Marion, 2004; Sabatini et al., 2015b). The drivers of forest soil heterogeneity are many and varied, both ecological and pedological, and differ from forest to forest. But models that upscale said drivers tend to resort to deterministic uncertainty of progressive and regressive processes that are more explanatory in nature than predictive (e.g., Phillips, 1993). Lacking is a more practical theory of soil heterogeneity at the scale of individual forest stands that encompasses soil formation, forest organisms, and ecosystem dynamics.

In soil science, pedologists from the start have not only described soil heterogeneity but also investigated the formation of heterogeneous soil landscapes (Glinka, 1914). Descriptions of soil heterogeneity include surveying soils for boundaries and phases, classifying soils into soil types and map legends, and analyzing soils for variances and “forms” within soil taxa (Beckett and Webster, 1971; Staff, 1999; Rossiter and Bouma, 2018). However, these approaches as practiced are not applied at scales suitable to forest stands. Modern classification uses morphology aligned with parent material, climate, and time; and assumes continuous soil formation at landscape and millennial scales (Staff, 1999; Ad-Hoc-Arbeitsgruppe Boden, 2005; IUSS Working Group WRB, 2014). Not included are organisms such as trees that are the source of much short- to medium-term soil processes as they are thought to be cyclical over annual or seasonal timescales, not unidirectional change of soil formation (van Breemen and Buurman, 2002). Yet soil formation is multi-directional in nature, with phases of convergence and divergence that result in evolutionary processes within dynamic ecosystems (Johnson and Watson-Stegner, 1987; Johnson et al., 1990; Phillips, 2001). The fact that fewer and fewer

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publications report complete soil taxa (Certini and Scalenghe, 2019) represents this disconnect between pedology, organisms, and ecology.

At scales of forest stands, ecology tends to ignore soil formation despite evidence to the contrary. For instance, individual trees as young as 45 years-old can alter soil pH, carbon, and nitrogen (Zinke, 1962; Dean et al., 2020). From a biodiversity perspective, however, only in clumps are tree species effects on soil carbon and nitrogen noticeable (Sercu et al., 2019). Ecosystem disturbance affects soil formation as well: Flooding in combination with topography creates patterns of forest vegetation and soil carbon (Cierjacks et al., 2010), while windthrow creates pit-mound formations that combined with woody debris maintains higher tree density up to eight decades (Šamonil et al., 2011; Sass et al., 2018b). Skid trails compact soil and open the canopy, thus leading to strips of new vegetation and soil dynamics that can recycle nutrients from harvest residues back into surrounding vegetation (Stutz et al., 2015, 2017b; Warlo et al., 2019). And woody debris itself can lead to patches of altered soil functions through the input of wood-derived organic matter (Stutz and Lang, 2017; Stutz et al., 2019).

In ecology, the closest recognition of organisms in soil heterogeneity-functioning relationships is the "hot-spot" concept, spatially and temporally limited locations with faster process rates than their surroundings (Table 1; McClain et al., 2003; Bernhardt et al., 2017). Examples of soil hot-spots include preferential flow along macropores (Bundt et al., 2001), new soil organic carbon accruing on patches of older carbon (Vogel et al., 2014), and intense denitrification near particulate organic matter (Parkin, 1987). Each of the above examples, however, are investigated at time scales rarely associated with soil formation even though hot-spots can become more permanent and functional as soil forms. For instance, accumulation of mor-type forest floors drive podzolization whereupon organic phosphorus is retained in complexes of soil organic matter and pedogenic oxides (Werner et al., 2017). Similarly, forest floor depressions are loci of translocation processes that advance acidification and weathering (Schaetzl, 1990; Schaetzl et al., 2020). Nonetheless, hot-spots are not incorporated into soil formation schemes due to their seemingly cyclical and transient nature, their limited spatial extent, and their apparent subordination to other soil-forming factors.

Potentially bridging the gap between forest organisms, soil formation, and ecosystem dynamics with regards to forest soil heterogeneity is the umbrella term "pedogenic patches", which is a variation of "pedogenic hot-spots" as coined by Stutz and Lang (2017). In that paper, we applied the latter to coarse woody debris due to its effect on soil formation and corresponding soil functions. But we also left the term undefined and unexplored. Pedogenic cold-spots could exist as well, and specific organisms—namely trees—are prime candidates. To rectify this oversight, we review the origin of the term "pedogenic hot-spots" as applied to woody debris before proposing a comprehensive definition and quantitative measures for "pedogenic patches" that encompasses individual trees and other patches of soil formation. We then explain forest soil heterogeneity through quantum soil formation of pedogenic patches and ecosystem disturbance, and outline possible applications as well as relevant opportunities.

2. Origin of concept

The term "pedogenic patch", the concept that soil formation can occur in patches, originates from observations of soil next to coarse woody debris and soil in the surroundings. Soil next to coarse woody debris differs from their surroundings in a variety of ways due to soil forming processes related to unique features of woody debris compared to other litter, functionally different decomposition pathways, and other soil forming factors as outlined below.

Coarse woody debris is unique morphologically compared to leaf litter and mineral soil, so much so that it is a challenge for current paradigms of biogeochemical cycling (Harmon, 2021) and woody debris in its entirety is considered to be its own organic parent material (Stutz et al., 2019). The uniqueness is due to the high proportion of lignocellulose compared to other cellular components in wood tissue and bark, which translates into different responses of soil to the input and persistence of fragmented and dissolved lignocellulosic decay products from woody debris in the forest floor and mineral soil (Kahl et al., 2012; Wambsganss et al., 2017; Stutz et al., 2019). Such detritus is thought to have quick turnover times due to their easy accessibility to decomposers relative to other, more stable organic fractions (von Lützow et al., 2006; Marschner et al., 2008). But a portion of the degraded lignocellulose persists in the form of more stable aromatic structures that can replace as well as displace older mineral-bound organic matter according to the cascading model (Kalbitz et al., 2003; Leinemann et al., 2018). Persistent lignocelullosic degradation products also increase cation exchange capacity, immobilize hydroxyl-Al, make other nutrients available through precipitation, assist mineral binding through cation bridging and hydrophobicity, and create macropore volume through aggregation (Stahr et al., 2018; Stutz et al., 2019; Šamonil et al., 2020).

Decomposing species and functional pathways within woody debris determine which decay products are produced from coarse woody debris. Only select decomposing species can digest woody lignocellulose as it has low amounts of available carbon, nutrients, and energy (Cornwell et al., 2009; Sauvadet et al., 2016; Peršoh and Borken, 2017). Such decomposers are not limited to saprotrophic fungi. Bacteria in termite guts to ectomycorrhizae symbionts of mycoheterotrophic orchids can degrade and metabolize lignocellulose (Geib et al., 2008; Cragg et al., 2015; Suetsugu et al., 2020). Functional pathways differ too. Brittle, lignified fragments from brown-rotted *Abies alba* (Mill.) are less functionalized and thus more inert than oxidized and soluble lignin residues from white-rotted *Fagus sylvatica* (L.) (Kirk, 1984; Stutz et al., 2017a). When tree species is controlled for, decay products still differ by functional pathway. For instance, brown-rot produces less dissolved organic matter with lower aromaticity than white-rot of the same species (Mosier et al., 2017, *Populus tremuloides* Michx.).

Other factors—organisms, parent material, climate, topography, and time—regulate the influence of coarse woody debris on forest soils. Organisms bioturbate lignocellulosic fragments into mineral soil only in mull forest floors, while dissolved lignocellulosic compounds percolate from woody debris into mineral horizons in most forest soils (Stutz et al., 2019). Ensuing changes in forest soil functions directly next to coarse woody debris depend on parent material. In acidic soils on silicate bedrock, degraded lignocellulose persists and facilitates base cation availability and soil porosity through cation bridging (Kappes et al., 2007; Stutz et al., 2017a, 2019). In soils on calcareous bedrock, degraded lignocellulose helps co-metabolize other organic matter and does not affect base cation availability or soil porosity (Kappes et al., 2007; Wambsganss et al., 2017; Stutz et al., 2019). Climatic and topographic features such as aspect and slope also influence decay, translocation, and soil functions through microclimate-regulated microbial activity (Bardelli et al., 2018), and sedimentation upslope of coarse woody debris (Spielvogel et al., 2009). With time as woody debris decomposes, cumulative input of degradation products can self-organize into positive feedbacks such as stable byproducts becoming protected in aggregates against further microbial transformation and thus contributing to higher organic carbon stocks (Wambsganss et al., 2017).

It should be noted that the outcome of soil processes induced by coarse woody debris is only identifiable when compared to properties of surrounding soil. In the last example where soil organic carbon stocks increase due to progressive decay and occlusion of organic matter in aggregates, the difference in carbon stocks only denotes a change in rates of aggregation and organic matter accumulation—i.e., pedogenic processes—relative to soil under canopy litter. It was this spatial and temporal distinctness that motivated our proposal to designate coarse

Table 1
Definitions of pedological and ecological terms including synonyms and close alternatives.

Term	Definition	Synonyms	References
Pedology & Ecology			
Hot-spot	A spatial or temporal location with more intense process rates than its surroundings; the type of hot-spot depends on what is changing (e.g., biogeochemical hot-spots have different rates of biogeochemical processes)	hot-moment, microsite, patch, ecosystem-control point	McClain et al. (2003), Kuzyakov and Blagodatskaya (2015), Bernhardt et al. (2017)
Pedogenic patch	Spatially limited and temporally defined locations where at least one soil-forming factor differs enough from their surroundings to cause differing intensities of soil processes and thus divergent pedogenic processes	pedogenic hot-spot/moment, pedogenic cold-spot/moment	Stutz and Lang (2017)
Pedology			
Pedogenic process	Any set or bundle of additions, removals, transformations, and translocations of soil material and energy that leads to profile-scale changes in a soil morphological property	process bundle, soil formation	Johnson and Watson-Stegner (1987)
Soil	Any body or system of layered mineral and organic solid, liquid, and gaseous matter that evolves through current and legacy pedogenic processes between soil-forming factors	(poly)pedon, tessera	Jenny (1941), Staff (1999), Hartemink (2016)
Soil formation	Progressive and regressive pedogenic processes as regulated by soil-forming factors; *quantum through movement of components of soil-forming factors and intensity of persistent/resilient pedogenic patches*	soil evolution, soil development, soil genesis, pedogenesis	Simonson (1959), Johnson and Watson-Stegner (1987), Staff (1999), Phillips (2017)
Soil-forming factors	Sum of independent ecosystem components that define the soil system; components are independent if they *can vary individually* from other factors; typically climate, organisms, topography (relief), parent material, and time, or some derivation thereof	state factor	Jenny (1941), Amundson (2021)
Ecology			
Disturbance	"Any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resource, substrate availability, or the physical environment"	perturbation	White and Pickett (1985)
Diversity	A system's differences in type, kind, and composition	heterogeneity	Pielou (1975), Messier et al. (2016)
Ecosystem	A complex system of organisms, an incorporated physical environment, and a structure of spatial, temporal, material, energetic, and entropic processes of and between biotic and abiotic components	biogeocoenosis	Tansley (1935), O'Neill et al. (1986)
Heterogeneity	A system component's differences in a given dimension (e.g., spatial, temporal, material, energetic, and entropic); descriptors are scale-dependent	inhomogeneity, variation, diversity	Li and Reynolds (1995)
Intensity	The "physical force of [an] event per area per time" that results from extensive and intensive parameters	force	White and Pickett (1985)
Memory	The extent to which a system or a part thereof is shaped by past events	legacies	Peterson (2002), Johnstone et al. (2016)
Process	A discrete interaction, reaction, or exchange between two or more entities	function, change	Leary (1985)
Property	The observed state (i.e., sum) of processes in a system or part thereof at a specified point in time	parameter	Leary (1985)
Resilience	"The capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks."	stability, buffer, capacity	Holling (1973), Walker et al. (2004)
Severity	"Impact on the organism, community, or ecosystem"	magnitude	White and Pickett (1985)

woody debris as "pedogenic hot-spots" of biogeochemical and biogeophysical processes that affect soil formation and functioning (Stutz and Lang, 2017). Woody debris, however, is one among many inducers of pedogenic processes and ensuing soil formation. Numerous ecosystem components such as trees and disturbance also contribute to the sometimes faster, sometimes slower formation of forest soils. Trees in particular amend carbon and nutrient balances, alter water fluxes, and adjust the stability of the anchoring substrate (Zinke, 1962; Pawlik and Kasprzak, 2018). Consequently, the umbrella term "pedogenic patch" requires a systematic definition and quantitative measures.

3. A definition

Before defining "pedogenic patches", a definition of soil formation is needed. Soil formation occurs through pedogenic processes resulting from differing intensities of soil processes—additions, removals, transformations, and translocations of matter and energy—established by soil-forming factors (Table 1; Jenny, 1941; Simonson, 1959; Johnson and Watson-Stegner, 1987). Thus, differences in soil-forming factors that alter soil processes result in different pedogenic processes as evident in soil properties.

We understand soil-forming factors to be the sum of ecosystem components that can vary individually within the system of other soil-forming factors (Table 1). For example, parent material is the entirety of inorganic and organic matter that can be present independently of climate, topography, and organisms. Similarly, the biotic soil-forming factor includes all organisms who are present on their own volition, even when their success may be affected by their relation to other soil-forming factors (Crocker, 1952; Amundson, 2021). In these terms, woody debris is a component of organic parent material as its presence is due to forces independent of soil, and from which soil can form together with other parent materials.[1]

We understand pedogenic processes to be any set or bundle of additions, removals, transformations, and translocations of soil material and energy that leads to a profile-scale change in a soil morphological property (Table 1). When woody debris or trees or other components of soil-forming factors induce different soil processes than those established by surrounding factors, pedogenic processes diverge and soil formation has been altered. Therefore, we propose "pedogenic patches" be defined as *spatially limited and temporally defined locations that have at least one soil-forming factor which differs enough from their surroundings to cause differing intensities of soil processes and thus divergent pedogenic processes*.

By "spatially limited" we mean a pedogenic patch has boundaries when represented on a coordinate plane. By "temporally defined" we mean a pedogenic patch has both a start date and an end date. Theoretically, a pedogenic patch is the size of what constitutes a soil body, namely a volume or system of soil material that experiences soil formation. This means a patch could be as small as a pedon or horizon, but more often a patch would be several meters along an axis; a patch's exact size could be tested through correlation lengths. Practically, a pedogenic patch is the size of what is technically and statistically feasible given a method's resolution.

Emphasis is placed on differences in soil-forming factors—i.e., different components thereof. Besides coarse woody debris and trees, other distinct components of soil-forming factors within forest ecosystems can be identified as pedogenic patches (Fig. 1). For instance, other distinct parent materials include stumps that lead to more soil organic carbon and thicker horizons (Pawlik and Šamonil, 2018), animal carcasses that induce anaerobic conditions and resulting pulses of ammonium and respiration (Keenan et al., 2018), and boulders that block solar radiation and reduce evaporation (Pérez, 1998). Bioturbating fauna create mounds as well as mix materials to form biomantles (Johnson, 1990; Wilkinson et al., 2009), and certain mycorrhiza create sizable hydrophobic mats (Kluber et al., 2010). Forest canopy gaps create new microclimates through enhanced solar radiation, evapotranspiration, and ion gradients that alter species recruitment, litter decomposition, and redox conditions (McCarthy, 2001; Bauhus et al., 2004; Hunting et al., 2021). Stream cut-banks establish sites of erosion and deposition, and river-borne sediments add new mineral and organic parent material to forest ecosystems (Graf-Rosenfellner et al., 2016).

This is not to discount pedogenic and soil processes, the temporal side of pedogenic patches. Discrete interactions, reactions, and exchanges—that is, processes (Table 1)—are the moments of change that make soils and indeed any ecosystem dynamic and evolutionary (Simonson, 1959; Johnson and Watson-Stegner, 1987; Johnson et al., 1990). In each of the examples above, soil-forming factors *and* soil processes change in tandem with one another. Consequently, when spatial and temporal differences in soil-forming factors lead to different soil processes of additions, removals, translocations, and transformations, and thus different pedogenic processes in evolving soil systems, a pedogenic patch may form.

While the role of pedogenic processes is easily recognized, it is less clear what constitutes a difference in pedogenic processes. A change in morphology indicates pedogenic processes have changed, which in turn is the result of a change in *net* intensities of soil processes that constitute a pedogenic process. Take the following soil processes of carbonate dissolution and precipitation, which are active in the pedogenic processes of decalcification and calcification. For example, carbonate dissolves in Soil A and precipitates in Soil B. This implies either:

1. Carbonate only dissolves in A and only precipitates in B.
2. Carbonate dissolves in both A and B, but *more* carbonate precipitates in B than dissolves.
3. Carbonate precipitates in both A and B, but *less* carbonate precipitates in A than dissolves.

The second and third options are the most analogous to the pedogenic patches and their surroundings. Yet to make sense of "more" or "less", we propose that Soils A and B experienced different quantities of each process within a specific unit of time, i.e., different process rates. Causes for different process rates are either a new steady state or being out of steady state due to disturbance or spatiotemporal decoupling of forward and reverse reactions. If carbonate dissolves and then eluviates to lower horizons, it cannot precipitate in the original horizon unless dissolved again and eluviated through capillary rise. When a specific process in a specific horizon is not taking place, its rate can be expressed as zero. Thus, differences in net soil process rates after a given amount of time that alter soil morphology—that is, differences in pedogenic processes as observed in different soil properties (Table 1)—are as necessary to the definition of pedogenic patches as are soil-forming factors.

Biogeochemical and microbial hot-spots as characterized by McClain et al. (2003) and Kuzyakov and Blagodatskaya (2015), both of which also stressed the importance of process rates, may qualify as pedogenic patches if they lead to divergent pedogenic processes. For example, part of a glossic horizon with more episodic anoxic microsites would reduce and eluviate more iron than their surroundings, thus resulting in progressive tonguing (Baish and Schaetzl, 2021).

4. Quantitative measures

As pedogenic patches can range from anoxic horizons to millennia-old trees, we recognize that not all pedogenic patches are equal. In a manner similar to Jenny (1941, page 19) and McBratney et al. (2003, page 7), a first approximation to measure pedogenic patch intensity is the following: Let soil property s be the result of pedogenic process f between m soil-forming factors $F_1, \ldots, F_m$ at coordinates x, y and time t (Eq. (1)). Then, by using the chain rule, the total difference in soil property ds between a pedogenic patch and its surroundings is a function ∂s of the differences in soil-forming factors $\partial F_1, \ldots, \partial F_m$ as they differ in space dx, dy and time dt (Eq. (2)).

$$s = f(\{F_1, F_2 \ldots, F_m\}(x, y, t)) \tag{1}$$

$$\begin{aligned} ds = & \left(\frac{\partial s}{\partial F_1} \frac{\partial F_1}{\partial x} + \cdots + \frac{\partial s}{\partial F_m} \frac{\partial F_m}{\partial x} \right) dx \\ & + \left(\frac{\partial s}{\partial F_1} \frac{\partial F_1}{\partial y} + \cdots + \frac{\partial s}{\partial F_m} \frac{\partial F_m}{\partial y} \right) dy \\ & + \left(\frac{\partial s}{\partial F_1} \frac{\partial F_1}{\partial t} + \cdots + \frac{\partial s}{\partial F_m} \frac{\partial F_m}{\partial t} \right) dt \end{aligned} \tag{2}$$

Some caveats should be noted when using these equations to quantify pedogenic patches. One, whether Eq. (1) is linear or nonlinear remains to be determined. Two, Eq. (1) assumes that pedogenic patches

[1] Soils developed from organic parent material include canopy/arboreal soils, histosols, and lignic forest floors. Mineral matter in such soils is either present as ash content or introduced by atmospheric deposition and turbation.

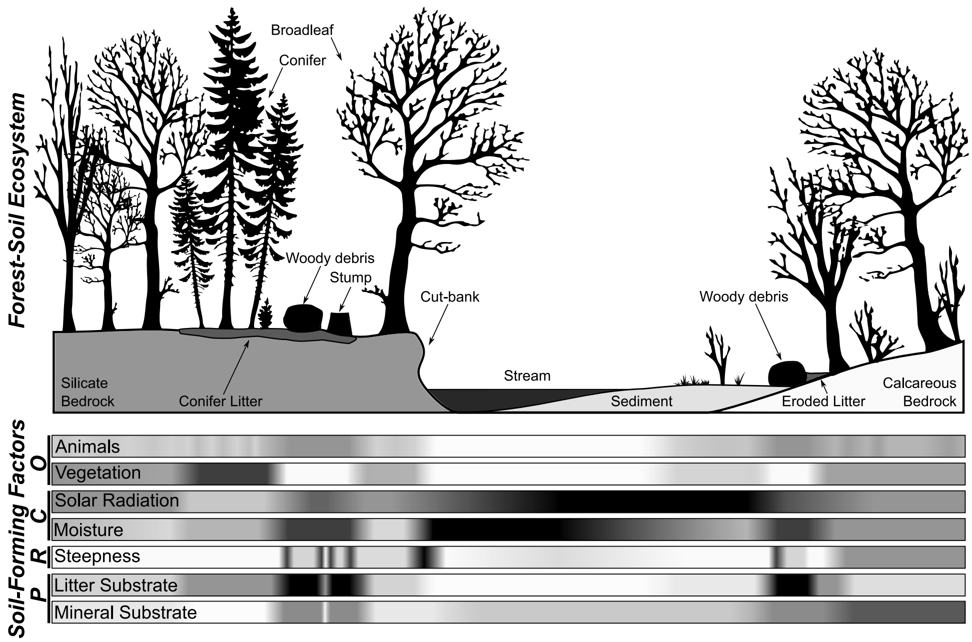

Fig. 1. Spatial representation of components of soil-forming factors in a forest-soil ecosystem. The soil-forming factors organisms (O), climate (C), relief (R), and parent material (P) are shaded to represent different types and differences within the following components: animal and vegetation type, solar irradiance, soil water content, slope steepness, litter type (e.g., woody debris), and mineral base saturation.
Source: Reprinted from Stutz (2019)

and their surroundings are continuous. As our definition implies that pedogenic patches are discontinuous from their surroundings, Eq. (2) is incorrect, but still suffices as an approximation when the scale is set accordingly with an degree of smoothing. Three, emergent properties may not be predicted until simulations are run. Yet, by explicitly including three dimensions x, y, t, some “apparent” emergence of other soil models may be explained.

With these equations and caveats in mind, quantitative parameters can be defined. Pedogenic patches can be characterized extensively by the *a) area* and *b) time* a soil-forming factor and process differ from their surroundings. These parameters are equivalent to dx, dy, and dt in Eq. (2). For example, a dominant *Sequoia sempervirens* ([Don] Endl.) covers substantially more area and a longer residence time than that of a suppressed *Notholithocarpus densiflorus* ([Hook. & Arn.] Manos, Cannon, & S. Oh).

Pedogenic patches also can be characterized intensively by the *c) number of* and *d) degree to which* soil-forming factors and processes within a pedogenic patch differ from their surroundings. In Eq. (2), these parameters are $\partial F_m/\partial x$, $\partial F_m/\partial y$, $\partial F_m/\partial t$ for soil-forming factors; and $\partial s/\partial F_m$ for processes. Again examples with woody debris: When a slope flattens midslope due to a perpendicular piece of downed woody debris, eroded mineral and organic material can accumulate, leading to increases in soil depth and soil organic matter stocks (Harmon et al., 1986; Spielvogel et al., 2007). More soil radiation due to canopy gaps or exposure also alters microbial communities and related decomposition rates of woody debris (Bardelli et al., 2018; Fravolini et al., 2018). And slower, hotter combustion of woody debris during fire results in localized high burn severity with reddening and magnetization of mineral soils in Mediterranean open woodlands (Goforth et al., 2005). Trees similarly alter soil formation not only through root-created pores and release of organic acids, but also through litterfall, intercepted solar irradiance, regulated water flow, and specific biological communities, especially in the rhizosphere (Weber and Bardgett, 2011; Spielvogel et al., 2016; Pawlik and Šamonil, 2018). For example, Zinke and Crocker (1962) reported 90 cm-deep and 150 cm-wide bark litter layers around millenia-old *Sequoiadendron giganteum* ([Lindl.] Buchholz).

Thus, as per Eq. (2), the intensity of soil formation at a pedogenic patch is a function of changes in the quantitative parameters size, age, number, and distinctness of soil-forming factors and processes. For instance, larger and older pedogenic patches with multiple soil-forming factors and processes have a greater effect on soil formation than shorter-term, smaller pedogenic patches with less distinct factors and processes. In terms of coarse woody debris, a *F. sylvatica* log and stump with lignocellulose, nutrients, water, and diverse organisms under a canopy break on conifer litter and base-poor, well-drained silicate bedrock is more distinct than a similar log at a canopy edge with accumulated broadleaf litter on carbon-, base-, and water-rich calcareous bedrock (Fig. 1; Stutz et al., 2019). By completing Eq. (2), the former has a more intense and divergent soil formation from their surroundings than the latter.

5. Forest soil patchiness

With a definition and quantitative intensity of pedogenic patches, we can regard forest soils as populations of patches that move and evolve into soilscapes of differing heterogeneities. By this we mean forest stands are landscapes of pedogenic patches that persist, transform, or move following disturbance, namely specific events that change system structures (Table 1) that per definition involve the creation or cessation of pedogenic patches.

First, persistence of pedogenic patches. Some pedogenic patches seem to persist when experiencing disturbance, when changes to soil-forming factors and pedogenic processes may maintain or enhance previous soil formation. In other words, a pedogenic patch can be said to have a degree of *memory*—i.e., persistence of legacy (Table 1)—ranging from permanent to none. Memory can be represented by interactions between $F_1, \ldots, F_m$ within f in Eq. (1), an additional memory parameter (e.g., α in Peterson, 2002), or a combination of both. The degree of memory depends on $f(F_1, \ldots, F_m)$ either remaining unchanged over time or self-reinforcing through positive feedbacks. The former is exemplified by selective memory as demonstrated by soil under stumps remaining distinct from their surroundings even after stem removal, but to a lesser extent than under living trees (Pawlik and Kasprzak, 2018). In comparison, the latter is more effective. If micropits or decay of vertical coarse roots from stumps increase eluviation of sesquioxides and organic matter, a persistent tongue of an E-horizon may develop faster than the surroundings. Similarly, illuviation of oxides and organic matter at the boundaries of albic tongues is self reinforcing due to increasing effectiveness of filtration in addition to precipitation (Schaetzl et al., 2020). Positive feedbacks are not inherent to every pedogenic patch. Within a population of *Virola surinamensis* ([Rol. ex Rottb.] Warb.), soil microbial communities of maternal trees reduce the performance of own seedlings compared to soil microbial communities of non-maternal trees (Eck et al., 2019).

Second, transformation of pedogenic patches. Following disturbance, some pedogenic patches may transform into a new pedogenic patch with similar physical boundaries but with little memory of past soil formation. Such patches have a higher chance of experiencing disturbance that has enough intensity to overcome memory and still the capacity to remain a pedogenic patch independent of memory. We propose to name this capacity a pedogenic patch's *resilience* to remain a functioning pedogenic patch, which could be expressed by including a resilience parameter per F_m in Eq. (1). We recognize that, in addition to functioning, resilience often implies the capacity to retain structure, identity, and feedbacks while absorbing disturbance (Table 1), but this is already expressed by a pedogenic patch's degree of memory, which when strong is often assumed to entail strong resilience (Johnstone et al., 2016). Rather, we see resilience of pedogenic patches as closer to the idea of self-perpetuating disturbance—i.e., a disturbance niche—and ensuing pockets of divergence: When a tree is uprooted by windthrow, the remaining pit contributes to high spatial heterogeneity (Lutz and Griswold, 1939; Schaetzl, 1990; Phillips and Marion, 2004, 4–11 soil series per 0.127-hectare plot). When monsoons induce shallow landslides only in gaps of the shallow-rooted, pioneer species *Phyllostachys nidularia* (Munnro) within mixed conifer forests, faster reestablishment of *P. nidularia* than saplings maintains a cycle of rapid growth, minimal root anchorage, shallow landslide, and recolonization that reduces soil horizonation and depth (Stokes et al., 2007). Conversely, pedogenic patches can lose resilience when any difference between pedogenic patches and their surroundings are removed for example through large-scale homogenization of forests and soils via salvage logging, agriculture-like soil preparation, and seedling planting in plantation forestry (Phillips and Marion, 2004; Sass et al., 2018a).

Third, movement of pedogenic patches. During disturbance, soil-forming factor components move—i.e., change position—in space and time, which is expressed by the interaction between x, y, t for each F_m in Eq. (1). Such movement can diminish or enhance the differences between a pedogenic patch and its surroundings—i.e., converge or diverge—depending on a pedogenic patch's intensity of persistent/resilient soil formation:

1. When factor components do not move either due to a lack of disturbance or too persistent/resilient soil formation, patches are stationary. Forest soils thus are patchy in a linear relationship to the number and intensity of pedogenic patches.
2. When factor components move and intensity of persistent/resilient soil formation is *low*, patches move without leaving a measurable impression. Forest soils thus appear homogeneous regardless of the number and intensity of pedogenic patches.
3. When factor components move and intensity of persistent/resilient soil formation is *high*, patches leave impressions as they move with factors. Forest soils thus become dynamic mixtures of pedogenic patches that are more heterogeneous than (2) but less so than (1).

Patchiness of forest soils through intensity and movement thus captures the breadth and instability of divergent and convergent soil formation needed for soil complexity (Phillips, 2017). Namely, it allows for both pockets of localized and heterogeneous soil morphology exemplified by forest soils and more limited and homogeneous soil morphology observed globally. This dynamic creates "quantum soil formation" where intensity and movement of persistent/resilient pedogenic patches are akin to particle and wave quantum mechanics via abundant, point-wise soil formation at smaller scales that appear continuous at larger scales.

6. Application in forest ecosystem studies

To summarize, forest soils undergo quantum soil formation through disturbance of persistent/resilient pedogenic patches that move. Thus, at any given point of time, forest soils are patchworks of pedogenic patches each with a different combination of soil-forming factors and rates of pedogenic processes. In forest ecosystem studies, pedogenic patches can be used as the quanta by which soil formation is identified, measured, and evaluated in relation to ecosystem functioning.

Any attempt to identify pedogenic patches entails identifying spatially delineated components of soil-forming factors and their links to pedogenic patches. The identification of soil-forming factors is facilitated by the fact that many of their components are identifiable aboveground. Forest inventories of soil-forming factor components could provide a first estimate of pedogenic patches. For example, Lutz et al. (2021) was able to determine the spatial heterogeneity and rates of woody debris creation through an annual census of a 25.6-ha, mixed *Tsuga heterophylla* ([Raf.] Sarg.)–*Pseudotsuga menziesii* ([Mirb.] Franco) forest. But the need for spatially explicit data within each plot makes such conventional mapping less practical compared to remote sensing techniques. For instance, Queiroz et al. (2019) mapped woody debris with > 80% completeness and > 92% correctness from light detection and ranging (LiDAR) aerial imagery with circa 40 points m^{-2} of a mixed boreal forest with *Pinus banksiana* (Lamb.), *Picea mariana* ([Mill.] Britton et al.), and *P. tremuloides*. Baltensweiler et al. (2019) achieved similar results for soil pH and microtopography from digital elevation models obtained through LiDAR datasets with 6.3–6.9 points m^{-2} and a raster resolution of 0.5 m.

Identifying pedogenic patches also requires patches have a minimum amount of soil formation or persistent memory, otherwise patches cannot be distinguished. Memory only can be determined from known indicators or markers of that memory. If known, above- and belowground patterns could be linked by validating high-resolution forest stand maps through belowground inventories (e.g., Frelich et al., 1993). Some markers are already known and utilized in scientific research, namely compounds and isotopes with a known origin. Compound-specific examples include phytoliths, DNA, RNA, wax-derived alkanes, lignin-derived phenols, and polycondensed aromatic pyrogenic carbon that mark the existence of organisms and disturbance (Glaser et al., 2000; Stutz et al., 2019); a novel example of the latter would be organic compound tracers of light-induced lignin degradation (Keiser et al., 2021) following canopy loss. Isotope-related examples include compound-specific stable isotope analysis for each compound class listed above (Glaser, 2005; Lloyd et al., 2021), inorganic isotope distribution in plant tissues such as $\delta^{44/40}$Ca in wood (Schmitt et al., 2018), and more classical age determination via radioactive, stable, and cosmogenic isotopes (e.g., Ugolini et al., 1981; Heimsath et al., 1999; Steger et al., 2019).

Once identified, soil formation could be measured by monitoring the distribution of pedogenic patches before, during, and after disturbance. During wind storms, high-resolution maps of forest stands can discern functional pedogenic patches that increase risk of windthrow (Mitchell, 2013), enhance regeneration around woody debris (Logan et al., 2020), and persist even after stands of *Quercus robur* (L.) and *P. sylvestris* reach maturity (Gruba et al., 2020). Repeated monitoring of pedogenic patches may also help quantify persistence/resilience of patches and any evolutionary pathways they constitute (Phillips, 2019). In Lo Papa et al. (2011), albeit without using the term "pedogenic patch", mapping with cellular automata quantified losses of heterogeneous soil formation in Sicily due to intensifying land-use. Similarly Daněk et al. (2016) established the importance of local disturbances for complex soil formation within larger geomorphological processes. Technical hurdles still exist, namely resolution, but this can be overcome by methods that retain distinct details of forest soil heterogeneity when upscaling maps (e.g., Costantini and L'Abate, 2016).

After being identified and measured, pedogenic patches can be the quantifiable points in various indices of heterogeneity, namely the degree of difference or inhomogeneity (Table 1). The choice of index is broad and varied: Soil patchiness can be quantified directly through standard deviations within a profile (Wanzek et al., 2018), coefficients of variance across functional soil groups (Grigal et al., 1991; Šamonil et al., 2011), and taxonomic distance of soil types (McBratney and Minasny, 2007). Soil patchiness also can be measured indirectly through image and spectral analysis (e.g., Maynard and Johnson, 2016; Fajardo et al., 2017) and assessment of upscaled heterogeneous fluxes (e.g., Ebrahimi and Or, 2018; Warner et al., 2019). Richness, evenness, and patchiness indices from information and systems sciences have been recommended decades ago for pedodiversity studies (Ibáñez et al., 1995) given their use in biodiversity research (Pielou, 1975) and landscape ecology (Turner, 1989). Alternatively, new indices can be created as demonstrated for forest structural diversity in Sabatini et al. (2015a) and Storch et al. (2018). Networks also provide an opportunity to assess dynamical system properties and conduct spatial analyses (Phillips et al., 2015; Phillips, 2016).

Pedogenic patches may enhance the applicability of certain indices by identifying the pedogenesis behind forest soil patchiness (Li and Wu, 2004). Indices based on pedogenic patches and corresponding soil disturbance regimes thus are strong candidates to be standard methods for assessing forest soil heterogeneity (Ibáñez and Brevik, 2019). Accordingly, survey and classification systems should include descriptors for common soil disturbance regimes to inform practitioners of potential pedogenic patch dynamics.

In forest soil ecology, pedogenic patches offer opportunities to realign frequencies and spatial distributions to new questions on the functioning of ecosystem heterogeneity (e.g., Fons et al., 1997; Raffard et al., 2018). A case in point: When (Blyth and MacLeod, 1978) recommended larger plots for predicting yield classes, the question was whether "short range soil variability" inaccurately described the relationship between tree growth and soil nutrient status. When (Prietzel, 2020) found that patches of phosphorus enrichment led to more aboveground biomass in *P. abies* seedlings, the question was whether phosphorus heterogeneity in forest soils regulated tree growth and vitality. The choice of question is limited when terminology and units are non-existent or ill-defined. Pedogenic patches can alleviate this limit by incorporating patchy soil formation in studies on forest ecosystem functioning.

7. Relevance and opportunities

In forest ecology, soil functions are often considered to be randomly distributed and either too dynamic (i.e., soil solution concentrations) or spatiotemporally constant. Soil dynamics at temporal and spatial scales of trees and stand structures, respectively, are rarely dealt with. Investigating peodgenic patches would bring new insights into the ecology of litter and soil properties, soil-regulated biodiversity, ecological evolution of forested landscapes through disturbance, and broader questions on ecosystem heterogeneity and functioning.

An immediate possibility is mechanistically linking soil functioning to litter and forest floor dynamics. General pathways by which litter transforms into the forest floor and soil organic matter are already known, but it is still debated which mechanisms are responsible for which pathway and which functions (Prescott and Vesterdal, 2021). Comparative studies with a medium-term pedogenic patch perspective can help identify those mechanisms. With paired samples adjacent to coarse woody debris and 2–3 m away in temperate hardwood forests, Stutz (2019) reported that up to 0.50 Mg ha^{-1} of organic carbon, 0.60 kmol$_c$ ha^{-1} of exchangeable Ca^{2+}, and 300 m^3 ha^{-1} of pore space in soil could be attributed to input of particulate and dissolved organic matter from 10–25 m^3 ha^{-1} of woody debris covering 5% of a forest stand (Table 2). Note that these values may not be the full effect of woody debris as the reference surroundings have a higher chance of being influenced by woody debris. Similar studies could be done for tree stumps, residue heaps, wood piles, ant mounds, and stand regeneration (Kristiansen and Amelung, 2001; Prietzel and Ammer, 2008). If not taken into account, contributions may be underestimated (e.g., Krueger et al., 2017).

Mechanistic links between pedogenic patches and forest biodiversity also can be established. For instance, coarse woody debris acts as long-term nutrient storage for wood debris-specific microbial and fauna communities as well as the wider forest ecosystem (Laiho and Prescott, 2004; Rousseau et al., 2018; Minnich et al., 2020). Patches, pits, and mounds associated with woody debris enhance the regeneration of understory plants and seedlings (Schaetzl et al., 1989; Goldin and Brookhouse, 2015; Sass et al., 2018b). Woody debris that are themselves seedbeds are known as nurse logs and non-exhaustively include: *Tsuga canadensis* ([L.] Carr.) in conifer-hardwood forests (Frelich et al., 1993), *Picea glauca* ([Moench] Voss) and *Thuja occidentalis* (L.) in boreal forests (Simard et al., 1998), and *A. alba* and *P. abies* in temperate forests (Szewczyk and Szwagrzyk, 1996; Stroheker et al., 2018). Both nutrients and regeneration affect a tree species's fitness to varying degrees of directness and effectiveness (Binkley and Giardina, 1998). In northern Michigan, for instance, tree-species specific soils resulted in a pattern of *T. canadensis* and *Acer saccharum* (Marsh.) that would persist for several millennia (Frelich et al., 1993). Pedogenic patch dynamics thus can create and maintain niches that underpin biodiversity and functioning of forest ecosystems.

A pedogenic patch perspective also can elucidate transitions between ecosystems at longer and larger scales by identifying legacy pedogenic patches due to forest disturbance (e.g., Henry and Swan, 1974). In alpine grasslands of Tasmania, for instance, vernal pools are orientated by the strongest winds rather than underlying mineral topography, and are the result of organic dams that accumulate slower than surrounding tussock grasses (Harrison-Day et al., 2019). Compared to spatial patterns of pits and mounds in nearby residual forests, Harrison-Day and Kirkpatrick (2019) concluded that such vernal pools were created hundreds to thousands of years ago through windthrow, subsequent fire, and post-fire animal burrowing. The same goes for other landscapes: In riparian and riverine systems, woody debris can create islands of deposited sediments (Wohl and Scott, 2017). Ecosystem management has similar effects through either post-disturbance maintenance or introduction—intentional as well as accidental—of pedogenic patches such as retaining biological legacies, assisting migration, and establishing permanent skid trails, respectively (Franklin et al., 2000; Perino et al., 2019; Warlo et al., 2019).

Conceptualizing forests as pedogenic patchworks provides new insights into questions on ecosystem heterogeneity and functioning. Ecological trade-offs of litter could be quantified by examining pedogenic patches in different forest plant communities. Pedogenic patches in the forest floor then could help identify strategies for ecosystem functioning such as those for phosphorus nutrition (Lang et al., 2016, 2017). Moreover, the risk of non-linear ecosystem strategies to global forest change could be assessed through individual pedogenic patches that fulfill specific ecosystem functions within a specific strategy (Messier et al., 2016; McDowell et al., 2020; Jackson, 2021). Longer-term measures of a disturbance's severity—i.e., impact on ecosystem functioning (Table 1)—thus could be predicted per ecosystem per disturbance.

All of the above would advance the field of ecological complexity by providing causal mechanisms of soil heterogeneity and ecosystem functioning that underpin self-organization and emergence (Cadenasso et al., 2006). One such advancement is the incorporation of spatial soil information into the much-studied role of disturbance in maintaining biodiversity (Jentsch and White, 2019). Another is the inclusion of spatiotemporal soil dynamics in biodiversity–ecosystem functioning relationships (Messier et al., 2019; Gottschall et al., 2021).

Table 2
Potential woody debris-induced changes to soil stocks of organic carbon (OC), base cations, and pore volume by site-decay class and surface area based on results from Stutz et al. (2019). Woody debris stocks [m^3 m^{-2}] are calculated from each stem's radius, length, and remaining volume; and the area of influence is assumed to be 1 m laterally in each direction regardless of width and length.[a] Potential changes (± standard error of the mean) in OC, Ca^{2+}, Mg^{2+}, total porosity (Ah only), and available water capacity (AWC; Ah only) equal changes in O and Ah horizon-densities summed and multiplied by % surface area; Ah horizon is assumed to be 10 cm in depth. Reprinted from Stutz (2019).

Site-Decay Class [m^3 m^{-2}][a]	Area [%]	Volume [m^3 ha^{-1}]	OC Stock [Mg ha^{-1}][b]	Base Cations [$kmol_c$ ha^{-1}][c] Ca^{2+}	Mg^{2+}	Pore Space [m^3 ha^{-1}][d] Porosity	AWC
Mull-Calcareous 0.023 ± 0.004	1%	2.3	+0.05 ± 0.05	+0.00 ± 0.25	+0.05 ± 0.02	−43 ± 17	−20 ± 10
	5%	11.5	+0.24 ± 0.27	+0.00 ± 1.23	+0.24 ± 0.09	−215 ± 82	−100 ± 49
	25%	57.5	+1.19 ± 1.34	+0.00 ± 6.14	+1.19 ± 0.47	−1077 ± 413	−500 ± 245
Mull-Silicate 0.026 ± 0.005	1%	2.6	−0.01 ± 0.07	+0.10 ± 0.06	+0.01 ± 0.02	+4 ± 26	+7 ± 12
	5%	12.8	−0.04 ± 0.34	+0.48 ± 0.30	+0.04 ± 0.08	+21 ± 132	+36 ± 61
	25%	64.1	−0.20 ± 1.70	+2.38 ± 1.49	+0.20 ± 0.39	+104 ± 660	+182 ± 304
Moder-Silicate 0.046 ± 0.011	1%	4.6	+0.00 ± 0.05	+0.12 ± 0.04	+0.01 ± 0.01	+62 ± 19	+4 ± 11
	5%	22.8	+0.01 ± 0.27	+0.60 ± 0.20	+0.07 ± 0.06	+310 ± 93	+21 ± 53
	25%	113.8	+0.03 ± 1.36	+2.99 ± 1.01	+0.36 ± 0.28	+1550 ± 467	+107 ± 266
Initial 0.060 ± 0.014	1%	6.0	+0.01 ± 0.07	+0.30 ± 0.14	+0.01 ± 0.01	+22 ± 24	+9 ± 11
	5%	29.8	+0.06 ± 0.37	+1.50 ± 0.72	+0.05 ± 0.05	+110 ± 120	+44 ± 56
	25%	148.8	+0.28 ± 1.86	+7.50 ± 3.58	+0.27 ± 0.27	+550 ± 598	+222 ± 278
Moderate 0.023 ± 0.004	1%	2.3	−0.03 ± 0.05	−0.01 ± 0.10	+0.02 ± 0.02	+12 ± 23	−26 ± 6
	5%	11.3	−0.17 ± 0.23	−0.07 ± 0.52	+0.08 ± 0.09	+61 ± 115	−129 ± 28
	25%	56.3	−0.87 ± 1.17	−0.33 ± 2.60	+0.40 ± 0.47	+306 ± 577	−647 ± 142
Advanced 0.026 ± 0.006	1%	2.6	+0.09 ± 0.06	−0.02 ± 0.22	+0.04 ± 0.01	−5 ± 25	+24 ± 14
	5%	13.2	+0.47 ± 0.30	−0.09 ± 1.10	+0.22 ± 0.06	−23 ± 123	+118 ± 70
	25%	66.0	+2.36 ± 1.49	−0.45 ± 5.49	+1.08 ± 0.31	−114 ± 616	+591 ± 351

[a] $m^3\ m^{-2} = \frac{\pi r^2 LV}{2(L+2)}$ where r is radius, L is length, and V is remaining volume.
[b] $Mg\ ha^{-1}$ = (O mg cm^{-2} + Ah mg cm^{-3} · 10 cm) · Mg mg^{-1} · cm^2 ha^{-1}.
[c] $kmol_c\ ha^{-1}$ = (O $mmol_c$ cm^{-2} + Ah $mmol_c$ cm^{-3} · 10 cm) · $kmol_c$ $mmol_c^{-1}$ · cm^2 ha^{-1}.
[d] $m^3\ ha^{-1}$ = cm^3 cm^{-3} · 10 cm · m^2 cm^{-2} · m^2 ha^{-1}.

8. Conclusions

Forest soils are by nature heterogeneous and dynamic ecosystems where components of soil-forming factors interact and mediate exchanges of matter, energy, and entropy in space and time. In heterogeneous soils, pedogenic patches exist as spatially limited and temporally defined locations that have at least one soil-forming factor which differs enough from their surroundings to cause differing intensities of soil processes and thus divergent pedogenic processes. From this perspective, forest soils evolve in discreet moments and quantum pedogenic patches of various sizes within scales and intervals previously considered inconsequential.

Memory and resilience of pedogenic patches need to be delineated to decipher how "soil remembers" specific events (Janzen, 2016), how every soil profile is a pedogenic patch, and therefore how soils perpetuate forest ecosystems. Only then can we begin to comprehend the true impact of disturbance—both natural and human—on forest ecosystems, where an event such as windthrow, bioturbation, fire, flooding, or harvesting directs the evolution of a forest soil for centuries and millennia to come. We therefore call for the analysis and application of temporally and spatially heterogeneous soil formation in pedological and ecological research instead of ignoring it.

CRediT authorship contribution statement

Kenton P. Stutz: Defined the term "pedogenic patch", Revised the manuscript, Writing – original draft. **Friederike Lang:** Defined the term "pedogenic patch", Revised the manuscript.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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