



Embracing the dynamic nature of soil structure: A paradigm illuminating the role of life in critical zones of the Anthropocene

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ABSTRACT

Soils form the skin of the Earth's surface, regulating water and biogeochemical cycles and generating production of food, timber, and textiles around the world. Changes in soil and its ability to perform a range of processes have important implications for Earth system function, especially in the critical zone (CZ)—the area that extends from the top of the canopy to the bottom of groundwater and that harbors most of Earth's biosphere. A key aspect of the way soil functions results from its structure, defined as the size, shape, and arrangement of soil particles and

Abbreviations: BNPP, belowground net primary productivity; CT, X-ray computed tomography; CUE, carbon-use efficiency; CZ, critical zone; EPS, extracellular polymeric substances; HSI, hyperspectral imaging; MLT, multi-stripe laser triangulation scanning; NCSS, National Cooperative Soil Survey; NMR, nuclear magnetic resonance; NRCS, Natural Resources Conservation Service; NSF, National Science Foundation; PEDS, Pedogenic and Environmental DataSet; REE, rare earth element; RTM, reactive transport model; SOC, soil organic carbon; UNSODA, UNsaturated Soil hydraulic DAtabase; CLM, Common Land Model; PFT, plant functional types; REWT, Root Exudation in Watershed-Scale Transport; AIAA, American Institute of Aeronautics and Astronautics.

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pores. The network of pores provides storage space for at least a quarter of Earth's biodiversity, while the abundance, size and connectivity of the pore space regulates fluxes of heat, water, nutrients and gases that define the physical and chemical environment. Here we review the nature of soil structure, focusing on its co-evolution with the plants and microbes that live within the soil, and the degree to which these processes have been incorporated into flow and transport models. Though it is well known that soil structure can change with wetting and drying events, often oscillating seasonally, the dynamic nature of soil structure that we discuss is a systematic shift that results in changes in its hydro-bio-geochemical function over decades to centuries, timescales over which major changes in carbon and nutrient cycles have been observed in the Anthropocene. We argue that the variable nature of soil structure, and its dynamics, need to be better understood and captured by land surface and ecosystem models, which currently describe soil structure as static. We further argue that modelers and empiricists both are well-poised to quantify and incorporate these dynamics into their studies. From these efforts, four fundamental questions emerge: 1) How do rates of soil aggregate formation and collapse, and their overall arrangements, interact in the Anthropocene to regulate CZ functioning from soil particle to continental scales? 2) How do alterations in rooting-depth distributions in the Anthropocene influence pore structure to control hydrological partitioning, biogeochemical transformations and fluxes, exchanges of energy and carbon with the atmosphere and climate, regolith weathering, and thus regulation of CZ functioning? 3) How does changing microbial functioning in a high CO₂, warmer world with shifting precipitation patterns influence soil organic carbon dynamics and void-aggregate profile dynamics? 4) How deeply does human influence in the Anthropocene propagate into the subsurface, how does this depth relate to profile structure, and how does this alter the rate at which the CZ develops? The United Nations has recently recognized that 33% of the Earth's soils are already degraded and over 90% could become degraded by 2050. This recognition highlights the importance of addressing these proposed questions, which will promote a predictive understanding of soil structure.

1. Embracing the dynamic nature of soil structure in the Anthropocene

Soil structure is the size, shape, and arrangement of solid particles and pores (Brewer, 1964; Letey, 1991; Rabot et al., 2018). Soil structure dictates the character and pace of many critical zone (CZ) processes such as chemical weathering, groundwater flow, and carbon cycling that both

govern and respond to Earth's climate (Fig. 1). Since the early 1900s, soil scientists have recognized that soil particles combine to form larger aggregates (see definitions in Table 1 of many terms used throughout this paper). Aggregates and their arrangement exert strong controls on terrestrial water, nutrients, gas, and heat fluxes (Yudina and Kuzyakov, 2019). Over long timescales (i.e., millennia), soil structure is broadly linked to climate (Lipman and Waynick, 1916; Baver, 1934; Jenny,

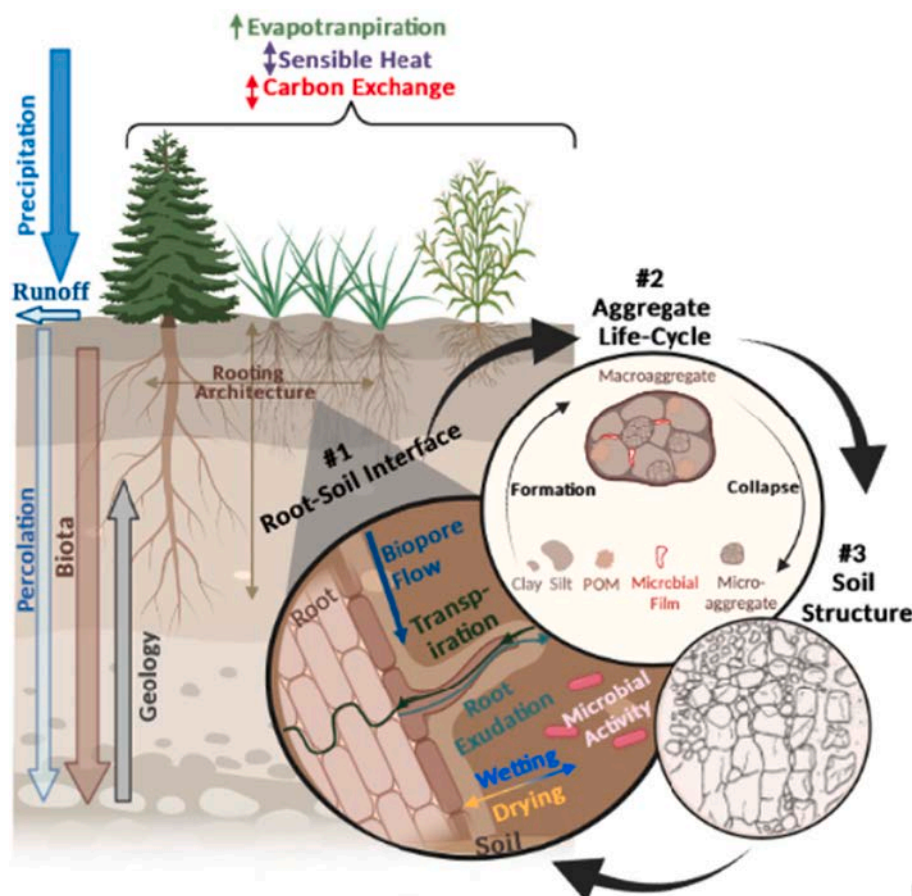


Fig. 1. Soil structure - the arrangement of particles (primary and secondary) that generates pore spaces in soil - dynamically responds to changes in climatic and biotic conditions. Here biotic processes such as root exudation and abiotic factors such as wetting and drying (#1) can alter the stability of aggregates causing either formation or collapse (#2). Along with overburden pressure that exerts stronger control at depth, the processes work together to result in a particular soil structure (#3). Arrows indicate the direction of interaction.

Table 1
Definitions of common terms related to soil structure

Term	Definition	Sources
Aggregate	A group of primary solid particles that are coated and become associated with organic matter and inorganic cements (carbonate, or iron and aluminum oxides) to form quasi-stable spatial clusters within the soil structural matrix.	Voroney and Heck, 2015
Aggregate life-cycle	Length of time an aggregate is formed in the soil system until it is broken down. It includes three stages: aggregate formation, aggregate stabilization and eventual disintegration.	Rillig et al., 2017
Clod	An artificial, compact, coherent mass of soil usually formed by cultivation or excavation.	SSSA, 2001; Rabot et al., 2018
Critical zone	A permeable layer from the vegetation canopy to the bottom of the groundwater.	White et al., 2015
Ecological structure	All of the biotic and abiotic physical components that make up that ecosystem. The more components that constitute an ecosystem, the more complex its structure becomes.	Barbier, 2013
Hydraulic properties	Group of soil properties that are influenced by structure and impact soil water dynamics, which includes soil water retention curves, and saturated/unsaturated hydraulic conductivity.	Jury and Horton, 2004
Infiltration	The process of water entering into the soil and becoming soil water.	Hillel, 1998a, 1998b
Ped	A naturally formed soil structural unit.	Turk et al., 2012
Percolation	The downward movement of water through the soil profile that leads water redistribution within the soil profile.	Blake et al., 2008
Pore-size distribution	The relative abundance or volume of each pore size class in a soil system.	Nimmo, 2004
Pore organization	The volume, spatial arrangement, and continuity of soil pore space.	Kuncoro et al., 2014
Preferential flow	Non-uniform, fast movement of water through the soil along certain pathways, which are often macropores, that bypass the soil matrix.	Jarvis, 2007
Matrix vs. macropore flow	Matrix flow is the process of water moving slowly through smaller pores of the surrounding soil matrix to spontaneously and continuously achieve equilibrium. Macropore flow is flow through a small part of the soil that contains a structural void or other conduit with a large opening.	White, 1985; Beven and Germann, 2013
Micro-, meso-, and macropores	Depending on opening size, pores can be classified as micropores, mesopores, and macropores; however, there are no unequivocal size thresholds between these categories. The differentiation between them is often arbitrary. From the perspective of pore functions, there is a clear distinction in the contribution of the three types of pores to different soil water processes. Macropores (several mm to cm), in which capillary force is nil, contribute to channel flow or preferential flow and are generally air-filled at field capacity. They are formed by biological activities or shrinking in clayey soils. Mesopores (several μm to mm) and micropores (less than ten μm) are capillary pores and responsible for the retention of soil water. Mesopores contribute to drainage and water redistribution, while micropores contribute to redistribution only. They are formed by soil aggregation processes.	Luxmoore, 1981; Hillel, 1998a, 1998b
Micro-, meso-, and macroaggregates	Aggregate diameters of 2–20 μm , 20–250 μm , and >250 μm are referred to as microaggregates, mesoaggregates, and macroaggregates, respectively.	Voroney and Heck, 2015; Tisdall and Oades, 1982
Rhizosphere	A soil microenvironment immediately surrounding the plant roots, where the physical, chemical and biological features of the soil are controlled by the roots.	Broeckling et al., 2008
Rooting depth	The deepest soil depth reached by the roots of a certain plant, or maximum rooting depth.	Schenk and Jackson, 2002
Runoff	The portion of the water supply to the surface that is neither absorbed by the soil nor accumulates on its surface, but that flows over the land surface.	Hillel, 1998a, 1998b
Soil horizonation	The development of identifiable horizons (distinct layers) within a soil profile that result from soil forming processes.	Buol et al., 2011; Weil and Brady, 2017
Soil structure	The size, shape, and arrangement of solid particles and pores.	Brewer, 1964; Letey, 1991
Weathering front	A transition zone between the intact bedrock and the weathered rock, saprolite, regolith, or soil that moves downward as weathering proceeds.	Phillips et al., 2019

1941; Mohammed et al., 2020). It is also well recognized in soil science, though perhaps not broadly in Earth science, that soil structure responds to daily and seasonal wetting and drying conditions. However, a knowledge gap persists for the larger scientific community at the scale of decades to centuries (i.e., meso-timescales): How does soil structure respond to systematic changes in drivers such as precipitation, temperature, and vegetation dynamics? What does this mean for our future predictions of terrestrial water, nutrients, gas, and heat fluxes? The decadal to century timescale is perhaps most pressing, given immediate concerns about soil productivity in a changing climate.

Evidence demonstrates that we have moved into the “Anthropocene”, a modern geologic epoch in which human activity has played a dominant role in governing environmental conditions, including land cover, atmospheric CO₂ concentrations, average annual global air temperatures, sea levels, and water, nitrogen and phosphorus cycles (Vitousek et al., 1997a, 1997b; Steffen et al., 2015; Lewis and Maslin, 2015; Zalasiewicz et al., 2019; Dawson et al., 2020). Changes in land-use practices and environmental conditions can influence the formation, stability, and disintegration of soil aggregates (Hubbell, 1947; Sharma and Aggarwal, 1984; Mbagwu and Bazzoffi, 1989; Six et al., 1998; Kasper et al., 2009; Spohn and Giani, 2011; Piazza et al., 2020). Current projections point to an acceleration in climate-carbon cycle feedbacks with rising temperatures whereby soil carbon losses increase in ecosystems experiencing decreased moisture or warming (Crowther et al., 2016; Carvalhais et al., 2014; Soong et al., 2021), and ecosystems shift from carbon sink to source (Liu et al., 2018). Changes in moisture regimes can also drive shifts in soil hydrological properties and biota

(Hirmas et al., 2018; Caplan et al., 2019; Robinson et al., 2016), possibly leading to alternative stable states in soils and regolith (Robinson et al., 2019). Finally, depth distributions of roots and their associated mycorrhizae are also responding to natural and anthropogenic perturbations in ways that alter critical zone functioning, and feedback to impact soil structure in the Anthropocene (Jackson et al., 1996; Ellis et al., 2010; Maeght et al., 2013; Pierret et al., 2016; Fan et al., 2017; Brantley et al., 2017; Billings et al., 2018).

Critical to this discussion is the mounting evidence that soil structure, aggregates and pore space, are systematically changing on time-scales of decades (Stamati et al., 2013; Andrianaki et al., 2017; Caplan et al., 2017; Kotronakis et al., 2017; Keidel et al., 2018), although the physical mechanisms governing these changes remain unclear despite considerable amount of work on structural dynamics (e.g., see Logsdon et al., 2013). Such timescales are far shorter than are often considered when we think about soil-formation processes (e.g., centuries to millennia). For example, analysis of continental-scale soil databases reveals that more humid conditions appear to reduce both residual (corrected for texture and organic matter) effective porosity and saturated hydraulic conductivity, while drier conditions increase these properties, and that these responses to hydrological conditions can occur within 50 years (Hirmas et al., 2018). Rainfall manipulation studies from diverse ecosystems have confirmed precipitation-induced changes in soil hydraulic properties (Robinson et al., 2016; Caplan et al., 2019). Critical analyses of the literature found that linkages between vegetation, climate and hydraulic properties are better expressed in dry climates (Thompson et al., 2010; Viglizzo et al., 2015). This evidence

strongly suggests that changes in soil moisture may be a key driver of changes in soil structure, and that those changes will be fairly rapid (i.e., within ~3 y in the study of Robinson et al., 2016 and ~20 y in Caplan et al., 2019). Robinson et al. (2019) and Vereecken et al. (2010) further suggest that soil hydraulic properties typically considered static over simulation time domains must become time-dependent over years to hundreds of years to account for environmental processes such as climate and land cover/use change.

An important hypothesis has recently emerged: the response of biota and climate-carbon cycle feedbacks appears to be accelerating at the global scale in the Anthropocene (Steffen et al., 2015; Lewis and Maslin, 2015). Specifically, changes in plant and microbial functioning are likely to prompt significant and detectable shifts in soil structure and its associated hydraulic and biogeochemical properties, and more rapidly than in many previous epochs. Thus, it seems timely to advance this hypothesis serving the goal of the larger scientific community for developing “rules of life.” Rules of life, as defined by the U.S. National Science Foundation, are sets of rules that predict interactions within and between levels of organization across scales of time and space (NSF, 2019). Here we seek to link concepts from soil science, hydrology, critical zone ecosystem science, and biogeochemistry to underscore a fundamental rule of life: *Rapid responses of vegetation and microbes to changes in climate and land use alter soil structure at increasing rates in the Anthropocene, governing the future of global water and carbon cycles.* Within often-isolated scientific fields, multiple components of this idea have been tested for decades, generating foundational knowledge about the role of soil structure in soil and whole-ecosystem functioning.

We review this knowledge base below and synthesize new ideas for future research trajectories. We first explore the mechanisms that can drive such changes in soil structure (Fig. 2) and provide examples that demonstrate the potential consequences of meso-timescale soil structural changes emerging in the literature. We then describe how soil structure is treated as slowly changing in response to long-term exposure to environmental forcings. Finally, we offer quantitative approaches that will help our scientific community further link and measure the two components of soil structure - the solids and voids - and incorporate this relationship into land surface and hydrologic models to better predict impacts on water, energy and carbon fluxes, thus allowing us to test this soil-based rule of life as a hypothesis. Though we acknowledge a diversity of agents of soil structural change, including soil fauna (Kumi et al., 2015; Platt et al., 2016; Mele et al., 2021; Meurer et al., 2020), we focus on three drivers known to be important for soil structure: soil

carbon, plants, and microbial communities. Table 1 includes definitions of key vocabulary. They are not the only way to define these terms but they provide a platform to ensure interdisciplinary communication.

2. Mechanisms that drive soil structural changes

Aggregates are the fundamental building blocks of mineral soil; they have long been examined for their role in governing soil water infiltration, plant-available water holding capacity, and root growth (e.g., Yudina and Kuzyakov, 2019; Dexter, 1988; Blevins and Frye, 1993; Nimmo, 2004; Nemati et al., 2002; Skvortsova, 2009). Aggregates form from interactions between clay minerals or from interactions among clay minerals, other colloidal material, and abiotic and biotic binding compounds (Six et al., 2004; Bronick and Lal, 2005; Araya and Ghezzehei, 2019; Weil and Brady, 2017). Examples of abiotic binding compounds include carbonate, iron oxides, and amorphous silica (Six et al., 2004; Bronick and Lal, 2005; Araya and Ghezzehei, 2019), while biotic compounds are typically comprised of decaying plant biomass, exudates from both roots and microbes, and microbial necromass (Six et al., 2004; Bronick and Lal, 2005; Araya and Ghezzehei, 2019). An aggregate's life-cycle may start with the formation of organo-mineral complexes (Banwart et al., 2011) that generate small aggregates (250 μm ; (Tisdall and Oades, 1982), which can remain stable or continue to increase in size (e.g., to macroaggregates) due to binding with particulate organic matter inputs, clay minerals or clay-sized particles, and microaggregates (Six et al., 2000). This aggregate growth is often aided by extracellular polymeric substances (EPSs) produced by soil microbes (Six et al., 2004). Alternatively, the literature has also shown that macroaggregates can form from particulate organic matter, and that microaggregates can form as those organic materials undergo decomposition (Oades, 1984; Angers et al., 1997; Stamati et al., 2013; Rabot et al., 2018). Eventually, aggregates can disintegrate through both physical (e.g., by root penetration, water-promoted disruption) and biochemical or chemical (e.g., soil organic carbon (SOC) decomposition, mineral dissolution) processes (Bronick and Lal, 2005).

Although aggregate size, stability, and arrangement govern many soil processes and correlate substantially with soil functioning (Banwart et al., 2019), we recognize that there has been skepticism about the usefulness of viewing soil processes and properties exclusively through the lens of aggregates, as opposed to focusing on the pores that surround them (e.g., van Genuchten, 1985; Letey, 1991; Baveye and Wander, 2019; Yudina and Kuzyakov, 2019). This debate may be prompted by

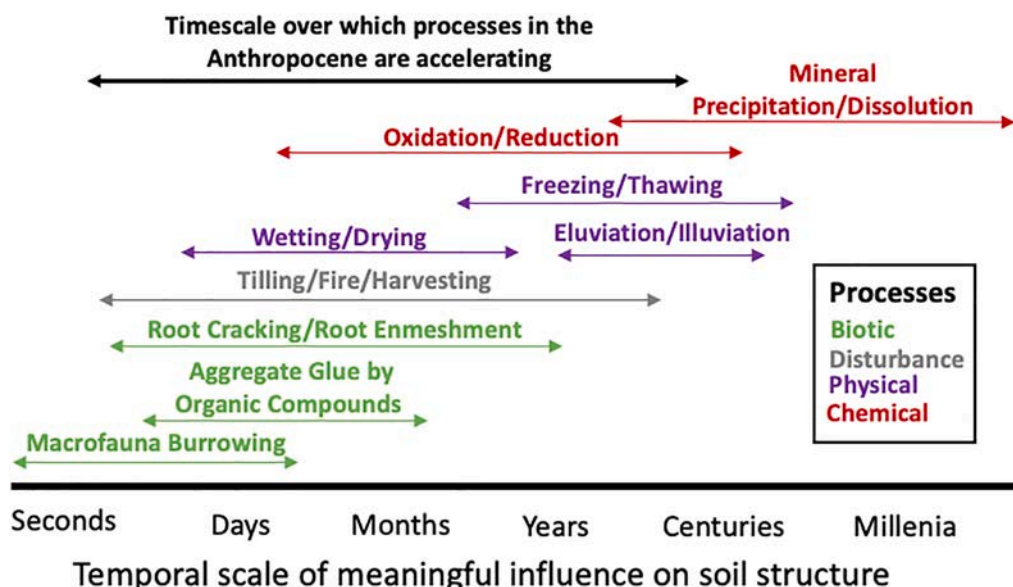


Fig. 2. Conceptual diagram of the timescales over which biotic and abiotic mechanisms induce meaningful change on soil structure, akin to the time and/or spatial scaling conceptualized in works such as Janzen (2004). Biotic (green) and disturbance (gray) processes dominate rapid changes, while abiotic physical (purple) and chemical processes (red) impact soil structure over much longer time periods. This logic prompts a new rule of life hypothesis: rapid responses of vegetation and microbes to changes in climate and land use alter soil structure at increasing rates in the Anthropocene, governing the future of global water and carbon cycles.

studies that exclusively examine pores or aggregates. However, given that soil structure deals with solids and voids, work highlighting that both aggregates and pore space are important for understanding soil functioning in a changing climate (Mangalassery et al., 2013; Kravchenko et al., 2015; Wang et al., 2019; Yudina and Kuzakov, 2019) helps to resolve such controversy. We focus on both solids and voids below.

2.1. Roots and mycorrhiza directly generate and clog pores

Roots certainly clog soil pores (e.g., Barley, 1953; Lu et al., 2020). For example, fine roots tend to grow along pores between the soil particles, effectively clogging them (Bruand et al., 1996; Maggi and Porporato, 2007; Koebernick et al., 2017). Roots also can reduce interparticle pore space and thus fluid permeability if root growth results in macroaggregate cracking (Banwart et al., 2019). However, the role of roots and their mycorrhizae in promoting pore generation and water flow appears more dominant than the effects of clogging and permeability reductions. Roots can promote flow through multiple means: 1) at the root-soil interface through the development of saturated films on the outer root surface or along the inside of the pore walls after root shrinkage (Bogner et al., 2010); 2) by promoting biopores as roots die and decay, generating a connected network of pores (Angers and Caron, 1998; Zhang et al., 2015; Lucas et al., 2019); 3) by encouraging leaching that can further modify biopore walls through deposition and accumulation of clay films, enhancing their ability to transport water and solutes deeper into the critical zone (Sigen et al., 1997); and 4) by creating pore networks to depths that enhance the drainage of saturated soil moisture (D'Odorico et al., 2012; Viglizzo et al., 2015; Pawlik et al., 2016), possibly shifting vegetation community structure to rely more heavily on deeper water sources. Finally, depending on moisture conditions, high densities of fine roots and associated mycorrhizae can directly influence aggregate formation by physically enmeshing primary soil particles or indirectly by supplying large inputs of organic matter that provides substrate to effectively glue particles together (Jastrow et al., 1998; Gyssels et al., 2005; Rillig et al., 2015). The results of these processes often create soils with granular structure (i.e., visible structural units or peds described in the field from an excavation wall that are approximately spherical in shape) that promote water movement (Oades, 1993; Mohammed et al., 2020). Indeed, because roots and mycorrhizae can generate soil macropores (Noguchi et al., 1997), small changes in rooting-depth distributions can significantly alter soil hydrologic fluxes (Watson and Luxmoore, 1986; Noguchi et al., 1997; Beven and Germann, 2013), even without altering the proportion of water that roots remove to meet transpiration demand, by opening hydrologic flow paths. Recent work highlights how human-induced land use change can prompt surprisingly deep and persistent changes in root abundances and associated soil structure (see Box).

Given the importance of roots and their mycorrhizae in governing soil pore space via their influence on soil organic matter and water cycles, it is logical that root turnover rates are important determinants of soil pore space. Root turnover rate constants, typically calculated as belowground net primary productivity (BNPP; $\text{g m}^{-2} \text{yr}^{-1}$) divided by standing root biomass (g m^{-2}), vary across ecosystems, climate histories, and soil depth. In grassland systems, root turnover is highest in the top 10 cm of the soil profile and varies across short timescales according to wetting and drying events (Hayes and Seastedt, 1987). Turnover varies within season, as root growth occurs following rain events and root mortality occurs as the soil dries (Hayes and Seastedt, 1987). Root turnover also varies across years, with greater turnover typically occurring in dry years ($\sim 40\%$) compared to wet ($\sim 25\%$) for a mesic temperate grassland (Hayes and Seastedt, 1987). Globally root turnover varies across biomes with the greatest percent turnover in the tropics ($> 60\%$ for all vegetation types), and the lowest rates in high latitude locations and for the coarsest woody roots (Gill and Jackson, 2000). Given fine-root lifespans ranging from ~ 100 to 350 d (multiple temperate

species; McCormack et al., 2012; Adams et al., 2013) and root survivorship exhibiting distinct trajectories due to nutrient availability on a timescale of days (Adams et al., 2013), it is no surprise that physical sculpting of the subsurface by roots can happen quickly as roots respond to changing environmental conditions. Longer-term changes are also important to consider: One precipitation-manipulation experiment (35% increase in precipitation) in grasslands found increased near-surface rooting densities when precipitation was increased over a 22-year period, which led to decreased rates of infiltration by $\sim 30\%$ (Caplan et al., 2019). Such studies help explain decadal-scale changes in soil structure linked to altered deep root abundances with land use change (see Box). In short, root turnover varies widely among biomes and tree species, reflects both short and long-term climate histories, and—perhaps most importantly for the biogeochemical implications of such changes—varies by soil depth. These differences have the potential to alter both the types and residence times of carbon in the soil, as well as modify infiltration pathways that accentuate wetting and drying soil profiles and subsequent modifications of the local hydrological cycle.

2.2. Roots influence pore generation and clogging and indirectly influence aggregate stability by altering subsurface moisture conditions

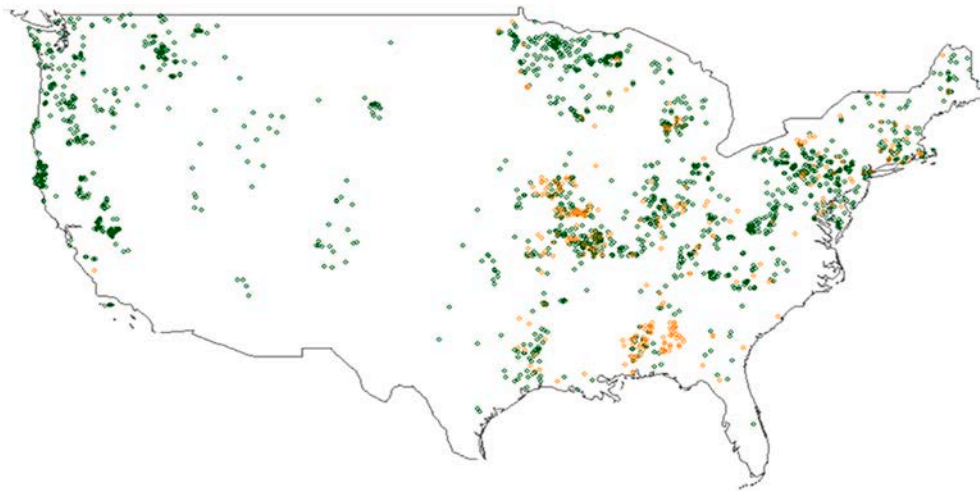
By changing the moisture regimes in the subsurface, roots can induce wet-dry cycles that control shrink and swell processes and may play an important role in forces that drive aggregate formation. Deep roots can promote the uptake of water from the subsurface (Schenk and Jackson, 2005), which can result in large amounts of water transferred from the soil to the atmosphere (Muench et al., 2016; Schwärzel et al., 2020; O'Keefe et al., 2020), even when water is transported to greater depths in the presence of deep preferential flow paths (Vero et al., 2018). The withdrawal of water from the soil profile induce wet-dry cycles that can promote aggregation, particularly when sufficient carbon substrates are available (Muneeb and Oades, 1989; Angers and Caron, 1998; Denef et al., 2001; Cosentino et al., 2006; Park et al., 2007; Bravo-Garza et al., 2009). This suggests that roots may promote aggregation through an alteration of soil hydrodynamics. Other studies suggest the opposite or are inconclusive (Utomo and Dexter, 1982; Singer et al., 1992; Degens and Sparling, 1995; Bronick and Lal, 2005), but regardless of the direction of change, the physical mechanisms driving apparent continental-scale changes to deep soil structure with a reduction in root abundances (see Box) are not well understood and need to be elucidated.

If changes in wet-dry cycles promoted by modification in rooting depths alter soil aggregation processes, the degree to which those potential changes influence soil structure is likely impacted by clay mineralogy. For example, where 2:1 clays dominate (i.e., clays with two tetrahedral sheets to one octahedral sheet), wet-dry cycles may prompt swelling and shrinking, disrupting aggregates (Singer et al., 1992) via bursting upon air becoming trapped within an aggregate during wetting, or differential swelling of clay minerals (Le Bissonnais, 1996). In contrast, where 1:1 clay minerals dominate, clay particles may disperse during wetting (Oades, 1984), but appear to undergo increased bridging between clay particles upon drying (Attou et al., 1998) that results in aggregate formation, especially of mid-sized to larger aggregates (i.e., between 0.5 and 1.0 mm in diameter; Singer et al., 1992). This behaviour of 1:1 clay minerals is consistent with conventional surface chemical theory that describes pore fluids as exhibiting high ionic strength; evaporative or transpirational loss of pore water, then, favors particle bridging through a decreasing of the thickness of the electrical double layer and associated enhancement of colloidal attractive forces binding particles together (Essington, 2015). Thus, the interaction of roots with the mineralogy of the soil matrix surrounding them can dictate the formation, durability, and collapse of soil aggregates and thus modify soil pore geometries.

Using observational data to probe the role of biota in governing soil fabric dynamism

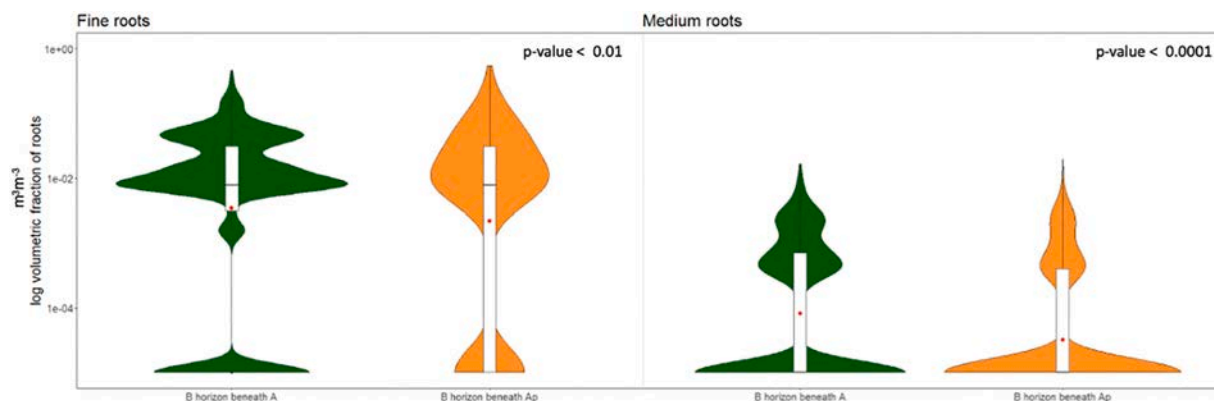
We can leverage the Pedogenic and Environmental DataSet (PEDS), which contains laboratory and field soil morphological data from over 48,000 pedons collected by the USDA Natural Resources Conservation Service (NRCS), National Cooperative Soil Survey (NCSS) (Mohammed et al., 2020; Koop et al., 2020). Morphological data include the designation of soil horizon (layer) boundaries, colors, texture, structure, consistence, and roots among others (for a comprehensive list of these types of data see (Schoeneberger et al., 2012)). We use this tool to explore B horizons (within depths of 30 to 100 cm) of pedons supporting forested lands with and without Ap horizons (Box Fig. 1). We select these pedons from the larger PEDS database for two reasons. Contrasting B horizons beneath A vs. Ap horizons can provide hints about the depths to which roots and soil-structural attributes can be modified by surficial disturbances. Presumably, soils with Ap horizons have at one point had natural root systems disturbed. Further, focusing on pedons where land cover was forest at the time of sampling allows us to make inferences about the persistence of any effect of presumed rooting density changes imposed by agriculture, because forests growing on Ap horizons have taken multiple decades to develop.

Box Fig. 1 Distribution of pedons in now forested ecosystems where the influence of plowed (Ap horizons; orange) and non-plowed sites (A horizons; green) on rooting and pore distributions could be compared in B horizons.



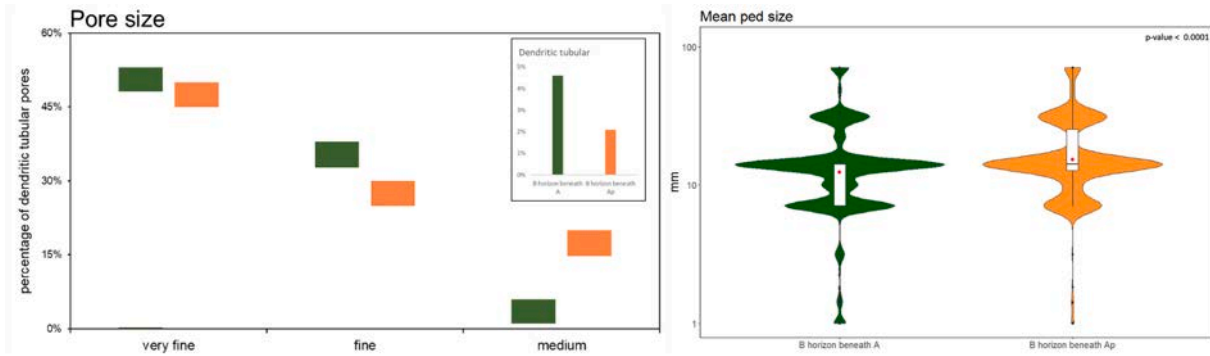
Pedon data within PEDS reveal that B horizons beneath Ap horizons have lower densities of very fine and fine roots (Box Fig. 2; significant differences at $p < 0.05$). In addition, violin plots reveal differences in the distribution of the data. For example, in B horizons beneath A horizons, fine roots (left panel in Box Fig. 2) exhibit a multi-modal distribution compared to the smoother, bulb-shaped distribution of the top of the violin representing B horizons beneath Ap horizons.

Box Fig. 2. Volume fraction root distributions for fine (left) and medium (right) roots in B horizons under A (green) and Ap (orange) horizons in currently forested ecosystems. Here, fine roots are defined as 1 mm to less than 2 mm in diameter and medium roots as 2 mm to less than 5 mm diameter.



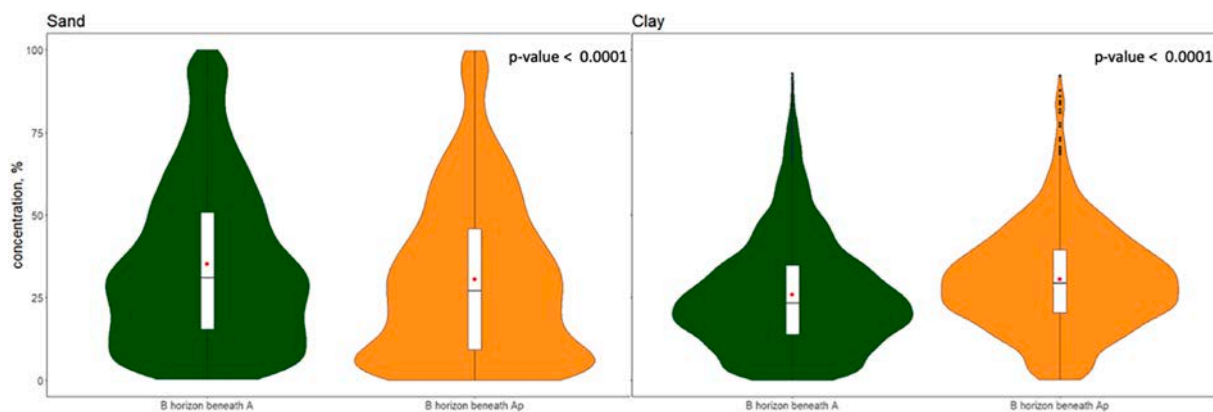
If roots are important agents of soil pore generation, we might expect to see a decline in relatively small pore sizes with a lower density of the smallest root size classes. Indeed, this is the case: dendritic tubular pore (typically considered to be created by roots; (Soil Science Division Staff, 2017)) sizes also appear to differ between B horizons beneath A vs. Ap horizons (Box Fig. 3), with an overall greater abundance (inset figure 3) in small to fine classes for B horizons under A horizons. Pedons with B horizons beneath Ap horizons also exhibit larger weighted ped size means (left panel in Box Fig. 3; significant differences at $p < 0.05$).

Box Fig. 3. The percent of dendritic tubular pores (left; very fine <1 mm; 1 mm < fine ≤ 2 mm; 2 mm < medium ≤ 5 mm) and the distributions of mean ped size (right; mm) for B horizons under A (green) and Ap (orange) horizons in currently forested ecosystems.



We also see a difference in soil texture when contrasting these two categories of B horizons; B horizons beneath Ap horizons exhibit greater concentrations of clay and a correspondingly lower concentration of sand (Box Fig. 4; significant differences at $p < 0.05$). We cannot know the extent to which pore size, ped-size mean, and textural differences between categories of B horizons are a reflection of selection bias vs. a result of the decline in root density or another modification imposed by historic (i.e., prior to afforestation or reforestation) agricultural practices. The likelihood of selection bias requires our inferences about biotic-soil structural linkages to be conservative, given that Ap horizons were generated on sites originally deemed worth plowing and thus likely exhibiting a multitude of differences from non-plowed sites. However, these data are also consistent with the idea that the change in density of relatively small roots imposed by agricultural disturbance create differences in soil structure that have meaningful consequences for hydrologic flow paths, solute and gas transport within and out of soil profiles, and soil development itself. These effects, if real, appear to propagate deeply, far beneath the plow line, and to persist even decades after frequent plowing disturbance has ceased.

Box Fig. 4. The distributions of sand (left) and clay (right) concentrations (%) for B horizons under A (green) and Ap (orange) horizons in currently forested ecosystems.



2.3. Microbes as agents of pore generation and clogging

Like roots, microbes can serve as agents of both pore generation and pore clogging. For example, as heterotrophic microbes induce the decay of SOC, take up assimilable compounds, and shunt some of the carbon to the respiratory pathway, SOC undergoes a phase transition to CO_2 . This process removes compounds that no longer contribute to the SOC pool, and thus contributes to void generation. This void is only partially filled with the microbial cells benefitting from these transactions because there is a net loss of carbon for each microbial transaction. Thus, microbes using SOC as an energy source serve as a key agent in soil void, or pore, generation (Poeplau et al., 2020). Whether SOC is physically available for microbial attack and subsequently lost from the system depends in large part on soil aggregates and their size distribution (Six and Paustian, 2014; Bach and Hofmockel, 2016; Qin et al., 2019) and on soil-mineral characteristics, which play an important role in the formation of mineral-protected SOC (Torn et al., 1997). An added layer of complexity results from the role of mineral surface area as a driver of formation of aggregates of different sizes and stabilities

(Fernández-Ugalde et al., 2013; Rillig et al., 2017). Thus, an intimate feedback exists between soil microbes and their capacity to promote soil voids via SOC losses, and soil structural and mineral attributes.

The functioning of soil microbes also can result in the clogging of soil voids (Vandevivere and Baveye, 1992). Soil microbial growth requires the transformation of SOC into CO_2 , organic exudates and waste products, and cell components. Those cells themselves clog soil pore space. Indeed, it is to a microbe's advantage to exhibit a high carbon-use efficiency (CUE; i.e., a robust propensity to transform assimilated carbon into biomass rather than CO_2 ; del Giorgio and Cole, 1998; Manzoni et al., 2012). Though the pool of microbial biomass is relatively small compared to the SOC pool (Liang et al., 2019) and can turn over on timescales of hours to days, bacterial and fungal necromass appears to accrue over many years to comprise a meaningful fraction of the SOC reservoir in a great diversity of soils (Miltner et al., 2012). The persistence of root and fungal necromass has been identified in boreal forests to contribute 50-70% of accumulated SOC, due in part to impaired decomposition and preservation of (particularly mycorrhizal) fungal biomass (Clemmensen et al., 2013). It is clear that above- and below-

ground plant residues that have not been transformed into microbial byproducts are a significant component of SOC pools (Angst et al., 2021), but a recent review suggests that up to 58% of the SOC pool may be comprised of microbial necromass (Liang et al., 2019). The persistence of microbial necromass is linked to compositional differences between bacterial and fungal biomass (Read and Perez-Moreno, 2003; Clemmensen et al., 2013), physical protection within soil aggregates (Tian et al., 2021) and organo-mineral associations (Wieder et al., 2014). There is a basic stoichiometric nutrient control on ecological selection of bacterial compared to fungal decomposition of plant litter and resulting necromass accumulation in soil. This control results from C:N ratios in plant litter sources, with grasses and leaves, particularly for legumes, having relatively lower C:N ratios compared to those of stems, roots and lignin-rich plants. Because of the much lower C:N ratio of bacterial biomass and therefore higher N requirements for growth compared to fungal biomass, decomposition of relatively N-enriched plant litter creates selection pressure that favours a bacterial pathway while lower N content, for example, of woody plants, is thought to favour decomposition pathways dominated by fungi (Read and Perez-Moreno, 2003; De Vries et al., 2006). Fungal necromass also tends to persist to a greater degree than bacterial necromass due to recalcitrance to enzymatic decomposition of fungal structural polymers such as lignin, polyphenols, carboxymethylcellulose and pectin. While a generalized description of mechanisms driving microbial necromass vs. plant detrital persistence remains unclear (Ahrens et al., 2020; Wang et al., 2021), we must consider that any environmental perturbation that alters microbial CUE and nutrient availability (De Vries et al., 2006; Manzoni et al., 2012; Ballantyne and Billings, 2018; Hagerty et al., 2018; Ye et al., 2019) necessarily will influence decomposition pathways, microbial growth rates and necromass production. The degree to which pore clogging results from necromass compounds is unknown and represents a frontier of soil research.

If microbes can both generate and clog soil pores, a question arises as to whether changing the composition of a soil microbiome can induce changes in these processes. The impact of abiotic and biotic perturbations on any potential tipping-points of functional and genetic diversity is a current research frontier in soil ecosystems research (Bardgett and Van Der Putten, 2014). A recent review of mechanistic linkages between vegetation biodiversity and the functioning of the soil microbiome points to the effects of shifts in vegetation to affect the quality and quantity of the plant supply of carbon, energy and organic nutrients to soil decomposer microorganisms at the base of the food web, as well as both synergistic and antagonistic plant-microbial associations including mycorrhizal fungi and plant microbial pathogens (Banwart et al., 2019). These connections suggest that climate-driven shifts in biome, particularly through changes in plant available water, will impact both the above- and below-ground biodiversity. A recent study by Bickel and Or (2020) proposes that climate – mediated by soil water status – is a major abiotic driver of soil microbial diversity and functioning. They argue that aqueous-phase extent and connectivity is a key driver for microbial diversity and soil pH; soil pH is known to influence the relative abundance of different microbes comprising soil microbial communities (Fierer and Jackson, 2006; Griffiths et al., 2011). It follows that changes to rainfall patterns (e.g., frequency, intensity) may cause shifts in microbial abundance and diversity. At the same time, known or unintended introduction of new microbial communities – as external biotic drivers – can also be catalysts of abrupt shifts in soil microbial communities. Such can occur, for example, as a result of soil translocation projects (Budge et al., 2011; Luan et al., 2014), the use of organic soil or plant improvers (Pérez-Piqueres et al., 2006), the activation of microbes in melting permafrost soils (Oh et al., 2020), or harvested peat being used as source of organic matter elsewhere (Bradford and Segal, 2009). However, it remains unclear whether altering the abundance of populations within a soil microbial community results in functional differences (Nannipieri et al., 2020).

2.4. The chemical fingerprints of life regulate soil structure

Roots and their associated microbial communities, including mycorrhizae, saprotrophic fungi, and bacteria, play a key role in aggregate life cycles by exuding and transforming chemical compounds (Banwart et al., 2019). Specifically, roots and microbes exude a diversity of carbon-rich compounds that promote soil aggregation by serving as binding agents, both in the rhizosphere and, to a lesser extent, in bulk soil (Oades, 1984; Jastrow et al., 1998; Chenu et al., 2000; Sher et al., 2020). The formation of aggregates and their stability depends on the abundance of such organic compounds, all of which interact with soil-mineral particles (Torn et al., 1997; Chorover and Amistadi, 2001; Masiello et al., 2004; Kramer and Chadwick, 2018). For example, variations in the degree of mineral weathering, governed by water-mineral interactions, will influence the propensity of organic compounds to undergo mineral adsorption. Less reactive clay minerals (e.g., kaolinite) generally provide less surface area for adsorption than less weathered, more expandable phyllosilicates (Weil and Brady, 2017; Reichenbach et al., 2021). Such adsorption serves as a key mechanism for organic matter preservation, in addition to the physical protection afforded to organic matter trapped within aggregates (Rovira and Greacen, 1957; Dignac et al., 2017). Moisture conditions interact with these processes as moisture limited environments – either due to low rainfall, plant water withdrawal, or both – can stabilize soil carbon through physical separation from reactive substrates and enzymes (Conant et al., 2011; Kleber et al., 2015). The persistence of such carbon compounds can function as an important feedback to SOC reservoirs and provide ample availability of binding agents for aggregate formation.

Importantly, some root exudates serve competing roles within the soil. Some exuded compounds can induce the dispersal of clays (Oades, 1984) and dissolution and hydrolysis of minerals, modulate soil pH (Russell et al., 2017), and alter mineral-water interactions (Hinsinger et al., 2003, 2011; Lucas et al., 2019), as well as induce the decay of organic matter (exo-enzymes; Thorley et al., 2015; Nannipieri et al., 2020; Hauser et al., 2020). Effects of root exudates on chemical weathering are well documented in ligand-promoted rate laws (Drever, 1994; Drever and Clow, 2018; Stillings et al., 1998) and in organic-metal complexation (Lawrence et al., 2014). The high concentrations of bacteria and fungi within and surrounding roots make these locations hotspots for the transformation of photosynthate into mineralized compounds (e.g., CO₂) and the exudation of organic acids. The net effect of root exudates as solutes or as CO₂ on chemical weathering and their interaction with aggregate stability also depends on the moisture content of the subsurface.

Natural production of CO₂ by roots and microbes both influences and responds to soil structure. In natural systems, CO₂ concentrations increase with depth as a result of respiration and diffusion limitations induced by water-filled pore space and soil texture (e.g., van Haren et al., 2017). These concentrations typically decrease below a depth of maximum concentration (Oh and Richter, 2005; Richter and Billings, 2015), where soil tortuosity and water content can limit its escape. Though CO₂ may diffuse into the profile due to an inversion of soil and air temperature (Roland et al., 2013; Cueva et al., 2019), most often CO₂ diffuses aboveground. These CO₂ dynamics help govern soil weathering patterns via the formation of carbonic acid. Over time, the generation of carbonic acid, especially that acid that leaches to depth, enhances soil porosity via mineral and bedrock weathering (Oh and Richter, 2004; Iversen, 2010) and helps generate the secondary minerals so critical for aggregate formation (Wilpiszeski et al., 2019). Thus, the respiratory signature of life within soil profiles can both be influenced by and influence soil structure.

3. Emerging data implicate altered soil structure as an agent of change in critical zone function

Above we presented the ways in which changes in moisture may

influence soil structure over years to decades (Robinson et al., 2016; Hirmas et al., 2018; Caplan et al., 2019). Research emanating from disciplines like ecosystem science, environmental science, and ecohydrology is also starting to implicate soil structural changes and shifts in aggregate cycling for observed patterns in watershed biogeochemical fluxes. For example, temporally evolving chemical composition of stream or ground water without obvious perturbations are consistent with soil structural changes prompting movement of different chemical species through profiles and watersheds. Chemical weathering generates dissolved products and secondary minerals altering soil development and composition of percolating waters. Monitoring of headwaters, particularly the first 10–20 ha of steep hillslope catchments (Johnson et al., 2000), can reveal changes in soil weathering within just a few decades as demonstrated by the congruent responses of stream and soil chemistry to changes in precipitation chemistry via transport of soluble materials (Armfield et al., 2019) and in response to reductions in atmospheric acid deposition (Garmo et al., 2014; Newell and Skjelkvåle, 1997; Kopáček et al., 2016). Changes in soil structure, specifically aggregates, can be demonstrated via small stream records of dissolved organic matter as decreases in ionic strength affect aggregate dispersion and can increase the release of dissolved organic matter (Cincotta et al., 2019).

There is also growing awareness of SOC transformations governing soil structure (Six et al., 2000; Stamati et al., 2013; Arnold et al., 1990; Robinson et al., 2019; Banwart et al., 2019). If environmental cues like temperature and soil-moisture dynamics change in a warming climate and SOC losses accelerate, as many studies suggest is the case (Tiemann and Billings, 2011; Manzoni et al., 2012; Manzoni et al., 2012; Soong et al., 2021), it begs the question of how soil structure may be influenced if SOC losses outpace SOC formation. It is difficult to imagine that changing transformation rates of the largest terrestrial carbon reservoir (~3000 Pg in the top 3 m; Scharlemann et al., 2014) could proceed without significant impacts on rates of pore generation and collapse. Given the important role of soil pores in ecosystem functioning, such linkages could serve as indirect, but important, feedbacks to climate. Accurate projections of such processes require knowledge of how SOC derived from relatively fresh photosynthate may influence soil structure differently than older or more microbially-derived material (Wieder et al., 2015). That is, the increase of input and output fluxes (Ziegler et al., 2017) could lead to changes in aggregate life cycles and associated pore space, even if the total pool of SOC is not changing quickly. Further adding to these ideas, the soil microbes responsible for SOC transformations and losses are also implicated in the formation of extracellular polymeric substances (EPS) and microbial necromass itself, both of which appear to serve important roles in soil moisture retention via pore clogging and in SOC preservation, respectively (Miltner et al., 2012; Liang et al., 2019; Tian et al., 2021).

In spite of new understanding of the connections between SOC dynamics, the vegetation inputs and microbial transformations that drive them, and soil structure, the impact of SOC on soil enhancing or degrading soil hydraulic properties remains largely unquantified and unexplored. Experimental data to quantify process rates and to test and develop the existing conceptual and mathematical models is extremely limited and remains a research frontier. While textbooks and common perception often associate SOC enhancements with greater soil water retention and greater hydraulic conductivity (e.g. Rawls et al., 2004; Bronick and Lal, 2005; Guo and Lin, 2018), data mining and meta-analysis efforts reveal that increased SOC has a limited effect on the water retention capacity of soil (Minasny and McBratney, 2018) and reduce the hydraulic conductivity (e.g. Nemes et al., 2005; Jarvis et al., 2013; Jorda et al., 2015; Araya and Ghezzehei, 2019). These observations have been attributed to increasing complexity and tortuosity of the resulting pores with more SOC. However, this effect appears to be nonlinear and non-uniform for soils of different texture and the phenomenon has rarely been addressed by targeted research (e.g. Wang et al., 2009; Larsbo et al., 2016).

The changes in soil structure imposed by changes in rooting distribution also result in modified critical zone functioning. Lu et al. (2020) highlight how roots can drive macro-aggregate cracking and micro-aggregate amalgamation, along with reorienting soil particles as main drivers of soil structure and hydraulic properties. Such processes are relevant to the globally observed encroachment of woody vegetation into grassland systems (Saintilan and Rogers, 2015). Here, the combination of deeper root penetration belowground and larger root diameters in woody plants can result in the formation of preferential flow paths along root wall-soil interfaces (e.g., Schreiner-McGraw et al., 2020; see the following for more details on the factors that cause preferential flow and ways to quantify it: Allaire et al., 2009; Jarvis et al., 2012; Guo and Lin, 2018). In this scenario, precipitation inputs bypassed the most superficial soil layers, moving soil moisture beyond the herbaceous rooting zone (top 1 m). These changes alter ecohydrology in favor of woody plants (Gaiser, 1952; Ghestem et al., 2011; Vero et al., 2018; Pawlik and Kasprzak, 2018). In addition, these differences in root distributions can change the geochemical responses of streams at woody encroached sites (Sullivan et al., 2019) and alter the generation of porosity (Hu et al., 2019; Hu et al., 2020; Wen et al., 2020). The effects of land use change on root depth distributions are another example. Soil compaction usually driven by agricultural practices can change the pore size distribution significantly and increase the soil density, inhibiting root penetration in these compacted horizons (Whalley et al., 1995). This possibly leads to a reduction in wetting and drying cycles deeper in the soil and consequently a loss of structure (Dexter, 1991). However, the degree to which rooting distributions change under agriculture depends on land management practices, such as conventional and no-tillage systems (Pagliai et al., 2004). Where the aboveground vegetation is removed during land conversion and roots are left in the soil to decay, preferential flow paths may be formed and can increase the soil hydraulic conductivity (Ghestem et al., 2011; Lu et al., 2020), affecting the soil geochemistry and nutrient discharge in streams.

Aquatic biogeochemists are also beginning to assess the potential of rapidly changing soil structure on aquatic environmental conditions and associated ecosystem functioning. Soil hydraulic properties control water and solute delivery to deeper mineral soils and transport to aquatic environments. Coupled with preferential flow paths, these properties control terrestrial to aquatic carbon and nutrient fluxes (Kaiser and Guggenberger, 2005; Mei et al., 2012; Terajima and Moriizumi, 2013; Burns et al., 2016) that reflect the ecosystem carbon balance (Lovett et al., 2006; Webb et al., 2019). Hydropedological units (HPUs) – distinct morphological groupings of hydrologic and biogeochemical processes (Bishop et al., 2004; Gannon et al., 2015) – are recognized for their spatial variation relevant to carbon accumulation (Bailey et al., 2014) and therefore sources of carbon for aquatic delivery (Gannon et al., 2015; Laudon et al., 2011). Aquatic biogeochemists recognize the dynamic nature of the physicochemical soil properties (i.e. soil solution chemistry), typically monitoring them at weekly to monthly scales (e.g. Gannon et al., 2015); however, they less frequently note the short-term nature of soil structure controlling hydraulic properties. This neglect of soil structural change is despite observed rapid change in water and organic matter delivery as a consequence of climate and land-use change (Bowering et al., 2020) that can impact mineral organic matter interactions controlling carbon sequestration in deeper mineral soils (Clarke et al., 2007; Fröberg et al., 2011; Kalbitz et al., 2005; Rosenqvist et al., 2010) and its delivery to the aquatic environment. For example, enhanced permafrost thawing and increased routing of surface soil-derived organic solutes into deeper mineral soils appears responsible for recent declines in dissolved organic carbon export by the Yukon River (Striegl et al., 2005). How are these rapid changes in solute fluxes in these high latitude environments likely to alter soil structure and its function?

4. Factors that have reinforced a static view of soil structure

The idea that soil structure is linked to climate had been documented by soil scientists from experimental and observational studies since at least the early twentieth century (Lipman and Waynick, 1916; Baver, 1934; Jenny, 1941). Multiple studies prompt the inference that soil structure can change rapidly as a result of environmental influences, even those reaching as far back as the Roman Empire (e.g., Columella; Olson, 1943). For example, Rice and Alexander (1938) discuss the maintenance of crumb structure via growth of grasses and legumes. The fundamental work by Lipman and Waynick (1916) documented structural changes within seven years of controlled climate manipulation. Despite this early evidence, the concept that structural changes can be induced by climate in natural systems at anthropogenically-relevant timescales has, until recently, largely been overlooked. This is even more intriguing when considering that formation of soil structure from parent material has been classified as a fast pedogenic process that takes between 1 and 100 y, depending on climatic conditions (Arnold et al., 1990; Targulian and Krasilnikov, 2007). These time estimates are supported by studies on reclaimed estuaries and dredge sediments undergoing ripening (Pons and Van der Molen, 1973; Dexter et al., 1984; Ellis and Atherton, 2003; Vermeulen et al., 2003), as well as on engineered soils (Séré et al., 2010; Jangorzo et al., 2013; Watteau et al., 2018). An exhaustive narrative describing the reasons for neglecting this knowledge is beyond the scope of this work. However, it is important to point out that the environmental science community largely relies on classical transport equations (e.g., Darcy's and Fick's laws) to solve for water and solute flows using transport coefficients (e.g., hydraulic conductivity and water retention properties) that are assumed to be static (Richter, 1987). Several features of 20th century and contemporary soil research stand out as reasons why the significance of climate-induced structural changes remains underappreciated, particularly at depth, by the various disciplinary communities working within the critical zone.

First, most of the attention paid to rapid soil structural changes has been focused on alterations to near-surface horizons in the short-term (days to months) following agricultural and land management practices. For example, rainfall or irrigation events are well known to induce rapid bulk density and macropore changes in freshly tilled soil as well as concomitant changes in soil hydraulic properties such as saturated hydraulic conductivity and water retention (Mapa et al., 1986; Schwen et al., 2011; Kool et al., 2019). Second, the effects of weather events on soil structure under tillage have been invoked to explain relatively short-term, seasonal variability (e.g., raindrop-induced breakdown of surface aggregates); sustained influence of these effects on soil structure are considered negligible (Somaratne and Smettem, 1993). Similarly, studies on the effects of freezing and thawing or wetting and drying processes on soil properties have been mostly restricted to seasonal changes (Hu et al., 2012; Jabro et al., 2014; Schwen et al., 2011) with focus paid on interannual variability. Little is known about the duration of these weather- and climate-linked influences on soil structure. Third, the changes to soil structure and macroporosity with climate or biotic modifications, especially in non-agricultural settings, are intertwined with the effects of other influential factors such as texture and chemical composition and obscured by the large spatial heterogeneity in many soil characteristics. The extreme nature of such heterogeneity is well-represented by soil water retention curves: Hirmas et al. (2013) observed as much variation in water retention between six samples representing a single horizon as across the entire continental-scale UNSaturated SOil hydraulic DATabase (UNSODA).

Nevertheless, the effects of climate and other important variables on soil structure can be untangled using databases collected with uniform methodology and with a wide spatial coverage (Hirmas et al., 2018). At the site scale, changes in soil structure with climate modifications are often subtle. For example, Caplan et al. (2019) report a change of less than 2% of the total pore soil volume induced by a 25-year irrigation treatment across a range of pore sizes spanning 0.3 to 1000 μm in

diameter. Because the magnitude of this change falls well within observed variability of soil porosity values (Nielsen et al., 1973), such changes are likely to be underreported. Though technology in the 20th century was not sufficiently sensitive to detect small, sustained changes in structure induced by climatic shifts, recent use of tension infiltrometry (e.g., Caplan et al., 2019); development of better in situ, high-resolution 2-D imaging techniques (e.g., Eck et al., 2013; Bagnall et al., 2020); and increased application of X-ray computed tomography (Taina et al., 2008) all indicate that even small shifts in soil structure can be reliably quantified, allowing discovery of sustained changes. These advances are important, and can eventually give way to constitutive equations that can represent soil structure as a dynamic property. For example, recent modelling and simulation developments are starting to couple soil flow and transport processes to soil structure dynamics, shedding light on how these dynamically alter soil hydraulic properties and how soil structure and hydraulic properties are influenced by factors in soil aggregation, such as vegetation input and microbial decomposition of SOC (Giannakis et al., 2017).

A final roadblock that may hinder the treatment of soils as dynamic compared to static is the way in which experiments often are designed in many plot-, watershed- and ecosystem-scale studies that could otherwise help us develop an understanding of the interactions among soil physical and chemical properties. Many soil features, important for ecosystem function – especially those in deep soil – are not considered to change on the short timescales of most studies, and are often not monitored in studies that last years to decades. Total stocks of organic matter and mineral-bound resources are assumed to change only on decadal to millennial timescales. For example, except in studies intended to extend for multiple years to decades, SOC is typically quantified once to characterize a site (Billings et al., 2021), often only to 30 cm (Post and Kwon, 2000; West and Post, 2002). In contrast, features such as concentrations of plant- and microbially-available nitrogen (and other nutrients) are commonly acknowledged to be transient, and are often quantified much more frequently (daily, weekly). Though the transformations of mineral-bound elements to bioavailable forms can happen on momentary timescales and their cumulative effects can be observable over years to decades (Hauser et al., 2020; Austin et al., 2020), deep mineral stocks observed in many soil profiles are assumed to change over millennia, a view supported by ecosystem and geologic hypotheses (Walker and Syers, 1976; Vitousek et al., 1997a). This paradigm of multiple soil chemical and physical attributes only slowly changing is inherited by soil structural attributes, as is evident in thousands of ecosystem-scale and plot-scale studies exploring environmental perturbations. For example, elevated CO_2 and soil and/or ecosystem warming studies conducted over years to decades often report nutrients as fluctuating in availability over seasons and years (Nadelhoffer et al., 1984; Finzi and Schlesinger, 2003; Melillo et al., 2011) while soil features such as aggregate structure (cf., Rillig et al., 2001) and pore geometries are assumed invariant, either explicitly or implicitly.

5. Quantifying soil structural changes and their impacts on water, energy, and carbon fluxes

To test the proposed rule of life hypothesis and quantify soil structural changes and their implication, we need to measure and model changes in factors that control SOC dynamics, the aggregate life cycle, soil structure, and pore distributions. We first focus on the methods to measure pores and aggregate life cycles. Due, in part, to the challenges of quantifying metrics of soil solids and pores and their arrangement, we highlight a set of studies selected as exemplars of the most relevant and tractable methodologies (Table 2). Once quantified these measurements of soil structure, aggregate life cycle and pore distributions can be linked to soil hydrologic properties through pedotransfer functions (see reviews by Lin, 2003 and Terribile et al., 2011), allowing us to explore the impact of soil structural changes across multiple scales. We then explore how these new measurements and relationships can be used to

Table 2

Examples of measurements used to explore the biotic impacts on aggregate life-cycles and water and carbon fluxes. Sources selected below are examples of the types of methods discussed to quantify soil structure.

Method	Scale	Measures	Sources
Spatial arrangement of soil aggregates, pore networks, and their relation to soil constituents			
X-ray computed tomography (CT)	Aggregate to core	Quantitative characterization of soil macro- and micro-aggregates internal structure as well as their associated pores, and provides direct geometric visualization of soil pore space	Ketcham and Carlson, 2001; Wildenschild et al., 2002; Deurer and Clothier, 2005
Multi-stripe laser triangulation scanning (MLT)	Ped to pedon	Profile-scale soil architecture at sub-millimeter resolution including measures of soil macroporosity, conduits for preferential flow, and aggregate size variability and the influence of tillage on soil structure	Hirmas, 2013; Eck et al., 2013; Hirmas et al., 2016; Bagnall et al., 2020
Proximally-sensed hyperspectral imaging (HSI) spectroscopy	Ped to pedon	Concentrations of heavy metals and organic matter composition at high spatial resolution; used to develop proxies of soil aggregate stability	Vohland et al., 2009; Peltre et al., 2011; Cañasveras et al., 2010; Hobley et al., 2018
Soil water retention curves (laboratory, or field in situ pore pressure and moisture sensors), mercury porosimetry, gas adsorption, inert gas diffusion dynamics	Core	Indirectly, soil pore size distributions	Amer et al., 2009; Yoon and Giménez, 2012; Jozefaciuk et al., 2015; Duwig et al., 2019; Ibrahim and Horton, 2021;
Aggregate life cycles			
Rare earth element (REE) labeling	Aggregate	Rate at which aggregates are generated and lost in varying experimental conditions	Zhang et al., 2001; De Gryze et al., 2006; Peng et al., 2017
Stable isotope labeling	Aggregate	How in situ carbon-rich compounds may serve as binding agents vs. Nourishment for microbes	Kramer et al., 2010; Billings and Ziegler, 2008
Distinguishing carbon pools			
Physical separation through density fractionation	Particles to aggregate	Free-light, aggregate, and mineral-associated SOC fractions	Sohi et al., 2001; Poirier et al., 2005; Six and Paustian, 2014
Chemical extraction	Molecular to aggregate	Soil organic matter associated with hydrolysis, desorption, and oxidation	Baldock and Skjemstad, 2000; von Lützow et al., 2007; Kögel-Knabner et al., 2008
Nuclear magnetic resonance (NMR)	Molecular	Constituents of total SOC non-destructively	Hockaday et al., 2009; Warren and Ziegler, 2017
Thermogravimetric analysis, scanning calorimetry	Molecular	Quantitative analysis of the fractions of inorganic and organic C compounds in soil	e.g. Lopez-Capel et al. (2005).
Pyrolysis gas chromatography mass spectrometry	Molecular	Molecular fingerprint of SOC organic compounds	e.g. Miralles et al. (2015)

parameterize and incorporate dynamic soil structure into models (Fig. 3; Table 3).

5.1. Empirical approaches for quantifying soil structure, aggregate life cycles, and their relationship to SOC

There are multiple techniques for quantifying soil structure, aggregate life cycles, and their relationship to SOC (Table 2). Although there is a long and rich history in soil micromorphology techniques that describe and quantify soil structure from thin sections (e.g., Kubišna, 1938; Brewer, 1964; Jongerius et al., 1972; Stoops, 2018; van der Meer and van Mourik, 2019), here we focus on those more recent and emerging techniques to highlight the diversity of approaches available. In particular, X-ray computed tomography (CT; Ketcham and Carlson, 2001; Wildenschild et al., 2002; Deurer and Clothier, 2005), high-resolution three-dimensional scanning [e.g., multi-stripe laser triangulation scanning (MLT); Hirmas, 2013; Eck et al., 2013; Hirmas et al., 2016; Bagnall et al., 2020], and proximally-sensed hyperspectral imaging spectroscopy (HSI; Vohland et al., 2009; Peltre et al., 2011; Cañasveras et al., 2010) have made it possible to quantitatively describe the internal spatial arrangement of soil aggregates, structural variability, pore networks, and their relation to soil constituents (e.g., binding agents such as soil organic matter, iron, and roots) at the horizon to pit-scales. These techniques overcome the limitations of indirect methods used to quantify soil pore space (e.g., soil water retention curves, mercury porosimetry, nitrogen adsorption; Nagpal et al., 1972; Dexter, 1988), which can miss important data on the near-saturated end of water retention curves where changes to soil structure would otherwise be detected. Together, HSI and MLT allow quantitative descriptions of soil architecture, biological and hydrological features, and chemical constituents to be integrated, thus advancing our understanding of the mechanisms underlying soil development. The resulting chemomaps

from these HSI techniques can be used to investigate the spatial distribution of chemical constituents and roots using geostatistical metrics and correlated to information of soil structural units and macropores arising from MLT (e.g., Hirmas et al., 2016).

At a finer scale, CT overcomes a major drawback of MLT, by providing a 3D image compared to the 2D characterization provided by MLT (Rabot et al., 2018). CT has been used to characterize soil pore dynamics under different agricultural management and land use (Pires et al., 2017; Singh et al., 2020, 2021; Singh et al., 2021). When coupled with experimental manipulations (e.g., incubations of soil; e.g., Kravchenko et al., 2015), CT scans can reveal how pore-size distributions influence carbon loss and alter the overall soil porosity. Indeed, many of the recent advances in our understanding of how soil structural changes influence macropore networks has arisen from CT scans (Jarvis et al., 2016). These CT measurements of pore distributions can then be linked to soil hydraulic properties (e.g., Koestel et al., 2018), helping to connect drivers with changes in both the solid and void matrix of the material.

To quantify the aggregate life cycles, new empirical tracer techniques have started to emerge that provide rates for aggregate formation and collapse, and the associated carbon transformations. For example, individual rare earth elements (REEs) can be added to aggregates of different sizes and those aggregates then mixed to comprise a soil sample. Incubating such soil samples under different controlled environmental conditions in the laboratory, followed by subsequent measurement of REE concentrations in different aggregate sizes, allows investigators to compute the rate at which aggregates were generated and lost in experimental conditions (Zhang et al., 2001; De Gryze et al., 2006; Peng et al., 2017). Such experiments require multiple separations of soil samples into distinct aggregate sizes and arguably are not conducted under natural conditions, but they provide insight into aggregate life-cycle dynamics with varying independent factors. Aggregates can also be isotopically labeled (i.e., ^{13}C -enriched) to understand how in situ

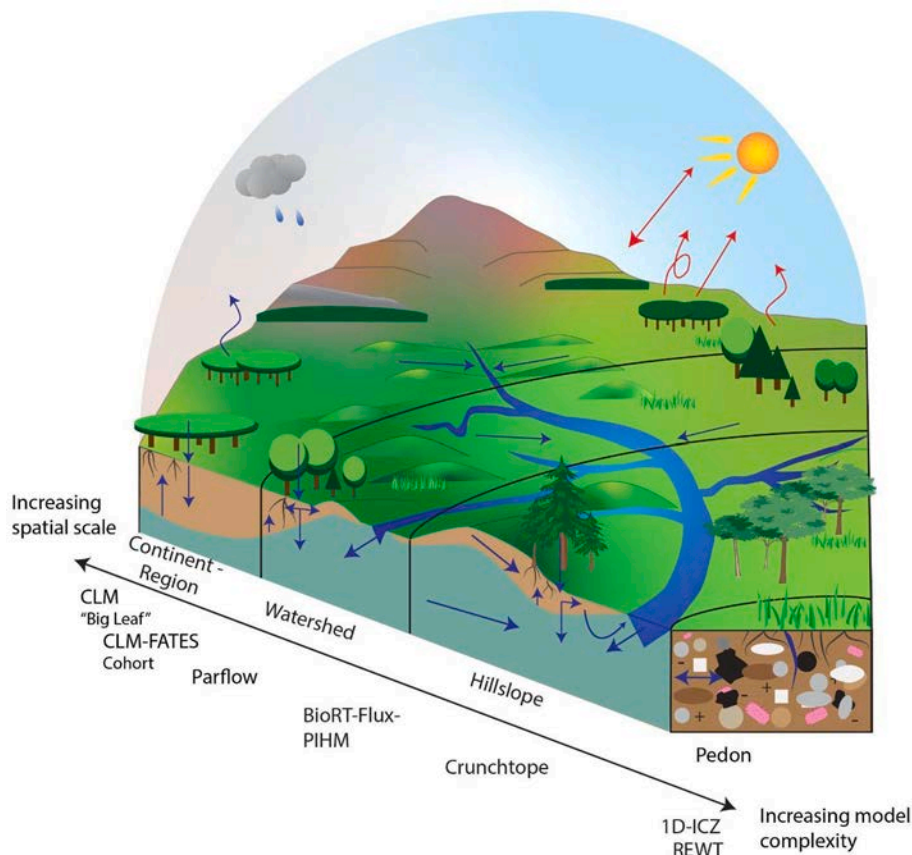


Fig. 3. Schematic of a conceptual land surface representing various spatial scales and processes in land surface, hydrological, and reactive transport models. These scales range from the largest (region to continent) to the smallest (pedon). Example models at their relevant scale are depicted in Table 3; note that several of these models are coupled across scales. The figure emphasizes the nested nature of models' spatial scales, and implies how biogeochemical and biogeophysical processes at one scale could impact processes at larger or smaller scales.

carbon-rich compounds may serve as binding agents versus nourishment for microbes. Combined, the use of REEs with stable-isotope labeling approaches can offer a way forward to understanding the rates at which aggregates form and collapse, and thus the rate at which pore geometries can change. Quantification of these rates across varying soil types and environmental conditions may provide the parameters by which aggregate dynamics can be incorporated into numerical models.

To quantify the role of SOC in aggregate cycling and soil structure formation, it is important to distinguish the different pools of carbon through the ease of microbial decomposition, constraints by the functional groups present in constituent organic matter, the energetic pay-offs to those microbes for accessing particular compounds, and physical ease of access to these forms of SOC (Six et al., 2006; Lajtha et al., 2014; Lavalley et al., 2020; Gmach et al., 2019). Common methods of separating SOC fractions range from physical separation through density fractionation to chemical extractions (Table 2; Kögel-Knabner et al., 2008). From these separations, ultra-fine-scale (nanometer) mass spectrometry can be conducted to identify the functional groups present in SOC by comparing the ratios of hydrogen to carbon and oxygen of the organic compounds present in soil, highlighting the availability of SOC fractions to decomposition in micropore spaces (Bailey et al., 2017). Additionally, nuclear magnetic resonance (NMR) spectroscopy can also be used to assess the constituents of total or fractionated SOC in a non-destructive manner (Hockaday et al., 2009), while larger-scale imaging techniques such as scanning transmission X-ray microscopy and Fourier-transform infrared spectroscopy preserve micro- and macro-aggregate structure while characterizing the spatial structure in the chemical state of SOC (Kleber et al., 2015; Vaz et al., 2014). While these methods give fine-scale estimates of the state of carbon and its chemical nature, their true power in explaining biogeochemical processes emerges when they are coupled with measurements of soil respiration under varying environmental conditions such that the rates of carbon

fluxes can be determined and incorporated into models (Billings et al., 2012; Bailey et al., 2018).

Applying these methods within the context of field-based experiments is likely to add significantly to our understanding of soil structural shifts through the Anthropocene (e.g., Caplan et al., 2019). However, one of the difficulties in using current ongoing field experiments is that pre-experimental characterizations of soil structure utilizing these quantitative metrics are rare although there are promising exceptions such as the work of Jangorzo et al. (2018); Watteau et al. (2019); and Koestel and Schlüter (2019). Therefore, we argue for greater attention in CZ research to long-term studies that incorporate these quantitative metrics of soil structure.

5.2. Models that can simulate soil structural changes and hydro-biogeochemical impacts

The key to capture soil structural changes and their impact on water, carbon and nutrient fluxes is to represent processes that control soil structure and aggregate cycling (see section 4) in models at various spatial scales and with differing degrees of complexity (Fig. 3; Table 3). As emphasized above most models represent soil hydraulic properties and rooting dynamics static in time. Below we outline and suggest improvements to models that simulate diverse spatial scales of land surface, hydrological, and biogeochemical processes, and that have the potential to be parameterized appropriately to help address some of the knowledge gaps we outline above. We highlight where empirical studies could improve model parameterization, and encourage the linking of different models to address synthetic questions across multiple scales. By nesting these models at different scales, we can learn how biogeochemical and biogeophysical processes at one scale could impact processes at others.

An important way forward for gaining insight about biotic influences

Table 3

Examples of models used to explore the biotic impacts of the aggregate life-cycle and impacts on water and carbon fluxes.

Model	Scales	Model Type	Advantages	Disadvantages	Example Questions	Example publications
DyRoot		root growth model	Simulating root growth, architecture (i.e., fine and coarse roots), and distribution driven by soil water and nitrogen availabilities	Intensive parameterization	How does water and nutrients drive the root growth rates and the root structure (depths, density, coarse versus fine)	Lu et al., 2019
1D-ICZ	Pedon	RTM	1D reactive transport with soil aggregation and nutrient dynamics and plant growth. Dynamic linking of aggregation to hydraulic properties	Intensive parameterization	How does carbon addition affect the particle size distribution, bulk density, porosity and hydraulic conductivity of the soil? What is the turnover times of the various carbon pools? How does tilling affect soil structure and carbon sequestration? How fast can we restore soil functions in degraded soils?	Giannakis et al., 2017 ; Kotronakis et al., 2017
REWT	Pedon	RTM	Simulating interactions between root exudation, transport, nutrient absorption, and coupled microbial processes a validated ecohydrologic model	Intensive parameterization	How does climate influence root exudation and soil carbon processes?	Roque-Malo et al., 2020
Crunchtope	Pedon/ Hillslope	RTM	Detailed representation of processes and soil structure and property heterogeneity	More detailed representation means more data requirement; cannot represent short term climatic conditions	How does subsurface structure and long-term property evolution regulate transformation and transport of carbon, nutrients, and other elements? Can deepening roots accelerate chemical weathering?	Wen et al., 2021 ; Xiao et al., 2021
BioRT-Flux-PIHM	Watershed	RTM	Integration of watershed hydrology and biogeochemical reactive transport processes	Data hungry; equifinality; computationally expensive when running in spatially explicit mode	How do climate conditions and a dynamic soil structure impact terrestrial carbon balance and export?	Zhi et al., 2019 ; Wen et al., 2020 ; Zhi et al., 2020
ParFlow	Watershed/ Regional	Hydrologic	Fully integrated surface water-groundwater model	Computationally intensive, lack of subsurface data to parameterize them	How do subsurface structure and properties impact land surface-subsurface coupling and water budget partitioning?	Kollet and Maxwell, 2008 ; Schreiner-McGraw and Ajami, 2020
CLM/CLM-FATES	Point/ Regional/ Continental	Land-Surface Hydrologic with connectivity to ESMs	Point or continental scale, integrates land-atmosphere and soil interactions	Computationally intensive. Soil thermal and hydraulic properties assumed from weighted average of mineral and SOM of soil (homogeneous).	Does a dynamic soil structure reduce the range (uncertainty?) in atmosphere-terrestrial C exchange predictions?	Wieder et al., 2019

RTM = Reactive Transport Model; ESM = Earth System Models

on soil structure is to develop models that can account for the temporal dynamics of rooting distributions and their 3D hydraulic architecture ([Couvreur et al., 2012](#)). Existing models often deem these characteristics static ([Lu et al., 2019](#)). Some models use empirical equations to estimate increases in rooting depth by considering the maximum rooting depth ([Gayler et al., 2014](#)). Process-based models such as DyRoot simulate the 3D root growth and distribution based on available soil water and nitrogen ([Lu et al., 2019](#)). R-SWMS ([Javaux et al., 2008, 2013](#)) is a 3D physically based root-soil water model that couples the 3D Richardson-Richards equation for simulating soil-water flow ([Richardson, 1922](#); [Richards, 1931](#)) and the Doussan equation with given 3D root-system hydraulic architecture ([Doussan et al., 1998](#)). The model can estimate 3D plant water-uptake distribution based on water-potential gradients between roots and soil and can simulate solute transport in soils and roots ([Dunbabin et al., 2013](#)). In addition, R-SWMS provides a means to understand how changes in wet-dry cycles and carbon dynamics such as root exudates may impact soil structure.

Although our current understanding of the physics of soil structural formation needs improvement, as the mechanisms and rates of soil structural change and root growth become more readily available, these

functions can be incorporated into models to simulate dynamic soil structure. Two models bringing us closer to this possibility are the 1D-Integrated Critical Zone model (1D-ICZ; [Giannakis et al., 2017](#)) and Root Exudation in Watershed-Scale Transport (REWT; [Roque-Malo et al., 2020](#)) model. The 1D-ICZ includes reaction networks that account for soil aggregation and structure dynamics, SOC dynamics and chemical weathering kinetics and bioturbation, plant productivity and nutrient uptake, water flow and solute transport and introduces the dynamics linking soil structure and hydraulic properties by allowing a pedo-transfer function to depend on fluctuating proportions of water stable aggregates, bulk density, and organic matter content. While this model does account for root and fungal exudates' influence on soil weathering processes, REWT incorporates the processes of root exudation, nutrient absorption, and microbial processes into an ecohydrologic model implemented currently with 1D vertical transport ([Roque-Malo et al., 2020](#)). Next steps forward should be to validate how these models capture root growth and exudation processes by collecting data that quantify the impact of root dynamics on aggregate stability and comparing them to model results. A logical progression then may be able to explicitly integrate how 3D root growth and exudation processes

control aggregate stability, perhaps leveraging root growth projections via R-SWMS, root exudation from REWT, and soil structural changes implemented in the 1D-ICZ model. Unfortunately, detailed studies that may provide the empirical basis for such advances are still missing.

Integrated hydrologic models such as ParFlow solve the 3D Richardson-Richards equation across the entire subsurface, and the shallow water equation at the land surface (Kollet and Maxwell, 2006). This approach offers another platform to examine the impact of changing biotic conditions on soil hydraulic properties and on water fluxes, though additional empirical data are needed to represent dynamic soil structure. ParFlow can be applied from watershed to continental scales (Maxwell et al., 2015), allowing us to quantify the impacts of soil structural changes on hydrologic fluxes at different spatial scales. Such models have also been coupled to the Common Land Model (CLM 3.0; Dai et al., 2003) to simulate terrestrial hydrologic processes, and therefore allow us to simulate processes from the top of the canopy to the lowest reaches of aquifers (Kollet and Maxwell, 2008). Thus, this modeling approach offers a means to capture how changes in soil structure can feed back to biotic and hydrologic processes. The most recent versions of CLM (now the Community Land Model versions 3.5 and higher) when coupled with ParFlow to represent groundwater dynamics can represent subsurface hydrologic processes, and as such can be used to explore the possible ramifications of changing climatic conditions on critical zone behavior at continental scales. CLM applications have advanced representation of 1) microbially modulated soil carbon dynamics (Wieder et al., 2014), 2) plant hydraulic stress and associated relationships with primary productivity (Kennedy et al., 2019), 3) hillslope-scale topography and its role in constraining moisture transport within watershed systems (Fan et al., 2017; Swenson et al., 2019) and 4) dynamic vegetation models [e.g., Functionally Assembled Terrestrial Ecosystem Simulator (FATES)] that consider competition for resources (Fisher et al., 2018).

When CLM is coupled with FATES, it is possible to represent spatial vegetation patterns as dynamic, allowing terrestrial land surface energy, nutrient, and hydrological fluxes to respond to changing biotic conditions. FATES represents multiple plant functional types (PFTs) at the patch level, which allows for different rooting depth profiles and their weighted distribution to estimate plant water stress. Water stress influences primary productivity and change in plant carbon allocation, all of which impact the amount of organic matter added back into the soil column. The representation of plants, roots, and nutrient allocation within FATES would provide a means to capture how biotic processes can alter soil structure. This new and still-developing suite of tools holds promise for conducting continental- and global-scale experiments to assess the multiscale interactions of root depth, soil structural changes, and form and function in Earth System Models (Pierret et al., 2016; Fan et al., 2017; Banwart et al., 2019; Drewniak, 2019). At these large scales, pedo- or pedon-transfer functions that incorporate biotic and climatic variables are promising and computationally inexpensive, such that they enable the incorporation of soil feedback to changing environmental conditions. Yet, data that links rooting dynamics to soil structure under varying climatic conditions are essential to generate these functions to better represent critical zone-climate feedbacks.

To more broadly investigate how changing soil structure can result in altered biogeochemical fluxes and patterns of soil development at pedon to hillslope and watershed scales, reactive transport models (RTMs) offer the ability to explicitly include biogeochemical reaction processes to understand how internal structure and external drivers alter carbon and weathering fluxes that control soil structure (e.g., Li et al., 2017; Li et al., 2021; Sullivan et al., 2020). RTMs can specify processes and timescales of interest. RTMs such as CrunchTope (or CrunchFlow) (Steeff and Lasaga, 1994), a widely used reactive transport code, can represent detailed soil and rock property distribution and can simulate the long-term evolution of the subsurface under “averaged” hydroclimatic conditions (Wen et al., 2021; Xiao et al., 2021). Calibrated models can be used to carry out numerical thought experiments to

predict watershed hydro-biogeochemical functioning responding to changing climate conditions. These models can update soil properties (e.g., porosity and hydraulic conductivity) based on mass and volume change of the solid phase due to reactions such as weathering and microbial growth, therefore simulating long term evolution of soil, hydrological, and biogeochemical changes (Li et al., 2010; Vilcaez et al., 2013). Watershed-scale models, such as the BioRT-Flux-PIHM code, simulate interactions between land surface, watershed hydrology, and reactive transport at minutes to decadal scales (Bao et al., 2017). They integrate watershed characteristics such as topography, vegetation, and temporal hydroclimatic variations with relatively coarse representation of subsurface structure to predict weathering rates and fluxes as well as carbon dynamics (Li, 2019; Zhi et al., 2019). Currently, representation of porosity distributions in these models do not update to change the hydraulic properties in a dynamic manner; rather, the models must be paused and a new parameter space assigned such that the physical structure can evolve in phases or steps with the biogeochemical processes. Devising RTMs whose parameter values evolve throughout model runs as a result of internal feedbacks offers an important way forward for those interested in investigating how soil structure governs regolith permeability and associated weathering and solute fluxes.

New concepts such as ‘digital twinning’ (Tao and Qi, 2019) might be useful to develop models that better incorporate a dynamic structural component for soil modelling. A digital twin is defined as ‘a computational model (or a set of coupled computational models) that evolves over time to persistently represent the structure, behavior and context of a unique physical asset such as a component, system or process’ (AIAA, 2020). Increasingly used in industry and engineering, the concept might be usefully applied in soil science. If the soil is viewed as the physical asset, then its twin is its model representation. The two coupled dynamical systems then co-evolve over time through their respective state spaces (Kapteyn et al., 2021). The digital twin is data driven, meaning sensor information regarding soil structure can be used to update the model at each iteration. The digital twin concept can be advantageous when the physical state space encapsulates variation in the state of the asset and could thus be a complex high-dimensional space and the physical state is typically not fully observable (Kapteyn et al., 2021), both of which are often the case for soils. Embracing these types of data model integration and feedback approaches (Blair et al., 2019) may lead to new ways of quantifying soil processes and uncovering hidden or unseen states occurring through feedbacks.

6. Conclusions

Soil structure is dynamic, responding to alterations in climatic and land cover conditions on timescales of immediate concern to humans. Because soils govern terrestrial water, carbon, and nutrient fluxes, understanding the rates at which soil structure is responding to changes in the Anthropocene over meso-timescales (i.e., decades to centuries) is vital for accurate projections of ecosystem functioning and for ecosystem management strategies. Increasingly, biota appear to have an important role in promoting some rapid meso-timescale soil structural changes, a phenomenon that seems logical given the fast-paced response of the biota to changes in climate and nutrient resource availability. We build on the growing “rules of life” initiative by the US National Science Foundation by offering scientists in relevant disciplines the hypothesis that the *rapid responses of vegetation and microbes to changes in climate and land use alter soil structure at increasing rates in the Anthropocene, governing the future of global water and carbon cycles*. Within often-isolated scientific fields, multiple components of this “rule of life” have been tested for decades, generating foundational knowledge about the role of soil structure in soil and whole-ecosystem functioning. Here, we integrate concepts from disciplines old and new to charge our communities to address the following questions:

- 1) How do life cycles and arrangements of soil aggregates interact in the Anthropocene to regulate water flow, carbon cycling, and solute and gas fluxes from soil particle to continental scales?
- 2) How do alterations in rooting depth distributions in the Anthropocene influence and interact with aggregates and their mineral and organic components, and thus pore structure, to control hydrological partitioning, biogeochemical transformation and fluxes, exchanges of energy and carbon to the atmosphere and climate, regolith weathering, and regulate CZ functioning?
- 3) How does changing microbial functioning in a high CO₂, warmer world with shifting precipitation patterns influence SOC dynamics and void-aggregate-profile dynamics, and how do these processes feedback to question #1?
- 4) How deeply does the influence of the Anthropocene propagate into the subsurface, how does this depth relate to profile structure, and how does this alter the rate at which the CZ develops?

Testing this hypothesis and addressing these questions requires that we traverse disciplinary silos and converse with unified vocabularies, support long-term monitoring and experimental manipulation of soil, and build global databases with appropriate spatial and temporal metadata. These will allow us to push past the bottleneck of needing to both increase collaboration and the degree of specialization needed for tool development. These efforts will unite researchers exploring questions via laboratory-based experiments, monitoring of natural and manipulated field experiments, big data analysis, and modeling. Critically, the resulting advances can promote the development of rate laws or principles for inclusion in models that allow soil structural parameters to emerge from environmental conditions and biotic responses to them, more accurately reflecting the rapidly changing conditions in Earth's critical zone.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Adams, T.S., McCormack, M.L., Eissenstat, D.M., 2013. Foraging strategies in trees of different root morphology: the role of root lifespan. *Tree Physiol.* 33 (9), 940–948.
- Ahrens, B., Guggenberger, G., Rethemeyer, J., John, S., Marschner, B., Heinze, S., et al., 2020. Combination of energy limitation and sorption capacity explains 14C depth gradients. *Soil Biol. Biochem.* 148, 107912.
- AIAA, 2020. Digital Twin: Definition and Value, An AIAA and AIA Position Paper, December 2020. AIAA. <https://www.aiaa-aerospace.org/report/digital-twin-paper/>.
- Allaire, S.E., Roulier, S., Cessna, A.J., 2009. Quantifying preferential flow in soils: A review of different techniques. *J. Hydrol.* 378 (1–2), 179–204.
- Amer, A.M.M., Logsdon, S.D., Davis, D., 2009. Prediction of hydraulic conductivity as related to pore size distribution in unsaturated soils. *Soil Sci.* 174 (9), 508–515.
- Andrianaki, M., Bernasconi, S.M., Nikolaidis, N.P., 2017. Quantifying the incipient development of soil structure and functions within a glacial forefield chronosequence. *Adv. Agron.* 142, 215–239.
- Angers, D.A., Caron, J., 1998. Plant-induced changes in soil structure: processes and feedbacks. *Biogeochemistry* 42 (1), 55–72.
- Angers, D.A., Recous, S., Aita, C., 1997. Fate of carbon and nitrogen in water-stable aggregates during decomposition of 13C15N-labelled wheat straw in situ. *Eur. J. Soil Sci.* 48 (2), 295–300.
- Angst, G., Mueller, K.E., Nierop, K.G., Simpson, M.J., 2021. Plant-or microbial-derived? A review on the molecular composition of stabilized soil organic matter. *Soil Biol. Biochem.* 108189.
- Araya, S.N., Ghezzehei, T.A., 2019. Using machine learning for prediction of saturated hydraulic conductivity and its sensitivity to soil structural perturbations. *Water Resour. Res.* 55 (7), 5715–5737.
- Armfield, J.R., Perdrial, J.N., Gagnon, A., Ehrenkranz, J., Perdrial, N., Cincotta, M., et al., 2019. Does stream water composition at Sleepers River in Vermont reflect dynamic changes in soils during recovery from acidification? *Front. Earth Sci.* 6, 246.
- Arnold, R.W., Szabolcs, I., Targulian, V.O. (Eds.), 1990. *Global Soil Change*. Institute for Applied Systems Analysis, Laxenburg, Austria.
- Attou, F., Bruand, A., Le Bissonnais, Y., 1998. Effect of clay content and silt—clay fabric on stability of artificial aggregates. *Eur. J. Soil Sci.* 49 (4), 569–577.
- Austin, J.C., Richter, D.D., Schroeder, P.A., 2020. Quantification of mixed-layer clays in multiple saturation states using NEWMOD2: implications for the potassium uplift hypothesis in the SE United States. *Clays Clay Minerals* 68 (1), 67–80.
- Bach, E.M., Hofmockel, K.S., 2016. A time for every season: soil aggregate turnover stimulates decomposition and reduces carbon loss in grasslands managed for bioenergy. *Gcb Bioenergy* 8 (3), 588–599.
- Bagnall, D.L., Jones, E.J., Balke, S., Morgan, C.L., McBratney, A.B., 2020. An in situ method for quantifying tillage effects on soil structure using multistripe laser triangulation. *Geoderma* 380, 114642.
- Bailey, S.W., Brousseau, P.A., McGuire, K.J., Ross, D.S., 2014. Influence of landscape position and transient water table on soil development and carbon distribution in a steep, headwater catchment. *Geoderma* 226, 279–289.
- Bailey, V.L., Smith, A.P., Tfaily, M., Fansler, S.J., Bond-Lamberty, B., 2017. Differences in soluble organic carbon chemistry in pore waters sampled from different pore size domains. *Soil Biol. Biochem.* 107, 133–143.
- Bailey, V.L., Bond-Lamberty, B., DeAngelis, K., Grandy, A.S., Hawkes, C.V., Heckman, K., et al., 2018. Soil carbon cycling proxies: Understanding their critical role in predicting climate change feedbacks. *Glob. Chang. Biol.* 24 (3), 895–905.
- Baldock, J.A., Skjemstad, J.O., 2000. Role of the soil matrix and minerals in protecting natural organic materials against biological attack. *Org. Geochem.* 31 (7–8), 697–710.
- Ballantyne IV, F., Billings, S.A., 2018. Model formulation of microbial CO₂ production and efficiency can significantly influence short and long term soil C projections. *ISME J.* 12 (6), 1395–1403.
- Banwart, S., Bernasconi, S.M., Bloem, J., Blum, W., Brandao, M., Brantley, S., et al., 2011. Soil processes and functions in critical zone observatories: hypotheses and experimental design. *Vadose Zone J.* 10 (3), 974–987.
- Banwart, S.A., Nikolaidis, N.P., Zhu, Y.G., Peacock, C.L., Sparks, D.L., 2019. Soil functions: connecting earth's critical zone. *Annu. Rev. Earth Planet. Sci.* 47, 333–359.
- Bao, C., Li, L., Shi, Y., Duffy, C., 2017. Understanding watershed hydrogeochemistry: 1. Development of RT-Flux-PIHM. *Water Resour. Res.* 53 (3), 2328–2345.
- Barbier, E.B., 2013. Economics of the Regulating Services. In: Levin, S.A. (Ed.), *Encyclopedia of Biodiversity*, (2nd Ed). Academic Press, pp. 45–54. <https://doi.org/10.1016/B978-0-12-384719-5.00183-0>.
- Bardgett, R.D., Van Der Putten, W.H., 2014. Belowground biodiversity and ecosystem functioning. *Nature* 515 (7528), 505–511.
- Barley, K.P., 1953. The root growth of irrigated perennial pastures and its effect on soil structure. *Aust. J. Agric. Res.* 4 (3), 283–291.
- Baveye, P.C., Wander, M., 2019. The (bio) chemistry of soil humus and humic substances: Why is the “new view” still considered novel after more than 80 years? *Front. Environ. Sci.* 7, 27.
- Beven, K., Germann, P., 2013. Macropores and water flow in soils revisited. *Water Resour. Res.* 49 (6), 3071–3092.
- Billings, S.A., Ziegler, S.E., 2008. Altered patterns of soil carbon substrate usage and heterotrophic respiration in a pine forest with elevated CO₂ and N fertilization. *Glob. Chang. Biol.* 14 (5), 1025–1036.
- Billings, S.A., Ziegler, S.E., Schlesinger, W.H., Benner, R., de B. Richter, D., 2012. Predicting carbon cycle feedbacks to climate: Integrating the right tools for the job. *EOS Trans. Am. Geophys. Union* 93 (19), 188.
- Bickel, S., Or, D., 2020. Soil bacterial diversity mediated by microscale aqueous-phase processes across biomes. *Nat. Commun.* 11 (1), 1–9.
- Billings, S.A., Hirmas, D., Sullivan, P.L., Lehmeier, C.A., Bagchi, S., Min, K., et al., 2018. Loss of deep roots limits biogenic agents of soil development that are only partially restored by decades of forest regeneration. *Elementa: Science of the Anthropocene* 6.
- Billings, S.A., Lajtha, K., Malhotra, A., Berhe, A.A., de Graaff, M.A., Earl, S., Wieder, W., 2021. Soil organic carbon is not just for soil scientists: measurement recommendations for diverse practitioners. *Ecol. Appl.* 31 (3), e02290.
- Bishop, S.R., Lau, M., Shapiro, S., Carlson, L., Anderson, N.D., Carmody, J., et al., 2004. Mindfulness: a proposed operational definition. *Clin. Psychol. Sci. Pract.* 11 (3), 230.
- Blair, G.S., Henrys, P., Leeson, A., Watkins, J., Eastoe, E., Jarvis, S., Young, P.J., 2019. Data science of the natural environment: a research roadmap. *Front. Environ. Sci.* 7, 121.

- Blake, G.R., et al., 2008. Percolation. In: Chesworth, W. (Ed.), *Encyclopedia of Soil Science*. Encyclopedia of Earth Sciences Series. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-3995-9_421.
- Blevins, R.L., Frye, W.W., 1993. Conservation tillage: an ecological approach to soil management. *Adv. Agron.* 51, 33–78.
- Bogner, C., Gaul, D., Kolb, A., Schmiedinger, I., Huwe, B., 2010. Investigating flow mechanisms in a forest soil by mixed-effects modelling. *Eur. J. Soil Sci.* 61 (6), 1079–1090.
- Bowering, K., Edwards, K., Prestegard, K., Zhu, X., Ziegler, S.E., 2020. Dissolved organic carbon mobilized from organic horizons of mature and harvested black spruce plots in a mesic boreal region. *Biogeosciences* 17, 581–595. <https://doi.org/10.5194/bg-17-581-2020>.
- Bradford, S.A., Segal, E., 2009. Fate of indicator microorganisms under nutrient management plan conditions. *J. Environ. Qual.* 38 (4), 1728–1738.
- Brantley, S.L., Eissenstat, D.M., Marshall, J.A., Godsey, S.E., Balogh-Brunstad, Z., Karwan, D.L., et al., 2017. Reviews and syntheses: on the roles trees play in building and plumbing the critical zone. *Biogeosciences* 14 (22), 5115–5142.
- Bravo-Garza, M.R., Bryan, R.B., Voroney, P., 2009. Influence of wetting and drying cycles and maize residue addition on the formation of water stable aggregates in Vertisols. *Geoderma* 151 (3–4), 150–156.
- Brewer, R., 1964. *Fabric and mineral analysis of soils*. John Wiley and Sons, New York.
- Broeckling, C.D., Manter, D.K., Paschke, M.W., Vivanco, J.M., 2008. Rhizosphere Ecology, Editor(s): Sven Erik Jørgensen. In: Fath, Brian D. (Ed.), *Encyclopedia of Ecology*.
- Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. *Geoderma* 124, 3e22.
- Bruand, A., Cousin, I., Nicoulaud, B., Duval, O., Begon, J.C., 1996. Backscattered electron scanning images of soil porosity for analyzing soil compaction around roots. *Soil Sci. Soc. Amer. J.* 60 (3), 895–901.
- Budge, K., Leifeld, J., Egli, M., Fuhrer, J., 2011. Soil microbial communities in (sub) alpine grasslands indicate a moderate shift towards new environmental conditions 11 years after soil translocation. *Soil Biol. Biochem.* 43 (6), 1148–1154.
- Buol, S.W., Southard, R.J., Graham, R.C., McDaniel, P.A., 2011. *Soil Genesis and Classification*, 6th ed. Wiley-Blackwell, Ames, IA.
- Burns, M.A., Barnard, H.R., Gabor, R.S., McKnight, D.M., Brooks, P.D., 2016. Dissolved organic matter transport reflects hillslope to stream connectivity during snowmelt in a montane catchment. *Water Resour. Res.* 52 (6), 4905–4923.
- Cañasveras, J.C., Barrón, V., Del Campillo, M.C., Torrent, J., Gómez, J.A., 2010. Estimation of aggregate stability indices in Mediterranean soils by diffuse reflectance spectroscopy. *Geoderma* 158 (1–2), 78–84.
- Caplan, J.S., Giménez, D., Subroy, Y., Heck, R.J., Prior, S.A., Runion, G.B., Torbert, H.A., 2017. Nitrogen-mediated effects of elevated CO₂ on intra-aggregate soil pore structure. *Glob. Chang. Biol.* 23 (4), 1585–1597.
- Caplan, J.S., Giménez, D., Hirmas, D.R., Brunzell, N.A., Blair, J.M., Knapp, A.K., 2019. Decadal-scale shifts in soil hydraulic properties as induced by altered precipitation. *Sci. Adv.* 5 (9), eaau6635.
- Carvalho, N., Forkel, M., Khomik, M., Bellarby, J., Jung, M., Migliavacca, M., et al., 2014. Global covariation of carbon turnover times with climate in terrestrial ecosystems. *Nature* 514 (7521), 213–217.
- Chenu, C., Le Bissonnais, Y., Arrouays, D., 2000. Organic matter influence on clay wettability and soil aggregate stability. *Soil Science Society of America Journal. Soil Science Society of America* 64 (4), 1479–1486.
- Chorover, J., Amistadi, M.K., 2001. Reaction of forest floor organic matter at goethite, birnessite and smectite surfaces. *Geochim. Cosmochim. Acta* 65, 95–109.
- Cincotta, M.M., Perdrial, J.N., Shavitz, A., Libenson, A., Landsman-Gerjoi, M., Perdrial, N., et al., 2019. Soil aggregates as a source of dissolved organic carbon to streams: an experimental study on the effect of solution chemistry on water extractable carbon. *Front. Environ. Sci.* 7, 172.
- Clarke, N., Wu, Y., Strand, L.T., 2007. Dissolved organic carbon concentrations in four Norway spruce stands of different ages. *Plant Soil* 299 (1), 275–285.
- Clemmensen, K.E., Bahr, A., Oskainen, O., Dahlberg, A., Ekblad, A., Wallander, H., et al., 2013. Roots and associated fungi drive long-term carbon sequestration in boreal forest. *Science* 339 (6127), 1615–1618.
- Conant, R.T., Ryan, M.G., Ågren, G.I., Birge, H.E., Davidson, E.A., Eliasson, P.E., et al., 2011. Temperature and soil organic matter decomposition rates—synthesis of current knowledge and a way forward. *Glob. Chang. Biol.* 17 (11), 3392–3404.
- Cosentino, D., Chenu, C., Le Bissonnais, Y., 2006. Aggregate stability and microbial community dynamics under drying–wetting cycles in a silt loam soil. *Soil Biol. Biochem.* 38 (8), 2053–2062.
- Couvreur, V., Vanderborght, J., Javaux, M., 2012. A simple three-dimensional macroscopic root water uptake model based on the hydraulic architecture approach. *Hydrol. Earth Syst. Sci.* 16 (8), 2957–2971.
- Crowther, T.W., Todd-Brown, K.E., Rowe, C.W., Wieder, W.R., Carey, J.C., Machmuller, M.B., et al., 2016. Quantifying global soil carbon losses in response to warming. *Nature* 540 (7631), 104–108.
- Cueva, A., Volkman, T.H., van Haren, J., Troch, P.A., Meredith, L.K., 2019. Reconciling negative soil CO₂ fluxes: Insights from a large-scale experimental hillslope. *Soil Syst.* 3 (1), 10.
- Dai, Y., Zeng, X., Dickinson, R.E., Baker, I., Bonan, G.B., Bosilovich, M.G., Yang, Z.L., 2003. The common land model. *Bull. Am. Meteorol. Soc.* 84 (8), 1013–1024.
- Dawson, T.E., Hahn, W.J., Crutchfield-Peters, K., 2020. Digging deeper: what the critical zone perspective adds to the study of plant ecophysiology. *New Phytol.* 226 (3), 666–671.
- De Gryze, S., Six, J., Merckx, R., 2006. Quantifying water-stable soil aggregate turnover and its implication for soil organic matter dynamics in a model study. *Eur. J. Soil Sci.* 57 (5), 693–707.
- De Vries, F.T., Hoffland, E., van Eekeren, N., Brussaard, L., Bloem, J., 2006. Fungal/bacterial ratios in grasslands with contrasting nitrogen management. *Soil Biol. Biochem.* 38 (8), 2092–2103.
- Degens, B.P., Sparling, G.P., 1995. Repeated wet-dry cycles do not accelerate the mineralization of organic C involved in the macro-aggregation of a sandy loam soil. *Plant Soil* 175 (2), 197–203.
- del Giorgio, P.A., Cole, J.J., 1998. Bacterial growth efficiency in natural aquatic systems. *Annu. Rev. Ecol. Syst.* 29 (1), 503–541.
- Denef, K., Six, J., Bossuyt, H., Frey, S.D., Elliott, E.T., Merckx, R., Paustian, K., 2001. Influence of dry–wet cycles on the interrelationship between aggregate, particulate organic matter, and microbial community dynamics. *Soil Biol. Biochem.* 33 (12), 1599–1611.
- Deurer, M., Clothier, B.E., 2005. Unraveling Microscale Flow and Pore Geometry: NMR and X-Ray Tomography.
- Dexter, A.R., 1988. Advances in characterization of soil structure. *Soil Tillage Res.* 11 (3–4), 199–238.
- Dexter, A.R., 1991. Amelioration of soil by natural processes. *Soil Tillage Res.* 20 (1), 87–100.
- Dexter, A.R., Kroesbergen, B., Kuipers, H., 1984. Some mechanical properties of aggregates of top soils from the IJsselmeer polders. 1. Undisturbed soil aggregates. *NJAS Wageningen J. Life Sci.* 32 (3), 205–214.
- Dignac, M.F., Derrien, D., Barré, P., Barot, S., Cécillon, L., Chenu, C., Chevallier, T., et al., 2017. Increasing soil carbon storage: Mechanisms, effects of agricultural practices and proxies. A Review. *Agronomy Sustain. Dev.* 37 (2), 14.
- D’Odorico, P., Okin, G.S., Bestelmeyer, B.T., 2012. A synthetic review of feedbacks and drivers of shrub encroachment in arid grasslands. *Ecology* 93 (5), 520–530.
- Doussan, C., Pagès, L., Vercambre, G., 1998. Modelling of the hydraulic architecture of root systems: an integrated approach to water absorption—model description. *Ann. Bot.* 81 (2), 213–223.
- Drever, J.L., 1994. The effect of land plants on weathering rates of silicate minerals. *Geochim. Cosmochim. Acta* 58 (10), 2325–2332.
- Drever, J.L., Clow, D.W., 2018. Weathering rates in catchments. In: *Chemical Weathering Rates of Silicate Minerals*. De Gruyter, pp. 463–484.
- Drewniak, B.A., 2019. Simulating dynamic roles in the energy exascale earth system land model. *J. Adv. Model. Earth Syst.* 11 (1), 338–359.
- Dunbabin, V.M., Postma, J.A., Schnepf, A., Pagès, L., Javaux, M., Wu, L., 2013. Modelling root–soil interactions using three-dimensional models of root growth, architecture and function. *Plant Soil* 372 (1), 93–124.
- Duwig, C., Prado, B., Tinet, A.J., Delmas, P., Dal Ferro, N., Vandervaere, J.P., et al., 2019. Impacts of land use on hydrodynamic properties and pore architecture of volcanic soils from the Mexican Highlands. *Soil Res.* 57 (6), 629–641.
- Eck, D.V., Hirmas, D.R., Giménez, D., 2013. Quantifying soil structure from field excavation walls using multistripe laser triangulation scanning. *Soil Sci. Soc. Am. J.* 77 (4), 1319–1328. <https://doi.org/10.2136/sssaj2012.0421>.
- Ellis, S., Atherton, J.K., 2003. Properties and development of soils on reclaimed alluvial sediments of the Humber estuary, eastern England. *Catena* 52 (2), 129–147.
- Ellis, E.C., Klein Goldewijk, K., Siebert, S., Lightman, D., Ramankutty, N., 2010. Anthropogenic transformation of the biomes, 1700 to 2000. *Glob. Ecol. Biogeogr.* 19 (5), 589–606.
- Essington, M.E., 2015. *Soil and Water Chemistry: An Integrative Approach*. CRC Press.
- Fan, Y., Miguez-Macho, G., Jobbágy, E.G., Jackson, R.B., Otero-Casal, C., 2017. Hydrologic regulation of plant rooting depth. *Proc. Natl. Acad. Sci.* 114 (40), 10572–10577.
- Fernández-Ugalde, O., Barré, P., Hubert, F., Virto, I., Girardin, C., Ferrage, E., 2013. Clay mineralogy differs qualitatively in aggregate-size classes: clay-mineral-based evidence for aggregate hierarchy in temperate soils. *Eur. J. Soil Sci.* 64 (4), 410–422.
- Fierer, N., Jackson, R.B., 2006. The diversity and biogeography of soil bacterial communities. *Proc. Natl. Acad. Sci.* 103 (3), 626–631.
- Finzi, A.C., Schlesinger, W.H., 2003. Soil–nitrogen cycling in a pine forest exposed to 5 years of elevated carbon dioxide. *Ecosystems* 6 (5), 444–456.
- Fisher, R.A., Koven, C.D., Anderegg, W.R., Christoffersen, B.O., Dietze, M.C., Farrior, C. E., et al., 2018. Vegetation demographics in Earth System Models: a review of progress and priorities. *Global Change Biol.* 24 (1), 35–54.
- Fröberg, M., Hansson, K., Kleja, D.B., Alavi, G., 2011. Dissolved organic carbon and nitrogen leaching from Scots pine, Norway spruce and silver birch stands in southern Sweden. *Forest Ecol. Manag.* 262 (9), 1742–1747.
- Gaiser, R.N., 1952. Readily available water in forest soils. *Soil Sci. Soc. Am. J.* 16 (4), 334–338.
- Gannon, J.P., Bailey, S.W., McGuire, K.J., Shanley, J.B., 2015. Flushing of distal hillslopes as an alternative source of stream dissolved organic carbon in a headwater catchment. *Water Resour. Res.* 51 (10), 8114–8128.
- Garmo, Ø.A., Skjelkvåle, B.L., de Wit, H.A., Colombo, L., Curtis, C., Fölster, J., et al., 2014. Trends in surface water chemistry in acidified areas in Europe and North America from 1990 to 2008. *Water Air Soil Pollut* 225 (3), 1–14.
- Gayler, S., Wöhling, T., Grzeschik, M., Ingwersen, J., Witzmann, H.D., Warrach-Sagi, K., et al., 2014. Incorporating dynamic root growth enhances the performance of Noah-MP at two contrasting winter wheat field sites. *Water Resour. Res.* 50 (2), 1337–1356.
- Ghestem, M., Sidle, R.C., Stokes, A., 2011. The influence of plant root systems on subsurface flow: Implications for slope stability. *BioScience* 61, 869–879.
- Giannakis, G.V., Nikolaidis, N.P., Valstar, J., Rowe, E.C., Moirgiorgou, K., Kotronakis, M., et al., 2017. Integrated critical zone model (1D-ICZ): a tool for dynamic simulation of soil functions and soil structure. *Adv. Agron.* 142, 277–314.
- Gill, R.A., Jackson, R.B., 2000. Global patterns of root turnover for terrestrial ecosystems. *New Phytol.* 147 (1), 13–31.

- Gmach, M.R., Cherubin, M.R., Kaiser, K., Cerri, C.E.P., 2019. Processes that influence dissolved organic matter in the soil: a review. *Sci. Agric.* 77.
- Griffiths, R.L., Bruce, C., Thomson, B.C., Phillip, James P., Bell, T., Bailey, M., Whiteley, A.S., 2011. The bacterial biogeography of British soils. *Environ. Microbiol.* 13 (6), 1642–1654.
- Guo, L., Lin, H., 2018. Addressing two bottlenecks to advance the understanding of preferential flow in soils. *Adv. Agron.* 147, 61–117.
- Gyssels, G., Poesen, J., Bochet, E., Li, Y., 2005. Impact of plant roots on the resistance of soils to erosion by water: a review. *Prog. Phys. Geogr.* 29 (2), 189–217.
- Hagerty, S.B., Allison, S.D., Schimel, J.P., 2018. Evaluating soil microbial carbon use efficiency explicitly as a function of cellular processes: implications for measurements and models. *Biogeochemistry* 140 (3), 269–283.
- Hauser, E., Richter, D.D., Markewitz, D., Brecheisen, Z., Billings, S.A., 2020. Persistent anthropogenic legacies structure depth dependence of regenerating rooting systems and their functions. *Biogeochemistry* 147 (3), 259–275.
- Hayes, D.C., Seastedt, T.R., 1987. Root dynamics of tallgrass prairie in wet and dry years. *Can. J. Bot.* 65 (4), 787–791.
- Hillel, D., 1998a. *Environmental Soil Physics*. Academic Press.
- Hillel, D., 1998b. *Environmental soil physics*. Academic Press, San Diego.
- Hinsinger, P., Brauman, A., Devau, N., Gérard, F., Jourdan, C., Laclau, J.P., et al., 2011. Acquisition of phosphorus and other poorly mobile nutrients by roots. Where do plant nutrition models fail? *Plant Soil* 348 1, 29–61.
- Hinsinger, P., Plassard, C., Tang, C., Jaillard, B., 2003. Origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints: a review. *Plant Soil* 248 (1), 43–59.
- Hirmas, D.R., 2013. A simple method for removing artifacts from moist fine-textured soil faces. *Soil Sci. Soc. Am. J.* 77 (2), 591–593.
- Hirmas, D.R., Giménez, D., Subroy, V., Platt, B.F., 2013. Fractal distribution of mass from the millimeter-to decimeter-scale in two soils under native and restored tallgrass prairie. *Geoderma* 207, 121–130.
- Hirmas, D., Steffens, M., Sullivan, P., Zhang, C., Giménez, D., 2016. Coupling multistripe laser triangulation with hyperspectral imaging VisNIR spectroscopy to elucidate the feedbacks between soil structure, hydrology, and organic matter, 18(1), p. 10651.
- Hirmas, D.R., Giménez, D., Nemes, A., Kerry, R., Brunzell, N.A., Wilson, C.J., 2018. Climate-induced changes in continental-scale soil macroporosity may intensify water cycle. *Nature* 561 (7721), 100–103. <https://doi.org/10.1038/s41586-018-0463-x>.
- Hobley, E., Steffens, M., Bauke, S.L., Kögel-Knabner, I., 2018. Hotspots of soil organic carbon storage revealed by laboratory hyperspectral imaging. *Sci. Rep.* 8 (1), 1–13.
- Hockaday, W.C., Masiello, C.A., Randerson, J.T., Smernik, R.J., Baldock, J.A., Chadwick, O.A., Harden, J.W., 2009. Measurement of soil carbon oxidation state and oxidative ratio by ^{13}C nuclear magnetic resonance. *J. Geophys. Res. Biogeosci.* 114 (G2).
- Hu, W., Shao, M.A., Si, B.C., 2012. Seasonal changes in surface bulk density and saturated hydraulic conductivity of natural landscapes. *Eur. J. Soil Sci.* 63 (6), 820–830.
- Hu, X., Li, X.Y., Guo, L.L., Liu, Y., Wang, P., Zhao, Y.D., et al., 2019. Influence of shrub roots on soil macropores using X-ray computed tomography in a shrub-encroached grassland in Northern China. *J. Soils Sediments* 19 (4), 1970–1980.
- Hu, X., Li, X.Y., Li, Z.C., Gao, Z., Wu, X.C., Wang, P., et al., 2020. Linking 3-D soil macropores and root architecture to near saturated hydraulic conductivity of typical meadow soil types in the Qinghai Lake Watershed, northeastern Qinghai-Tibet Plateau. *Catena* 185, 104287.
- Hubbell, D.S., 1947. Effect of soil aggregates on water movement in two calcareous soils 1. *Agron. J.* 39 (9), 762–770.
- Ibrahim, A., Horton, R., 2021. Biochar and compost amendment impacts on soil water and pore size distribution of a loamy sand soil. *Soil Sci. Soc. Am. J.* 85, 1021–1036.
- Iversen, C.M., 2010. Digging deeper: fine-root responses to rising atmospheric CO_2 concentration in forested ecosystems. *New Phytol.* 186 (2), 346–357.
- Jabro, J.D., Iversen, W.M., Evans, R.G., Allen, B.L., Stevens, W.B., 2014. Repeated freeze-thaw cycle effects on soil compaction in a clay loam in Northeastern Montana. *Soil Sci. Soc. Am. J.* 78 (3), 737–744.
- Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H.A., Sala, O.E., Schulze, E.D., 1996. A global analysis of root distributions for terrestrial biomes. *Oecologia* 108 (3), 389–411.
- Jangorzo, N.S., Watteau, F., Schwartz, C., 2013. Evolution of the pore structure of constructed Technosols during early pedogenesis quantified by image analysis. *Geoderma* 207, 180–192.
- Jangorzo, N.S., Watteau, F., Schwartz, C., 2018. Ranking of wetting-drying, plant, and fauna factors involved in the structure dynamics of a young constructed Technosol. *J. Soils Sediments* 18, 2995–3004.
- Janzen, H.H., 2004. Carbon cycling in earth systems—a soil science perspective. *Agric. Ecosyst. Environ.* 104 (3), 399–417.
- Jarvis, N.J., 2007. A review of non-equilibrium water flow and solute transport in soil macropores: Principles, controlling factors and consequences for water quality. *Eur. J. Soil Sci.* 58 (3), 523–546.
- Jarvis, N.J., Moeys, J., Koestel, J., Hollis, J.M., Lin, H., 2012. Preferential flow in a pedological perspective. In: *Hydrogeology: Synergistic Integration of Soil Science and Hydrology*, pp. 75–120.
- Jarvis, N., Koestel, J., Messing, I., Moeys, J., Lindahl, A., 2013. Influence of soil, land use and climatic factors on the hydraulic conductivity of soil. *Hydrol. Earth Syst. Sci.* 17 (12), 5185–5195.
- Jarvis, N., Koestel, J., Larsbo, M., 2016. Understanding preferential flow in the vadose zone: Recent advances and future prospects. *Vadose Zone J.* 15 (12), 1–11.
- Jastrow, J.D., Miller, R.M., Lussenhop, J., 1998. Contributions of interacting biological mechanisms to soil aggregate stabilization in restored prairie. *Soil Biol. Biochem.* 30 (7), 905–916.
- Javaux, M., Schröder, T., Vanderborght, J., Vereecken, H., 2008. Use of a three-dimensional detailed modeling approach for predicting root water uptake. *Vadose Zone J.* 7, 1079–1088.
- Javaux, M., Couvreur, V., Vanderborght, J., Vereecken, H., 2013. Root water uptake: From three-dimensional biophysical processes to macroscopic modeling approaches. *Vadose Zone J.* 12 <https://doi.org/10.2136/vzj2013.02.0042>, 1–16 [vzj2013.02.0042](https://doi.org/10.2136/vzj2013.02.0042).
- Jenny, H., 1941. *Factors of Soil Formation*. McGraw-Hill, New York, p. 281.
- Johnson, C.E., Driscoll, C.T., Siccama, T.G., Likens, G.E., 2000. Element fluxes and landscape position in a northern hardwood forest watershed ecosystem. *Ecosystems* 3 (2), 159–184.
- Jongierius, A.G., Schoonderbeek, D., Jager, A., 1972. The application of Quantimet 720 in soil micromorphometry. *Microscope* 20, 243–254.
- Jorda, H., Bechtold, M., Jarvis, N., Koestel, J., 2015. Using boosted regression trees to explore key factors controlling saturated and near-saturated hydraulic conductivity. *Eur. J. Soil Sci.* 66 (4), 744–756.
- Jozefaciuk, G., Czachor, H., Lamorski, K., Hajnos, M., Swieboda, R., Franus, W., 2015. Effect of humic acids, sesquioxides and silica on the pore system of silt aggregates measured by water vapour desorption, mercury intrusion and microtomography. *Eur. J. Soil Sci.* 66 (6), 992–1001.
- Jury, W.A., Horton, R., 2004. *Soil physics*. John Wiley & Sons, New Jersey, USA.
- Kaiser, K., Guggenberger, G., 2005. Storm flow flushing in a structured soil changes the composition of dissolved organic matter leached into the subsoil. *Geoderma* 127 (3–4), 177–187.
- Kalbitz, K., Schwesig, D., Rethemeyer, J., Matzner, E., 2005. Stabilization of dissolved organic matter by sorption to the mineral soil. *Soil Biol. Biochem.* 37 (7), 1319–1331.
- Kaptein, M.G., Pretorius, J.V., Willcox, K.E., 2021. A probabilistic graphical model foundation for enabling predictive digital twins at scale. *Nature Comput. Sci.* 1 (5), 337–347.
- Kasper, M., Buchan, G.D., Mentler, A., Blum, W.E.H., 2009. Influence of soil tillage systems on aggregate stability and the distribution of C and N in different aggregate fractions. *Soil Tillage Res.* 105 (2), 192–199.
- Keidel, L., Lenhart, K., Moser, G., Müller, C., 2018. Depth-dependent response of soil aggregates and soil organic carbon content to long-term elevated CO_2 in a temperate grassland soil. *Soil Biol. Biochem.* 123, 145–154.
- Kennedy, D., Swenson, S., Oleson, K.W., Lawrence, D.M., Fisher, R., Lola da Costa, A.C., Gentile, P., 2019. Implementing plant hydraulics in the community land model, version 5. *J. Adv. Model. Earth Syst.* 11 (2), 485–513.
- Ketcham, R.A., Carlson, W.D., 2001. Acquisition, optimization and interpretation of X-ray computed tomographic imagery: applications to the geosciences. *Comput. Geosci.* 27 (4), 381–400.
- Kleber, M., Eusterhues, K., Keilueit, M., Mikutta, C., Mikutta, R., Nico, P.S., 2015. Mineral-organic associations: formation, properties, and relevance in soil environments. *Adv. Agron.* 130, 1–140.
- Koestel, J., Schlüter, S., 2019. Quantification of the structure evolution in a garden soil over the course of two years. *Geoderma* 338, 597–609.
- Koebnick, N., Daly, K.R., Keyes, S.D., George, T.S., Brown, L.K., Raffan, A., et al., 2017. High-resolution synchrotron imaging shows that root hairs influence rhizosphere soil structure formation. *New Phytol.* 216 (1), 124–135.
- Koestel, J., Dathe, A., Skaggs, T.H., Klakegg, O., Ahmad, M.A., Babko, M., et al., 2018. Estimating the permeability of naturally structured soil from percolation theory and pore space characteristics imaged by X-ray. *Water Resour. Res.* 54 (11), 9255–9263.
- Kögel-Knabner, I., Guggenberger, G., Kleber, M., Kandeler, E., Kalbitz, K., Scheu, S., et al., 2008. Organo-mineral associations in temperate soils: Integrating biology, mineralogy, and organic matter chemistry. *J. Plant Nutr. Soil Sci.* 171 (1), 61–82.
- Kollet, S.J., Maxwell, R.M., 2006. Integrated surface-groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model. *Adv. Water Resour.* 29 (7), 945–958.
- Kollet, S.J., Maxwell, R.M., 2008. Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model. *Water Resour. Res.* 44 (2).
- Kool, D., Tong, B., Tian, Z., Heitman, J.L., Sauer, T.J., Horton, R., 2019. Soil water retention and hydraulic conductivity dynamics following tillage. *Soil Tillage Res.* 193, 95–100.
- Koop, A.N., Hirmas, D.R., Sullivan, P.L., Mohammed, A.K., 2020. A generalizable index of soil development. *Geoderma* 360, 113898.
- Kopáček, J., Hejzlar, J., Krám, P., Oulehle, F., Posch, M., 2016. Effect of industrial dust on precipitation chemistry in the Czech Republic (Central Europe) from 1850 to 2013. *Water Res.* 103, 30–37.
- Kotronakis, M., Giannakis, G.V., Nikolaidis, N.P., Rowe, E.C., Valstar, J., Paranychanakis, N.V., Banwart, S.A., 2017. Modeling the impact of carbon amendments on soil ecosystem functions using the 1D-ICZ model. *Adv. Agron.* 142, 315–352.
- Kramer, M.G., Chadwick, O.A., 2018. Climate-driven thresholds in reactive mineral retention of soil carbon at the global scale. *Nat. Clim. Chang.* 8 (12), 1104–1108.
- Kramer, C., Trumbore, S., Fröberg, M., Dozal, L.M.C., Zhang, D., Xu, X., et al., 2010. Recent (< 4 year old) leaf litter is not a major source of microbial carbon in a temperate forest mineral soil. *Soil Biol. Biochem.* 42 (7), 1028–1037.
- Kravchenko, A.N., Negassa, W.C., Guber, A.K., Rivers, M.L., 2015. Protection of soil carbon within macro-aggregates depends on intra-aggregate pore characteristics. *Sci. Rep.* 5 (1), 1–10.
- Kubiéna, W.L., 1938. *Micropedology*. Collegiate Press, Ames.
- Kumi, F., Hanping, M., Jianping, H., Ullah, I., 2015. Review of applying X-ray computed tomography for imaging soil-root physical and biological processes. In: *J. Agricult. Biol. Eng.* 8 (5), 1–14.

- Kuncoro, P.H., Koga, K., Satta, N., Muto, Y., 2014. A study on the effect of compaction on transport properties of soil gas and water I: Relative gas diffusivity, air permeability, and saturated hydraulic conductivity. *Soil Tillage Res.* 143, 172–179.
- Lajtha, K., Bowden, R.D., Nadelhoffer, K., 2014. Litter and root manipulations provide insights into soil organic matter dynamics and stability. *Soil Sci. Soc. Am. J.* 78, S261.
- Larsbo, M., Koestel, J., Kätterer, T., Jarvis, N., 2016. Preferential transport in macropores is reduced by soil organic carbon. *Vadose Zone J.* 15 (9), 1–7.
- Laudon, H., Berggren, M., Ågren, A., Buffam, I., Bishop, K., Grabs, T., et al., 2011. Patterns and dynamics of dissolved organic carbon (DOC) in boreal streams: the role of processes, connectivity, and scaling. *Ecosystems* 14 (6), 880–893.
- Lavallee, J.M., Soong, J.L., Cotrufo, M.F., 2020. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Global Change Biol* 26 (1), 261–273.
- Lawrence, C., Steefel, C., Maher, K., 2014. Abiotic/biotic coupling in the rhizosphere: a reactive transport modeling analysis. *Proced. Earth Planet. Sci.* 10, 104–108.
- Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *Eur. J. Soil Sci.* 47 (4), 425–437.
- Letey, J., 1991. The study of soil structure-science or art. *Soil Res.* 29 (6), 699–707.
- Lewis, S.L., Maslin, M.A., 2015. Defining the anthropocene. *Nature* 519 (7542), 171–180.
- Li, L., 2019. Watershed reactive transport. *Rev. Mineral. Geochem.* 85 (1), 381–418.
- Li, L., Steefel, C.I., Kowalsky, M.B., Englert, A., Hubbard, S.S., 2010. Effects of physical and geochemical heterogeneities on mineral transformation and biomass accumulation during biostimulation experiments at Rifle, Colorado. *J. Contam. Hydrol.* 112 (1–4), 45–63.
- Li, L., Maher, K., Navarre-Sitchler, A., Druhan, J., Meile, C., Lawrence, C., et al., 2017. Expanding the role of reactive transport models in critical zone processes. *Earth Sci. Rev.* 165, 280–301.
- Li, L., Sullivan, P.L., Benettin, P., Cirpka, O.A., Bishop, K., Brantley, S.L., et al., 2021. Toward catchment hydro-biogeochemical theories. *Wiley Interdiscip. Rev. Water* 8 (1), e1495.
- Liang, C., Amelung, W., Lehmann, J., Kästner, M., 2019. Quantitative assessment of microbial necromass contribution to soil organic matter. *Glob. Chang. Biol.* 25 (11), 3578–3590.
- Lin, H., 2003. *Hydropedology: Bridging disciplines, scales, and data*. *Vadose Zone J.* 2 (1), 1–11.
- Lipman, C.B., Waynick, D.D., 1916. A detailed study of effects of climate on important properties of soils. *Soil Sci* 1 (1), 5–48.
- Liu, Z., Ballantyne, A.P., Poulter, B., Anderegg, W.R., Li, W., Bastos, A., Ciais, P., 2018. Precipitation thresholds regulate net carbon exchange at the continental scale. *Nat. Commun.* 9 (1), 1–10.
- Quantifying and modeling soil structure dynamics. In: Logsdon, S., Berli, M., Horn, R. (Eds.), 2013. *Advances in Agricultural Systems Modeling: Transdisciplinary, Research, Synthesis, and Application*. Soil Science Society of America, Madison, WI.
- Lopez-Capel, E., Sohi, S.P., Gaunt, J.L., Manning, D.A., 2005. Use of thermogravimetry-differential scanning calorimetry to characterize modelable soil organic matter fractions. *Soil Sci. Soc. Am. J.* 69 (1), 136–140.
- Lovett, G.M., Cole, J.J., Pace, M.L., 2006. Is net ecosystem production equal to ecosystem carbon accumulation? *Ecosystems* 9 (1), 152–155.
- Lu, H., Yuan, W., Chen, X., 2019. A processes-based dynamic root growth model integrated into the ecosystem model. *J. Adv. Model. Earth Syst.* 11 (12), 4614–4628.
- Lu, J., Zhang, Q., Werner, A.D., Li, Y., Jiang, S., Tan, Z., 2020. Root-induced changes of soil hydraulic properties - A review. *J. Hydrol.* 589, 125203.
- Luan, J., Liu, S., Chang, S.X., Wang, J., Zhu, X., Liu, K., Wu, J., 2014. Different effects of warming and cooling on the decomposition of soil organic matter in warm-temperate oak forests: a reciprocal translocation experiment. *Biogeochemistry* 121 (3), 551–564.
- Lucas, M., Schlüter, S., Vogel, H.J., Vetterlein, D., 2019. Roots compact the surrounding soil depending on the structures they encounter. *Sci. Rep.* 9 (1), 1–13.
- Luxmoore, R.J., 1981. Micro-, meso-, and macroporosity of soil. *Soil Sci. Soc. Am. J.* 45 (3), 671–672.
- Maeght, J.L., Rewald, B., Pierret, A., 2013. How to study deep roots—and why it matters. *Front. Plant Sci.* 4, 299.
- Maggi, F., Porporato, A., 2007. Coupled moisture and microbial dynamics in unsaturated soils. *Water Resour. Res.* 43 (7).
- Mangalassery, S., Sjögersten, S., Sparkes, D.L., Sturrock, C.J., Mooney, S.J., 2013. The effect of soil aggregate size on pore structure and its consequence on emission of greenhouse gases. *Soil Tillage Res.* 132, 39–46.
- Manzoni, S., Taylor, P., Richter, A., Porporato, A., Ågren, G.I., 2012. Environmental and stoichiometric controls on microbial carbon-use efficiency in soils. *New Phytol.* 196 (1), 79–91.
- Mapa, R.B., Green, R.E., Santo, L., 1986. Temporal variability of soil hydraulic properties with wetting and drying subsequent to tillage. *Soil Sci. Soc. Am. J.* 50 (5), 1133–1138.
- Masiello, C.A., Chadwick, O.A., Southon, J., Torn, M.S., Harden, J.W., 2004. Weathering controls on mechanisms of carbon storage in grassland soils. *Glob. Biogeochem. Cycles* 18, 1–9.
- Maxwell, R.M., Condon, L.E., Kollet, S.J., 2015. A high-resolution simulation of groundwater and surface water over most of the continental US with the integrated hydrologic model ParFlow v3. *Geosci. Model Dev.* 8 (3), 923–937.
- Mbagwu, J.S.C., Bazzoffi, P., 1989. Properties of soil aggregates as influenced by tillage practices. *Soil Use Manag.* 5 (4), 180–188.
- McCormack, M.L., Adams, T.S., Smithwick, E.A., Eissenstat, D.M., 2012. Predicting fine root lifespan from plant functional traits in temperate trees. *New Phytol.* 195 (4), 823–831.
- Mei, Y., Hornberger, G.M., Kaplan, L.A., Newbold, J.D., Aufdenkampe, A.K., 2012. Estimation of dissolved organic carbon contribution from hillslope soils to a headwater stream. *Water Resour. Res.* 48 (9).
- Mele, G., Buscemi, G., Gargiulo, L., Terribile, F., 2021. Soil burrow characterization by 3D image analysis: Prediction of macroinvertebrate groups from biopore size distribution parameters. *Geoderma* 404, 115292.
- Melillo, J.M., Butler, S., Johnson, J., Mohan, J., Steudler, P., Lux, H., et al., 2011. Soil warming, carbon–nitrogen interactions, and forest carbon budgets. *Proc. Natl. Acad. Sci.* 108 (23), 9508–9512.
- Meurer, K., Barron, J., Chenu, C., Coucheney, E., Fielding, M., Hallett, P., et al., 2020. A framework for modelling soil structure dynamics induced by biological activity. *Glob. Chang. Biol.* 26 (10), 5382–5403.
- Miltner, A., Bombach, P., Schmidt-Brücken, B., Kästner, M., 2012. SOM genesis: microbial biomass as a significant source. *Biogeochemistry* 111 (1), 41–55.
- Minasny, B., McBratney, A.B., 2018. Limited effect of organic matter on soil available water capacity. *Eur. J. Soil Sci.* 69 (1), 39–47.
- Miralles, I., Piedra-Buena, A., Almendros, G., González-Vila, F.J., González-Pérez, J.A., 2015. Pyrolytic appraisal of the lignin signature in soil humic acids: assessment of its usefulness as carbon sequestration marker. *J. Anal. Appl. Pyrolysis* 113, 107–115.
- Mohammed, A.K., Hirmas, D.R., Nemes, A., Giménez, D., 2020. Exogenous and endogenous controls on the development of soil structure. *Geoderma* 357, 113945. <https://doi.org/10.1016/j.geoderma.2019.113945>.
- Muench, A.T., O'Keefe, K., Nippert, J.B., 2016. Comparative ecohydrology between *Cornus drummondii* and *Solidago canadensis* in upland tallgrass prairie. *Plant Ecol.* 217 (3), 267–276.
- Munier, M., Oades, J.M., 1989. The role of Ca-organic interactions in soil aggregate stability. III. Mechanisms and models. *Soil Res.* 27 (2), 411–423.
- Nadelhoffer, K.J., Aber, J.D., Melillo, J.M., 1984. Seasonal patterns of ammonium and nitrate uptake in nine temperate forest ecosystems. *Plant Soil* 80 (3), 321–335.
- Nagpal, N.K., Boersma, L., DeBacker, L.W., 1972. Pore size distributions of soils from mercury intrusion porosimetry data. *Soil Sci. Soc. Am. J.* 36 (2), 264–267.
- Nannipieri, P., Ascher-Jenull, J., Ceccherini, M.T., Pietramellara, G., Renella, G., Schloter, M., 2020. Beyond microbial diversity for predicting soil functions: A mini review. *Pedosphere* 30 (1), 5–17.
- Nemati, H.R., Steiger, D.M., Iyer, L.S., Herschel, R.T., 2002. Knowledge warehouse: an architectural integration of knowledge management, decision support, artificial intelligence and data warehousing. *Decis. Support. Syst.* 33 (2), 143–161.
- Nemes, A., Rawls, W.J., Pachepsky, Y.A., 2005. Influence of organic matter on the estimation of saturated hydraulic conductivity. *Soil Sci. Soc. Am. J.* 69 (4), 1330–1337.
- Newell, A.D., Skjelkvåle, B.L., 1997. Acidification trends in surface waters in the international program on acidification of rivers and lakes. *Water Air Soil Pollut* 93 (1), 27–57.
- Nielsen, D.R., Biggar, J.W., Erh, K.T., 1973. Spatial variability of field-measured soil-water properties. *Hilgardia* 42 (7), 215–259.
- Nimmo, J.R., 2004. Porosity and pore size distribution. *Encycl. Soils Environ.* 3 (1), 295–303.
- Noguchi, S., Tsuboyama, Y., Sidle, R.C., Hosoda, I., 1997. Spatially distributed morphological characteristics of macropores in forest soils of Hitachi Ohta Experimental Watershed, Japan. *J. For. Res.* 2 (4), 207–215.
- NSF (National Science Foundation), 2019. NSF's 10 Big Ideas—Special Report.
- Oades, J.M., 1984. Soil organic matter and structural stability: mechanisms and implications for management. *Plant Soil* 76 (1), 319–337.
- Oades, J.M., 1993. The role of biology in the formation, stabilization and degradation of soil structure. In: *Soil Structure/Soil Biota Interrelationships*. Elsevier, pp. 377–400.
- Oh, N.H., Richter Jr., D.D., 2004. Soil acidification induced by elevated atmospheric CO₂. *Global Change Biol* 10 (11), 1936–1946.
- Oh, N.H., Richter, D.D., 2005. Elemental translocation and loss from three highly weathered soil–bedrock profiles in the southeastern United States. *Geoderma* 126 (1–2), 5–25.
- Oh, Y., Zhuang, Q., Liu, L., Welp, L.R., Lau, M.C., Onstott, T.C., et al., 2020. Reduced net methane emissions due to microbial methane oxidation in a warmer Arctic. *Nat. Clim. Chang.* 10 (4), 317–321.
- O'Keefe, K., Bell, D.M., McCulloh, K.A., Nippert, J.B., 2020. Bridging the flux gap: sap flow measurements reveal species-specific patterns of water use in a tallgrass prairie. *J. Geophys. Res. Biogeosci.* 125 (2), e2019JG005446.
- Olson, L., 1943. Columella and the beginning of soil science. *Agric. Hist.* 17 (2), 65–72.
- Pagliai, M., Vignozzi, N., Pellegrini, S., 2004. Soil structure and the effect of management practices. *Soil Tillage Res.* 79 (2), 131–143.
- Park, E.J., Sul, W.J., Smucker, A.J.M., 2007. Glucose additions to aggregates subjected to drying/wetting cycles promote carbon sequestration and aggregate stability. *Soil Biol. Biochem.* 39 (11), 2758–2768.
- Pawlik, Ł., Kasprzak, M., 2018. Regolith properties under trees and the biomechanical effects caused by tree root systems as recognized by electrical resistivity tomography (ERT). *Geomorphology* 300, 1–12.
- Pawlik, Ł., Phillips, J.D., Samonil, P., 2016. Roots, rock, and regolith: Biomechanical and biochemical weathering by trees and its impact on hillslopes—A critical literature review. *Earth Sci. Rev.* 159, 142–159.
- Peltre, C., Thuries, L., Barthes, B., Brunet, D., Morvan, T., Nicolardot, B., Parnaudeau, V., Houot, S., 2011. Near infrared reflectance spectroscopy: a tool to characterize the composition of different types of exogenous organic matter and their behaviour in soil. *Soil Biol. Biochem.* 43 (1), 197–205.
- Peng, X., Zhu, Q., Zhang, Z., Hallett, P.D., 2017. Combined turnover of carbon and soil aggregates using rare earth oxides and isotopically labelled carbon as tracers. *Soil Biol. Biochem.* 109, 81–94.

- Pérez-Piqueres, A., Edel-Hermann, V., Alabouvette, C., Steinberg, C., 2006. Response of soil microbial communities to compost amendments. *Soil Biol. Biochem.* 38 (3), 460–470.
- Phillips, J.D., Pawlik, Ł., Šamonil, P., 2019. Weathering fronts. *Earth Sci. Rev.* 198, 102925.
- Piazza, G., Pellegrino, E., Moscatelli, M.C., Ercoli, L., 2020. Long-term conservation tillage and nitrogen fertilization effects on soil aggregate distribution, nutrient stocks and enzymatic activities in bulk soil and occluded microaggregates. *Soil Tillage Res.* 196, 104482.
- Pierret, A., Maeght, J.L., Clément, C., Montoroi, J.P., Hartmann, C., Gonkhamdee, S., 2016. Understanding deep roots and their functions in ecosystems: an advocacy for more unconventional research. *Ann. Bot.* 118 (4), 621–635.
- Pires, L.F., Borges, J.A., Rosa, J.A., Cooper, M., Heck, R.J., Passoni, S., Roque, W.L., 2017. Soil structure changes induced by tillage systems. *Soil Tillage Res.* 165, 66–79.
- Platt, B.F., Kolb, D.J., Kunhardt, C.G., Milo, S.P., New, L.G., 2016. Burrowing through the literature: The impact of soil-distributing vertebrates on physical and chemical properties of soil. *Soil Sci.* 181, 175–191.
- Poelau, C., Sigurðsson, P., Sigurdsson, B.D., 2020. Depletion of soil carbon and aggregation after strong warming of a subarctic Andosol under forest and grassland cover. *Soil* 6 (1), 115–129.
- Poirier, N., Sohi, S.P., Gaunt, J.L., Mahieu, N., Randall, E.W., Powlson, D.S., Evershed, R. P., 2005. The chemical composition of measurable soil organic matter pools. *Org. Geochem.* 36 (8), 1174–1189.
- Pons, L.J., Van der Molen, W.H., 1973. Soil genesis under dewatering regimes during 1000 years of polder development. *Soil Sci.* 116 (3), 228–235.
- Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: processes and potential. *Glob. Chang. Biol.* 6 (3), 317–327.
- Qin, S., Chen, L., Fang, K., Zhang, Q., Wang, J., Liu, F., et al., 2019. Temperature sensitivity of SOM decomposition governed by aggregate protection and microbial communities. *Sci. Adv.* 5 (7), eaau1218.
- Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H.J., 2018. Soil structure as an indicator of soil functions: A review. *Geoderma* 314, 122–137. <https://doi.org/10.1016/j.geoderma.2017.11>.
- Rawls, W.J., Nemes, A., Pachepsky, Ya.A., 2004. Effect of soil organic matter on soil hydraulic properties. In: Pachepsky, A., Rawls, W.J. (Eds.), *Development of pedotransfer functions in Soil Hydrology. Developments in Soil Science*, vol 30. Elsevier, Amsterdam, pp. 95–114. ISBN 0-444-51705-7. Chapter 6.
- Read, D.J., Perez-Moreno, J., 2003. Mycorrhizas and nutrient cycling in ecosystems: a journey towards relevance? *New Phytol.* 157 (3), 475–492. Special Issue: Soil Microbes and Plant Production (Mar., 2003).
- Reichenbach, M., Fiener, P., Garland, G., Griepentrog, M., Six, J., Soetert, S., 2021. The role of geochemistry in organic carbon stabilization in tropical rainforest soils. *Soil*. <https://doi.org/10.5194/soil-2020-92>.
- Rice, T.D., Alexander, L.T., 1938. The physical nature of soil. In: Kellogg, C.E. (Ed.), *Soils and Men: Part IV. Fundamentals of Soil Science, Yearbook of Agriculture*. US Dep. of Agric., US Gov. Print. Office, Washington, DC.
- Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. *Physics* 1 (5), 318–333.
- Richardson, L.F., 1922. *Weather Prediction by Numerical Process*. Cambridge University Press.
- Richter, J., 1987. *The Soil as a Reactor: Modelling Processes in the Soil*. Catena paperback, Cremlingen, Germany.
- Rillig, M.C., Wright, S.F., Kimball, B.A., Pinter, P.J., Wall, G.W., Ottman, M.J., Leavitt, S. W., 2001. Elevated carbon dioxide and irrigation effects on water stable aggregates in a Sorghum field: a possible role for arbuscular mycorrhizal fungi. *Glob. Chang. Biol.* 7 (3), 333–337.
- Richter, D.D., Billings, S.A., 2015. One physical system: Tansley's ecosystem as Earth's critical zone. *New Phytol.* 206 (3), 900–912.
- Rillig, M.C., Aguilar-Trigueros, C.A., Bergmann, J., Verbruggen, E., Veresoglou, S.D., Lehmann, A., 2015. Plant root and mycorrhizal fungal traits for understanding soil aggregation. *New Phytol.* 205 (4), 1385–1388.
- Rillig, M.C., Muller, L.A., Lehmann, A., 2017. Soil aggregates as massively concurrent evolutionary incubators. *ISME J.* 11 (9), 1943–1948. <https://doi.org/10.1038/ismej.2017.56>.
- Robinson, D.A., Jones, S.B., Lebron, I., Reinsch, S., Domínguez, M.T., Smith, A.R., Jones, D.L., Marshall, M.R., Emmett, B.A., 2016. Experimental evidence for drought induced alternative stable states of soil moisture. *Sci. Rep.* 6 (1), 20018. <https://doi.org/10.1038/srep20018>.
- Robinson, D.A., Hopmans, J.W., Filipovic, V., van der Ploeg, M., Lebron, I., Jones, S.B., Reinsch, S., Jarvis, N., Tuller, M., 2019. Global environmental changes impact soil hydraulic functions through biophysical feedbacks. *Glob. Chang. Biol.* 25 (6), 1895–1904. <https://doi.org/10.1111/gcb.14626>.
- Roland, M., Serrano-Ortiz, P., Kowalski, A.S., Goddérís, Y., Sánchez-Cañete, E.P., Ciais, P., et al., 2013. Atmospheric turbulence triggers pronounced diel pattern in karst carbonate geochemistry. *Biogeosciences* 10 (7), 5009–5017.
- Roque-Malo, S., Woo, D.K., Kumar, P., 2020. Modeling the role of root exudation in critical zone nutrient dynamics. *Water Resour. Res.* 56 (8) (e2019WR026606).
- Rosenqvist, L., Kleja, D.B., Johansson, M.B., 2010. Concentrations and fluxes of dissolved organic carbon and nitrogen in a Picea abies chronosequence on former arable land in Sweden. *Forest Ecol. Manag.* 259 (3), 275–285.
- Rovira, A.D., Greacen, E.L., 1957. The effect of aggregate disruption on the activity of microorganisms in the soil. *Aust. J. Agric. Res.* 8, 659–673.
- Russell, A.E., Hall, S.J., Raich, J.W., 2017. Tropical tree species traits drive soil cation dynamics via effects on pH: a proposed conceptual framework. *Ecol. Monogr.* 87 (4), 685–701.
- Saintilan, N., Rogers, K., 2015. Woody plant encroachment of grasslands: a comparison of terrestrial and wetland settings. *New Phytol.* 205 (3), 1062–1070.
- Scharlemann, J.P., Tanner, E.V., Hiederer, R., Kapos, V., 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Manag.* 5 (1), 81–91.
- Schenk, H.J., Jackson, R.B., 2002. Rooting depths, lateral root spreads and below-ground/above-ground allometries of plants in water-limited ecosystems. *J. Ecol.* 90 (3), 480–494.
- Schenk, H.J., Jackson, R.B., 2005. Mapping the global distribution of deep roots in relation to climate and soil characteristics. *Geoderma* 126 (1–2), 129–140.
- Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Soil Survey Staff, 2012. *Field book for describing and sampling soils, Version 3.0*. In: Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.
- Schreiner-McGraw, A.P., Ajami, H., 2020. Impact of uncertainty in precipitation forcing data sets on the hydrologic budget of an integrated hydrologic model in mountainous terrain. *Water Resour. Res.* 56 (12) e2020WR027639.
- Schreiner-McGraw, A.P., Vivoni, E.R., Ajami, H., Sala, O.E., Throop, H.L., Peters, D.P., 2020. Woody plant encroachment has a larger impact than climate change on dryland water budgets. *Sci. Rep.* 10 (1), 1–9.
- Schwärzel, K., Zhang, L., Montanarella, L., Wang, Y., Sun, G., 2020. How afforestation affects the water cycle in drylands: A process-based comparative analysis. *Glob. Chang. Biol.* 26 (2), 944–959.
- Schwen, A., Bodner, G., Scholl, P., Buchan, G.D., Loiskandl, W., 2011. Temporal dynamics of soil hydraulic properties and the water-conducting porosity under different tillage. *Soil Tillage Res.* 113 (2), 89–98.
- Séré, G., Schwartz, C., Ouvrard, S., Renat, J.C., Watteau, F., Villemin, G., Morel, J.L., 2010. Early pedogenic evolution of constructed Technosols. *J. Soils Sediments* 10 (7), 1246–1254.
- Sharma, P.K., Aggarwal, G.C., 1984. Soil structure under different land uses. *Catena* 11 (1), 197–200.
- Sher, Y., Baker, N.R., Herman, D., Fossum, C., Hale, L., Zhang, X., Nuccio, Erin, et al., 2020. Microbial extracellular polysaccharide production and aggregate stability controlled by switchgrass (*Panicum Virgatum*) root biomass and soil water potential. *Soil Biol. Biochem.* 143, 107742.
- Sigen, C., Franklin, R.E., Johnson, A.D., 1997. Clay film effects on ion transport in soil. *Soil Sci.* 162 (2), 91–96.
- Singer, M.J., Southard, R.J., Warrington, D.N., Janitzky, P., 1992. Stability of synthetic sand-clay aggregates after wetting and drying cycles. *Soil Sci. Soc. Am. J.* 56 (6), 1843–1848.
- Singh, J., Singh, N., Kumar, S., 2020. X-ray computed tomography-measured soil pore parameters as influenced by crop rotations and cover crops. *Soil Sci. Soc. Am. J.* 84 (4), 1267–1279.
- Singh, N., Kumar, S., Udawatta, R.P., Anderson, S.H., de Jonge, L.W., Katuwal, S., 2021. Grassland conversion to croplands impacted soil pore parameters measured via X-ray computed tomography. *Soil Sci. Soc. Am. J.* 85 (1), 73–84.
- Six, J., Elliott, E.T., Paustian, K., Doran, J.W., 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. *Soil Sci. Soc. Am. J.* 62 (5), 1367–1377.
- Six, J., Frey, S.D., Thiet, R.K., Batten, K.M., 2006. Bacterial and fungal contributions to carbon sequestration in agroecosystems. *Soil Sci. Soc. Am. J.* 70 (2), 555–569.
- Six, J., Paustian, K., 2014. Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. *Soil Biol. Biochem.* 68, A4–A9.
- Six, J., Paustian, K., Elliott, E.T., Combrink, C., 2000. Soil structure and organic matter I. Distribution of aggregate-size classes and aggregate-associated carbon. *Soil Sci. Soc. Am. J.* 64 (2), 681–689.
- Six, J., Bossuyt, H., Degryse, S., Denef, K., 2004. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res.* 79 (1), 7–31.
- Skvortsova, E.B., 2009. Changes in the geometric structure of pores and aggregates as indicators of the structural degradation of cultivated soils. *Euras. Soil Sci.* 42 (11), 1254–1262.
- Sohi, S.P., Mahieu, N., Arah, J.R., Powlson, D.S., Madari, B., Gaunt, J.L., 2001. A procedure for isolating soil organic matter fractions suitable for modeling. *Soil Sci. Soc. Am. J.* 65 (4), 1121–1128.
- Soil Science Division Staff, 2017. Examination and description of soil profiles. In: Ditzler, C., Scheffe, K., Monger, H.D. (Eds.), *USDA Handbook 18. Government Printing Office, Washington, D.C.*, pp. 83–233.
- Soil Science Society of America, 2001. *Glossary of Soil Science Terms*. Soil Science Society of America, Madison, WI.
- Somararatne, N.M., Smettem, K.R.J., 1993. Effect of cultivation and raindrop impact on the surface hydraulic properties of an Alfisol under wheat. *Soil Tillage Res.* 26 (2), 115–125.
- Soong, J.L., Castanha, C., Pries, C.E.H., Ofiti, N., Porras, R.C., Riley, W.J., et al., 2021. Five years of whole-soil warming led to loss of subsoil carbon stocks and increased CO₂ efflux. *Sci. Advan.* 7 (21), eabd1343.
- Spohn, M., Giani, L., 2011. Impacts of land use change on soil aggregation and aggregate stabilizing compounds as dependent on time. *Soil Biol. Biochem.* 43 (5), 1081–1088.
- Stamati, F.E., Nikolaidis, N.P., Banwart, S., Blum, W.E., 2013. A coupled carbon, aggregation, and structure turnover (CAST) model for topsoils. *Geoderma* 211, 51–64.
- Steele, C.I., Lasaga, A.C., 1994. A coupled model for transport of multiple chemical species and kinetic precipitation/dissolution reactions with application to reactive flow in single phase hydrothermal systems. *Am. J. Sci.* 294 (5), 529–592.
- Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., Ludwig, C., 2015. The trajectory of the Anthropocene: the great acceleration. *Anthropocene Rev.* 2 (1), 81–98.

- Stillings, L.L., Drever, J.I., Poulson, S.R., 1998. Oxalate adsorption at a plagioclase (An47) surface and models for ligand-promoted dissolution. *Environmen. Sci. Technol.* 32 (19), 2856–2864.
- Stoops, G., 2018. Micromorphology as a tool in soil and regolith studies. In: Stoops, G., et al. (Eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*, 2nd ed. Elsevier, Amsterdam, pp. 1–19.
- Sullivan, P.L., Stoops, M.W., Macpherson, G.L., Li, L., Hirmas, D.R., Dodds, W.K., 2019. How landscape heterogeneity governs stream water concentration-discharge behavior in carbonate terrains (Konza Prairie, USA). *Chem. Geol.* 527, 118989.
- Striegl, R.G., Aiken, G.R., Dornblaser, M.M., Raymond, P.A., Wickland, K.P., 2005. A decrease in discharge-normalized DOC export by the Yukon River during summer through autumn. *Geophys. Res. Lett.* 32 (21).
- Sullivan, P.L., Li, L., Goddér, Y., Brantley, S.L., 2020. Poised to Hindcast and Earthcast the Effect of Climate on the Critical Zone: Shale Hills as a Model. *Biogeochemical Cycles: Ecological Drivers and Environmental Impact*, pp. 207–222.
- Swenson, S.C., Clark, M., Fan, Y., Lawrence, D.M., Perket, J., 2019. Representing intrahillslope lateral subsurface flow in the community land model. *J. Adv. Model. Earth Syst.* 11 (12), 4044–4065.
- Taina, I.A., Heck, R.J., Elliot, T.R., 2008. Application of X-ray computed tomography to soil science: A literature review. *Can. J. Soil Sci.* 88 (1), 1–19.
- Tao, F., Qi, Q., 2019. Make more digital twins. *Nature* 573, 490–491.
- Targulian, V.O., Krasilnikov, P.V., 2007. Soil system and pedogenic processes: Self-organization, time scales, and environmental significance. *Catena* 71 (3), 373–381.
- Terajima, T., Morizumi, M., 2013. Temporal and spatial changes in dissolved organic carbon concentration and fluorescence intensity of fulvic acid like materials in mountainous headwater catchments. *J. Hydrol.* 479, 1–12.
- Terribile, F., Coppola, A., Langella, G., Martina, M., Basile, A., 2011. Potential and limitations of using soil mapping information to understand landscape hydrology. *Hydrol. Earth Syst. Sci.* 15 (12), 3895–3933.
- Thompson, S.E., Harman, C.J., Heine, P., Katul, G.G., 2010. Vegetation-infiltration relationships across climatic and soil type gradients. *J. Geophys. Res. Biogeosci.* 115 (G2).
- Thorley, R.M., Taylor, L.L., Banwart, S.A., Leake, J.R., Beerling, D.J., 2015. The role of forest trees and their mycorrhizal fungi in carbonate rock weathering and its significance for global carbon cycling. *Plant Cell Environ* 38 (9), 1947–1961.
- Tian, J., Zong, N., Hartley, I.P., He, N., Zhang, J., Powlson, D., et al., 2021. Microbial metabolic response to winter warming stabilizes soil carbon. *Glob. Chang. Biol.* 27 (10), 2011–2028.
- Tiemann, L.K., Billings, S.A., 2011. Changes in variability of soil moisture alter microbial community C and N resource use. *Soil Biol. Biochem.* 43 (9), 1837–1847.
- Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. *Journal of Soil Science* 32 (2), 141–163.
- Torn, M.S., Trumbore, S.E., Chadwick, O.A., Vitousek, P.M., Hendricks, D.M., 1997. Mineral control of soil organic carbon storage and turnover. *Nature* 389, 170–173.
- Turk, J.K., Chadwick, O.A., Graham, R.C., 2012. Pedogenic processes, p. 30–1–30–29. In: Huang, P.M., et al. (Eds.), *Handbook of Soil Sciences: Properties and Processes*, 2nd ed. CRC Press, Boca Raton, FL.
- Utomo, W.H., Dexter, A.R., 1982. Changes in soil aggregate water stability induced by wetting and drying cycles in non-saturated soil. *J. Soil Sci.* 33 (4), 623–637.
- van der Meer, J.J.M., van Mourik, J.M., 2019. Soil micromorphology. In: van Mourik, J. M., van der Meer, J.J.M. (Eds.), *Reading the Soil Archives. Developments in Quaternary Sciences*, vol. 18. Elsevier, Amsterdam, pp. 1–30.
- van Genuchten, M.Th., 1985. General Approach for Modeling Solute Transport in Structured Soils (No. DOE/ER/60152–1-PT. 2).
- van Haren, J., Dontsova, K., Barron-Gafford, G.A., Troch, P.A., Chorover, J., Delong, S.B., et al., 2017. CO₂ diffusion into pore spaces limits weathering rate of an experimental basalt landscape. *Geology* 45 (3), 203–206.
- Vandevivere, P., Baveye, P., 1992. Effect of bacterial extracellular polymers on the saturated hydraulic conductivity of sand columns. *Appl. Environ. Microbiol.* 58 (5), 1690–1698.
- Vaz, C., Tuller, M., Lasso, P., Crestana, S., 2014. New Perspectives for the Application of High-Resolution Benchtop X-Ray MicroCT for Quantifying Void, Solid and Liquid Phases in Soils. In: Teixeira, W., Ceddia, M., Ottoni, M., Donnagema, G. (Eds.), *Application of Soil Physics in Environmental Analyses. Progress in Soil Science*. Springer, Cham, pp. 261–281. https://doi.org/10.1007/978-3-319-06013-2_12.
- Vereecken, H., Weynants, M., Javaux, M., Pachepsky, Y., Schaap, M.G., van Genuchten, M.Th., 2010. Using pedotransfer functions to estimate the van Genuchten–Mualem soil hydraulic properties: A review. *Vadose Zone J.* 9 (4), 795–820.
- Vermeulen, J., Grotenhuis, T., Joiasse, J., Rulkens, W., 2003. Ripening of clayey dredged sediments during temporary upland disposal a bioremediation technique. *J. Soils Sediments* 3 (1), 49–59.
- Vero, S.E., Macpherson, G.L., Sullivan, P.L., Brookfield, A.E., Nippert, J.B., Kirk, M.F., et al., 2018. Developing a conceptual framework of landscape and hydrology on tallgrass prairie: A critical zone approach. *Vadose Zone J.* 17 (1), 1–11.
- Viglizzo, E.F., Noretto, M.D., Jobbágy, E.G., Ricard, M.F., Frank, F.C., 2015. The ecohydrology of ecosystem transitions: a meta-analysis. *Ecohydrology* 8 (5), 911–921.
- Vilcaez, J., Li, L., Wu, D., Hubbard, S.S., 2013. Reactive transport modeling of induced selective plugging by leuconostoc mesenteroides in carbonate formations. *Geomicrobiol J.* 30 (9), 813–828.
- Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997a. Human domination of Earth's ecosystems. *Science* 277 (5325), 494–499.
- Vitousek, P.M., Chadwick, O.A., Crews, T.E., Fownes, J.H., Hendricks, D.M., Herbert, D., 1997b. Soil and ecosystem development across the Hawaiian islands. *GSA Today* 7, 3–7.
- Vohland, M., Bossung, C., Fründ, H.C., 2009. A spectroscopic approach to assess trace-heavy metal contents in contaminated floodplain soils via spectrally active soil components. *J. Plant Nutr. Soil Sci.* 172 (2), 201–209.
- von Lützw, M., Kögel-Knabner, I., Ekschmitt, K., Flessa, H., Guggenberger, G., Matzner, E., Marschner, B., 2007. SOM fractionation methods: relevance to functional pools and to stabilization mechanisms. *Soil Biol. Biochem.* 39 (9), 2183–2207.
- Voroney, R.P., Heck, R.J., 2015. Chapter 2 - the soil habitat. In: Paul, Eldor A. (Ed.), *Soil Microbiology, Ecology and Biochemistry*, Fourth edition. Academic Press.
- Wang, T., Wedin, D., Zlotnik, V.A., 2009. Field evidence of a negative correlation between saturated hydraulic conductivity and soil carbon in a sandy soil. *WRR* 45, W07503. <https://doi.org/10.1029/2008WR006865>.
- Walker, T.W., Syers, J.K., 1976. The fate of phosphorus during pedogenesis. *Geoderma* 15 (1), 1–19.
- Wang, B., Brewer, P.E., Shugart, H.H., Lerda, M.T., Allison, S.D., 2019. Soil aggregates as biogeochemical reactors and implications for soil-atmosphere exchange of greenhouse gases—A concept. *Glob. Chang. Biol.* 25, 373–385.
- Wang, C., Qu, L., Yang, L., Liu, D., Morrissey, E., Miao, R., Liu, Z., Wang, Q., Fang, Y., Bai, E., 2021. Large-scale importance of microbial carbon use efficiency and necromass to soil organic carbon. *Glob. Chang. Biol.* 27, 2039–2048.
- Warren, J., Ziegler, S.E., 2017. A solid phase extraction method for isolating HF-extractable soil organic matter for NMR analysis. *Org. Geochem.* 111, 1–8.
- Watson, K.W., Luxmoore, R.J., 1986. Estimating macroporosity in a forest watershed by use of a tuot infiltration meter. *Soil Sci. Soc. Am. J.* 50 (3), 578–582.
- Watteau, F., Huot, H., Séré, G., Begin, J.C., Rees, F., Schwartz, C., Morel, J.L., 2018. Micropedology to reveal pedogenetic processes in Technosols. *Spanish J. Soil Sci.* 8 (2), 148–163.
- Watteau, F., Jangorzo, N.S., Schwartz, C., 2019. A micromorphological analysis for quantifying structure descriptors in a young constructed Technosol. *Bol. Soc. Geol. Mex.* 71 (1), 11–20.
- Webb, J.R., Santos, I.R., Maher, D.T., Finlay, K., 2019. The importance of aquatic carbon fluxes in net ecosystem carbon budgets: a catchment-scale review. *Ecosystems* 22 (3), 508–527.
- Weil, R.R., Brady, N.C., 2017. *The Nature and Properties of Soil*. Pearson Publishing, New York.
- Wen, H., Perdrial, J., Abbott, B.W., Bernal, S., Dupas, R., Godsey, S.E., et al., 2020. Temperature controls production but hydrology regulates export of dissolved organic carbon at the catchment scale. *Hydrol. Earth Syst. Sci.* 24 (2), 945–966.
- Wen, H., Sullivan, P.L., Macpherson, G.L., Billings, S.A., Li, L., 2021. Deepening roots can enhance carbonate weathering by amplifying CO₂-rich recharge. *Biogeosciences* 18 (1), 55–75.
- West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Sci. Soc. Am. J.* 66 (6), 1930–1946.
- Whalley, W.R., Dumitru, E., Dexter, A.R., 1995. Biological effects of soil compaction. *Soil Tillage Res.* 35 (1–2), 53–68.
- White, R.E., 1985. The influence of macropores on the transport of dissolved and suspended matter through soil. In: Stewart, B.A. (Ed.), *Advances in Soil Science*, vol. 3. Springer, New York, NY. https://doi.org/10.1007/978-1-4612-5090-6_3.
- White, T., Brantley, S., Banwart, S., Chorover, J., Dietrich, W., Derry, L., et al., 2015. The role of critical zone observatories in critical zone science. In: *Developments in Earth Surface Processes*, vol. 19. Elsevier, pp. 15–78.
- Wieder, W.R., Grandy, A.S., Kallenbach, C.M., Bonan, G.B., 2014. Integrating microbial physiology and physio-chemical principles in soils with the Microbial-Mineral Carbon Stabilization (MIMICS) model. *Biogeosciences* 11 (14), 3899–3917.
- Wieder, W.R., Grandy, A.S., Kallenbach, C.M., Taylor, P.G., Bonan, G.B., 2015. Representing life in the Earth system with soil microbial functional traits in the MIMICS model. *Geosci. Model Dev.* 8 (6), 1789–1808.
- Wieder, W.R., Lawrence, D.M., Fisher, R.A., Bonan, G.B., Cheng, S.J., Goodale, C.L., et al., 2019. Beyond static benchmarking: Using experimental manipulations to evaluate land model assumptions. *Glob. Biogeochem. Cycles* 33 (10), 1289–1309.
- Wildenschild, D., Vaz, C.M.P., Rivers, M.L., Rikard, D., Christensen, B.S.B., 2002. Using X-ray computed tomography in hydrology: systems, resolutions, and limitations. *J. Hydrol.* 267 (3–4), 285–297.
- Wilpieszski, R.L., Aufrecht, J.A., Retterer, S.T., Sullivan, M.B., Graham, D.E., Pierce, E. M., Zablocki, O.D., Palumbo, A.V., Elias, D.A., 2019. Soil aggregate microbial communities: Towards understanding microbiome interactions at biologically relevant scales. *Appl. Environ. Microbiol.* 85 <https://doi.org/10.1128/AEM.00324-19> e00324-19.
- Xiao, D., Brantley, S.L., Li, L., 2021. Vertical connectivity regulates water transit times and chemical weathering at the hillslope scale. *Water Resour. Res.* 57 (8) <https://doi.org/10.1029/2020WR029207> e2020WR029207.
- Ye, J.S., Bradford, M.A., Dacal, M., Maestre, F.T., García-Palacios, P., 2019. Increasing microbial carbon use efficiency with warming predicts soil heterotrophic respiration globally. *Global Change Biol.* 25 (10), 3354–3364.
- Yoon, S.W., Giménez, D., 2012. Entropy characterization of soil pore systems derived from soil-water retention curves. *Soil Sci.* 177 (6), 361–368.
- Yudina, A., Kuzakov, Y., 2019. Saving the face of soil aggregates. *Glob. Chang. Biol.* 25 (11), 3574–3577.
- Zalasiewicz, J., Waters, C.N., Williams, M., Summerhayes, C.P. (Eds.), 2019. *The Anthropocene as a Geological Time Unit: A Guide to the Scientific Evidence and Current Debate*. Cambridge University Press.
- Zhang, X.C., Friedrich, J.M., Nearing, M.A., Norton, L.D., 2001. Potential use of rare earth oxides as tracers for soil erosion and aggregation studies. *Soil Sci. Soc. Am. J.* 65 (5), 1508–1515.

- Zhang, Y., Niu, J., Yu, X., Zhu, W., Du, X., 2015. Effects of fine root length density and root biomass on soil preferential flow in forest ecosystems. *Forest Syst.* 24 <https://doi.org/10.5424/fs/2015241-06048>.
- Zhi, W., Li, L., Dong, W., Brown, W., Kaye, J., Steefel, C., Williams, K.H., 2019. Distinct source water chemistry shapes contrasting concentration-discharge patterns. *Water Resour. Res.* 55 (5), 4233–4251.
- Zhi, W., Shi, Y., Wen, H., Saberi, L., Ng, G.H.C., Li, L., 2020. BioRT-Flux-PIHM v1. 0: a watershed biogeochemical reactive transport model. *Geosci. Model Dev. Discuss.* 1–41.
- Ziegler, S.E., Benner, R., Billings, S.A., Edwards, K.A., Philben, M., Zhu, X., Laganière, J., 2017. Climate warming can accelerate carbon fluxes without changing soil carbon stocks. *Front. Earth Sci.* 5, 2.
- Baver, L.D., 1934. A classification of soil structure and its relation to the main soil groups. *Soil Sci. Soc. Am. J.* 15 (2001), 107.