Received: 17 July 2020 | Revised: 4 May 2021 | Accepted: 20 July 2021

DOI: 10.1111/ejss.13152

INVITED OPINION ARTICLE

European Journal of Soil Science WILEY

# A holistic perspective on soil architecture is needed as a key to soil functions

Hans-Jörg Vogel[1] | Maria Balseiro-Romero[2] | Alexandra Kravchenko[3] | Wilfred Otten[4] | Valérie Pot[5] | Steffen Schlüter[1] | Ulrich Weller[1] | Philippe C. Baveye[6]

[1]Helmholtz Centre for Environmental Research - UFZ, Permoserstr, Leipzig, Germany

[2]CRETUS-Multidisciplinary Group in the Field of Environmental Technologies, Universidade de Santiago de Compostela, Santiago de Compostela, Spain

[3]Department of Plant, Soil and Microbial Sciences, Michigan State University, East Lansing, Michigan, USA

[4]School of Water, Energy and Environment, Cranfield University, Cranfield, UK

[5]INRAE, AgroParisTech. UMR ECOSYS, Thiverval-Grignon, France

[6]Saint Loup Research Institute, Saint Loup Lamairé, France

**Correspondence**

Hans-Jörg Vogel, Helmholtz Centre for Environmental Research - UFZ, Permoserstr. 15, 04318 Leipzig, Germany.
Email: hans-joerg.vogel@ufz.de

**Abstract**

Soil functions, including climate regulation and the cycling of water and nutrients, are of central importance for a number of environmental issues of great societal concern. To understand and manage these functions, it is crucial to be able to quantify the structure of soils, now increasingly referred to as their "architecture," as it constraints the physical, chemical and biological processes in soils. This quantification was traditionally approached from two different angles, one focused on aggregates of the solid phase, and the other on the pore space. The recent development of sophisticated, non-disturbing imaging techniques has led to significant progress in the description of soil architecture, in terms of both the pore space and the spatial configuration of mineral and organic materials. We now have direct access to virtually all aspects of soil architecture. In the present article, we review how this affects the perception of soil architecture specifically when trying to describe the functions of soils. A key conclusion of our analysis is that soil architecture, in that context, imperatively needs to be explored in its natural state, with as little disturbance as possible. The same requirement applies to the key processes taking place in the hierarchical soil pore network, including those contributing to the emergence of a heterogeneous organo-mineral soil matrix by various mixing processes, such as bioturbation, diffusion, microbial metabolism and organo-mineral interactions. Artificially isolated aggregates are fundamentally inappropriate for deriving conclusions about the functioning of an intact soil. To fully account for soil functions, we argue that a holistic approach that centres on the pore space is mandatory while the dismantlement of soils into chunks may still be carried out to study the binding of soil solid components. In the future, significant progress is expected along this holistic direction, as new, advanced technologies become available.

**Highlights**

- We highlight the crucial importance of the temporal dynamics of soil architecture for biological activity and carbon turnover.
- We reconcile controversial concepts relative to how soil architecture is formed and reshaped with time.
- Soil is demonstrated to be a heterogeneous porous matrix and not an assembly of aggregates.
- Biological and physical mixing processes are key for the formation and dynamics of soil architecture.

**KEYWORDS**

aggregation, bioturbation, organic matter, soil functions, soil mechanics, soil structure

## 1 | INTRODUCTION

A strong consensus exists among soil, environmental and agricultural science communities about the importance of soil structure and its role in soil functioning. Soils are widely recognized as highly heterogeneous three-dimensional porous systems (Six, Bossuyt, Degryze, & Denef, 2004), where pores define the boundaries among solid components. Thereby, the term “structure” is increasingly replaced by the term “architecture” (Baveye et al., 2018) to emphasize the close relationship between the arrangement of soil physical constituents in space and the functions that such arrangement enables. Soil architecture is manifested through spatial configuration of pore networks produced by well-known processes of root growth, faunal activity, swell–shrink dynamics, and freezing–thawing cycles, within a soil matrix containing primary pores between particles, variably cemented by organic molecules and physicochemical interactions. Evidently, there are a number of different architects involved in shaping soils, having different relative contributions depending on soil and site characteristics. The resulting architecture provides an enormous diversity of habitats for a myriad of soil organisms, including plants, and it allows water retention and the movement of water, gases and solutes across local gradients. Soil architecture can also be considered as a complex, heterogeneous, biogeochemical interface (Totsche et al., 2010) forming the basis for all essential soil functions, including plant growth, water storage, nutrient cycling, decomposition of contaminants and long-term storage of organic matter.

Despite a general consensus about its importance, there is considerable disagreement in the soil literature regarding the best strategy to study soil architecture, its formation and continuous reshaping (Rabot, Wiesmeier, Schlüter, & Vogel, 2018). Two fundamentally different approaches/perspectives have been developed. One focuses on the pore structure and pore–solid interfaces in undisturbed samples; for brevity, we will refer to it as the pore approach. The other one focuses on the composition and stability of isolated solid fragments (aggregates) as the central building blocks of soil architecture. We will refer to it as the aggregate approach. The two approaches emerged very early in the development of soil science (Figure 1) and remain in conflict to this day (Kravchenko, Otten, Garnier, Pot, & Baveye, 2019; Wang, Brewer, Shugart, Lerdau, & Allison, 2019a; Yudina & Kuzyakov, 2019). Recently, the conflict became more and more apparent and deepened as the general focus of soil science research shifted towards a more holistic process-based analysis of soil functioning (Meurer et al., 2020; Or, Keller, & Schlesinger, 2021). The latter is driven by recognition of the pressing need to identify the contributions of soils to the changing climate, to the processes involved, and to their modelling. This on-going shift was the main stimulus prodding us to re-evaluate the two approaches for their suitability for process-based predictions of the role of soils in the global environment.

One major point of controversy between the two approaches is that matter and energy fluxes through a volume of soil are affected if the volume is isolated and removed from the soil matrix where it originated. Gas, liquid and nutrient fluxes are expected to differ depending on whether or not this volume is at its original position, embedded in the three-dimensional context of an undisturbed soil (Kravchenko, Otten, et al., 2019). When it comes to the evaluation of soil functions such difference certainly matters. The pore approach recognizes the importance of the spatial position within a large-scale context of an undisturbed soil. The aggregate approach focuses on the small-scale context of individual aggregates, discarding their original positions within the soil matrix.

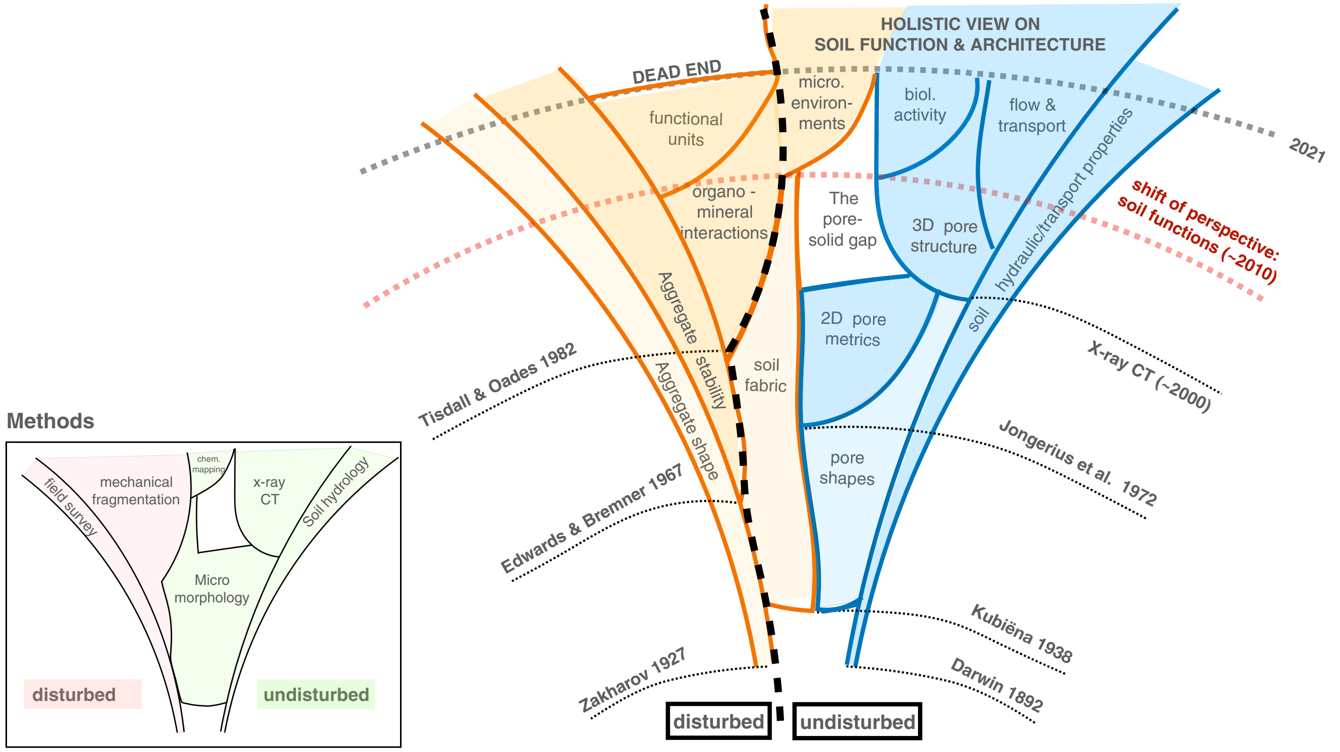


**FIGURE 1** Historical development of exploring soil structure. The pore perspective is in blue, the solid perspective in ochre. Dark colours and light colours indicate quantitative and qualitative analysis, respectively. New branches of developments with respect to research foci are marked by milestone publications or new technical developments

When looking at a more general picture of soil functioning, including carbon turnover, nutrient cycling, functional biodiversity, decomposition of contaminants, transport of water and solutes as well as stability and resilience of a soil system as a whole, it is important to know how the fabric of mineral and organic compounds is changing in time. The aggregate perspective attempts to infer these dynamics from assemblages of unconnected small soil fragments, thus overlooking the contributions of the larger-scale flows and movements. Whereas an aggregate can be a meaningful and convenient study object to analyse phenomena that take place at spatial scales of a few to tens of microns, the findings cannot be upscaled without considering large-scale processes. Yet, there are worrisome tendencies to view aggregates as distinct functional units having a certain lifetime and decay (Stamati, Nikolaidis, Banwart, & Blum, 2013; Wang et al., 2019a), based on the idea that mineral grains and organic matter rearrange in some self-organized process to form aggregates. The pore perspective suggests that, although the outcomes of changes in soil architecture can be quantified by enumerating aggregate size distributions and stabilities, such enumerations are not pertinent to the study of the processes driving the actual changes. Alternatively, the pore perspective recognizes the leading role of flow and mixing processes, including bioturbation and diffusion of dissolved organic carbon (DOC), generating a heterogeneous but coherent organo-mineral soil matrix permeated by a hierarchical pore system that disintegrates into fragments of different stability when mechanically loaded (Young, Crawford, & Rappoldt, 2001).

Whether we follow the one or the other perspective has important implications for what we consider to be the most relevant processes of soil structure formation and their impacts on biological activity as well as the turnover and stabilization of soil organic matter. Future avenues of research on soil functioning will depend on our understanding of the processes taking place within the three-dimensional architecture of the soil body and its temporal dynamics. Direct observations of this dynamics in natural, undisturbed soils are virtually impossible. Hence, the aggregate approach and soil sieving, as it is a fast and inexpensive tool of soil structure quantification, remained the mainstream of soil structure studies for decades, spanning a wealth of experiments and theoretical developments on the origin and turnover of the sieved aggregate outcomes. Recent major advancements in novel techniques enabling intact soil analyses with high spatial resolutions, for example, X-ray and neutron computed tomography scanning, XRF imaging, etc., bring the goal of observing the natural dynamic of soil architecture, along with exciting possibilities of observing water dynamic and chemical compositions, much more within reach. Accessibility to such tools for large soils science communities continues to grow. The analytical progress is the second major reason that we advocate for the need to re-evaluate the current perceptions of soil architecture.

In this general context, the present article provides an in-depth reflection on the state of the science concerning the architecture of soils, and on the questions that will need to be addressed on the path ahead. The article is organized as follows. The first section elaborates on the historical developments in how we approach the challenge of exploring and quantifying soil architecture (Figure 1). This includes a review of the progress made over the last 15 years on the study of the architecture of soils. The subsequent section deals with a holistic framework of the dynamics of soil architecture allowing for a consistent interpretation of observed phenomena. This also describes how insights into mechanisms of soil structure formation gained in the past via the aggregate approach, provided it be slightly reoriented, could easily be integrated into that framework. Then we critique the concepts of aggregates as “functional units” or “biogeochemical reactors” as fundamentally unsound. Finally, we discuss the implications of addressing soil functions based on soil architecture and outline possible paths for future research.

## 2 | HISTORICAL OVERVIEW OF EXPLORING SOIL ARCHITECTURE

The opaque nature of soil has always been a critical hurdle in investigating soil architecture. This was considerably improved by technical developments during the last decades. From early on (Figure 1), there were the two perspectives of either looking at the pore space or at the way soil disintegrates into characteristic solid fragments. For example, Darwin (1892) looked at pores and their importance for water infiltration and as a pathway for the incorporation of organic matter into soil by the action of earthworms. Hydraulic properties such as hydraulic conductivity, infiltration capacity and water retention characteristics are indirect methods to address pore scale attributes or functions that are still widely used today. Early in the last century, Zakharov (1927) proposed a classification scheme to characterize soil fragments and aggregates – Zakharov used both terms as synonyms – with respect to their size, shape and surface roughness. In principle, this approach is still part of soil mapping protocols in the field today. These two perspectives also differ in the way soils are investigated. Whereas the characterization of fragments requires dismantling the soil, the investigation of the pore space is only possible on undisturbed soil samples.

An essential cornerstone was set by one of the giants of soil science, Walter L. Kubiëna, who developed soil micromorphology based on impregnated soil samples (Kubiëna, 1939). This technique allowed researchers to investigate the pore space and the composition of the solid phase at the same time for a given sample with minimal disturbance. The latter was of central importance to Kubiëna. In Kubiëna's celebrated treatise on soil micromorphology, Kubiëna wrote that “a crushed or pulverized soil is related to the soil formed by nature like a pile of debris to a demolished building” (Kubiëna, 1939). Micromorphological analyses provided valuable insight into the relative distribution of pores and solid components pertinent for pedologic features and processes, such as the translocation of clay, the location of iron-oxides relative to the pore space, the distribution of faunal casts reflecting the decomposition pathways of organic litter, as well as mixing of organic and mineral compounds within the soil fabric. The latter was considered as a rigid skeleton of mineral grains partly impregnated by submicroscopic more mobile “plasma” of clay particles and organic compounds (Brewer & Sleeman, 1960). However, micromorphology suffered from the fact that it mainly allowed only qualitative analyses and, therefore, a lot of effort has been put into a well-defined terminology (FitzPatrick, 1993). Increasing computing power led to the first tools for automated image analysis, such as the Quantimet first applied to soils by Jongerius, Schoonderbeek, and Jager (1972). With that, the study of pore structures visible on thin sections and polished blocks could be raised to a quantitative level (Murphy, Bullock, & Turner, 1977). Yet, the restriction to two-dimensional sections out of the three-dimensional reality remained a sizeable challenge.

With the access to synchrotrons in various countries, and with the development and widespread commercialization of X-ray computed tomography (CT) scanners, the situation has changed drastically, starting from the early 1990s. From then on, as pointed out by Young et al. (2001), nothing stood in the way of fully three-dimensional explorations of the soil architecture. Much of the very significant progress achieved in that context since the early 2000s has been reviewed in detail by Baveye et al. (2018). X-ray CT almost completely replaced pore structure analysis of 2D sections. It provided the means to directly link soil architecture and functions.

Various mathematical techniques were developed to extract from three-dimensional CT images a wealth of quantitative information about the tortuosity, connectivity and topology of the pore space (Perret, Prasher, Kantzas, & Langford, 1999; Pierret, Capowiez, &

Moran, 2002; Vogel, Weller, & Schlüter, 2010). Initially, the essential focus was on soil physics of water and solute transport (Clausnitzer & Hopmans, 1999; Martys & Chen, 1996; Wildenschild & Sheppard, 2013). Another area where significant research is being carried out at the moment, generating substantial progress, concerns the effect of soil fauna on the geometry of the pore space in soils, and in particular on the development of biopores. The pioneering work carried out 30 years ago by Joschko et al. (1991) on earthworm burrow systems, monitored via low-resolution X-ray CT, has inspired various other authors to investigate the effects of bioturbation by earthworms on pore space geometry in repacked soil columns (Balseiro-Romero, Mazurier, Monoshyn, Baveye, & Clause, 2020; Capowiez, Gilbert, Vallat, Poggiale, & Bonzom, 2021; Capowiez, Monestiez, & Belzunces, 2001; Capowiez, Sammartino, & Michel, 2011) as well as in undisturbed soil cores (Cheik, Bottinelli, Minh, Doan, & Jouquet, 2019; Sauzet, Cammas, Gilliot, Bajard, & Montagne, 2017). In recent years, this research has been extended to other faunal groups than earthworms. Once they have been created by various organisms, the geometry and transport properties of biopores can evolve over time when they are colonized by plant roots (Yang, Varga, Liu, & Scheibe, 2017; Zhou et al., 2021).

Following the other path to studying soil fragments and aggregates, a considerable amount of work has been carried out during the last decades to analyse the constituents found in aggregates of different sizes and to explore the interactions and binding mechanisms involved. As recently summarized in the review by Totsche et al. (2018), there is a hierarchy of binding forces with decreasing strength starting from strong short-range van der Waals and electrostatic bindings, through organic compounds as gluing and cementing agents, such as oxides and hydroxides, down to more loose bindings by roots, hyphae or extracellular polymeric substances. Based on this hierarchy of binding forces, Edwards and Bremner (1967) introduced the notion of microaggregates using different methods for dispersing soils, such as ultrasonic vibrations and shaking with Na saturated solutions. They concluded that the increased binding forces in small aggregates are produced by interactions between clay minerals, organic molecules and polyvalent cations and they found the size of such microaggregates to be <250 μm. In larger aggregates, the binding forces are lower due to the presence of larger particles and also larger pores and particulate organic matter. This concept was adopted and further developed by Tisdall and Oades (1982) and Oades (1984), who laid the foundation for the hierarchical concept of aggregation considering the different scales across which the various binding forces are effective. They exemplified this concept for one soil type, noting that this hierarchy is expected to depend on the soil type. Organic fragments were presumed to be encrusted by clay particles to form aggregates.

With the development of standardized methods for the application of mechanical energy to dismantle soil in the laboratory the entities studied were considered to be fragments that are produced following a certain protocol. Díaz-Zorita, Perfect, and Grove (2002) found that this fragmentation process is continuous, with an inverse, non-linear relationship between the size of fragments and the applied mechanical stress. In parallel with these advances, the exploration of aggregate stability got a boost from an increased standardization of methods (Le Bissonnais, 1996). It should be noted that the aggregates produced by sieving procedures can be of both artificial and pedogenetic origin. There are well-known biological, physical and chemical processes leading to natural aggregate formation. This includes faecal pellets from various soil fauna groups, shrinkage of clay-rich soils leading to polyhedric aggregates, and the formation of pseudosands in tropical Oxisols. Although these aggregates can be easily detected even without special techniques, the origin of the fragments obtained after sieving is not at all obvious.

An important development based on aggregates was to study the organo-mineral interactions responsible for a considerable part of the binding forces (Totsche et al., 2018). This was amplified by the emerging understanding that the physical protection of soil organic matter is a highly relevant mechanism accounting for its long-term stabilization (Dungait, Hopkins, Gregory, & Whitmore, 2012; Schmidt et al., 2011) and that this is often associated with the occlusion of organic matter within dense parts of the soil matrix that could be sampled by fragmentation.

By the end of the 1980s, the two approaches to assessing soil structure – one based on aggregates and the other on the structure of the pore space – coexisted without much argument because there was not much intersection in terms of the research questions addressed. In Figure 1, this separation of research lines is illustrated by the “pore-solid gap”. During the last decade, however, the general research focus shifted for good reasons towards a more holistic understanding of soil functions and the role of soil architecture therein. This includes the importance of soil for carbon cycling, for the emissions of greenhouse gases, for water storage and purification, for biodiversity, and, last but not least, for the production of food and fibre.

To relate soil architecture and soil functions, it was common until then to define the soil structure as the “size, shape and arrangement of the solid particles and voids”, as noted by Letey (1991) and frequently expressed in this or similar ways by many others. Thus, the solid and the pore perspectives were the two sides of the same coin. Today there is an increasing trend to consider soil aggregates as self-organized functional units formed around organic kernels to act as bioreactors that control soil's functionality (Segoli et al., 2013; Stamati et al., 2013; Wang, Brewer, Shugart, Lerdau, & Allison, 2019b). We are convinced that this is a critical misconception. Many central soil processes, such as biological activity or the storage and transport of water and solutes, are clearly associated with the pore network. Hence, it is futile to study soil architecture as an assembly of aggregates.

There are recent developments in the field of chemical imaging providing a new possibility to analyse the structure of pores and that of the organo-mineral soil matrix together in undisturbed soils. This has great potential to boost our understanding of how soil functions are related to soil architecture and its dynamics. Today, it is also possible to visualize the distribution of organic matter relative to the 3D pore space using osmium as a tracer sorbed to organic compounds using X-ray CT (Peth et al., 2014). When looking at exposed two-dimensional surfaces, it is now possible to apply many different, powerful spectroscopic techniques to explore the chemical structure of the solid phase, as recently reviewed by Baveye et al. (2018). Admittedly, all these methods are afflicted by the problem of only providing information about two-dimensional sections, as was formerly the case with micromorphology. But today these methods can be combined with tomographic images of, for example, the pore structure, so that the results can be embedded in the three-dimensional representation of soil architecture. In the first article exploring this route, Hapca, Wang, Otten, Wilson, and Baveye (2011) combined chemical maps produced by SEM–EDX with 3D X-ray computed microtomographic images. This correlative microscopy approach has since been adopted to address various research questions (Juyal et al., 2019; Kravchenko et al., 2019; Lucas, Pihlap, Steffens, Vetterlein, & Kögel-Knabner, 2020; Schlüter, Eickhorst, & Mueller, 2018) and will certainly support the development of the required holistic approach to soil architecture in years to come.

## 3 | A HOLISTIC APPROACH TO SOIL ARCHITECTURE

As indicated in Figure 1, we call for a holistic view that integrates the spatial configuration of the pore space and the related spatial distribution of mineral and organic compounds. It is of critical importance to look at the natural architecture of soil with as little disturbance as possible. As described above, we do have the required technical tools at hand today.

Imaging techniques reveal soils as highly heterogeneous porous material, including primary pores between particles, secondary pores formed by roots or soil fauna, and abiotic processes. The impact of soil fauna includes the formation of bio-pores and the mixing of soil constituents in their guts to form casts of species-specific composition and density, while microorganisms are the main actors in the decomposition of organic matter. Soil architecture provides the required habitats for coexistence of a huge number of different species working hand in hand from a soil ecological point of view (Raynaud & Nunan, 2014). To build up and maintain the architecture of soils, the required energy is mainly provided in the form of organic matter originating from plants.

The supply of organic matter to the mineral soil matrix mainly happens along two major pathways. First, through litter at the soil surface mixed into soil via bioturbation or in the form of DOC with infiltrating water (Kaiser & Kalbitz, 2012), and second, via plants in the rhizosphere, which is a biologically highly active zone associated with the secondary pore systems where plant roots are growing and decaying (Vetterlein et al., 2020). Organic tissues from litter, dead roots or organic molecules from root exudates are to a large extent reconfigured to build up microbial biomass or more stable organic compounds. A considerable part is finally decomposed to organic molecules decreasing in molecular weight with time (Lehmann & Kleber, 2015). Thereby, organic matter is getting more and more mobile in the form of DOC. This mobile organic fraction can be metabolized and mineralized by microorganisms but, to some extent, may also permeate the soil mineral fabric by advection or diffusion. This may happen over very short distances that are nevertheless large enough to get out of reach for microbes and impair further decomposition. In this way organic molecules come into close contact with mineral surfaces where they can be attached through physicochemical interactions while the binding forces between mineral particles are substantially increased. This stabilization process is happening at the μm scale but contributes to the coherence of particles at the 100 μm scale. Bioturbation is another highly relevant mixing process acting at much larger scales (mm to cm). Especially earthworms but also many other organisms, belonging to a vast array of different faunal groups (e.g., Briones, 2014, 2018; Zanella, Ponge, and Briones, 2018) are kneading mineral and organic matter in their guts and bringing the different components into close contact. Thereby, they constantly create new pores of different sizes. The growth of fungal hyphae into narrow pores within the soil matrix, leaving behind organic

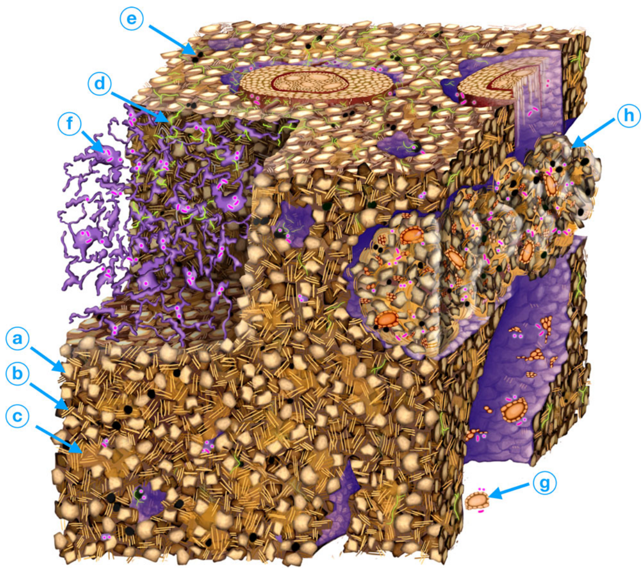


**FIGURE 2** Schematic sketch of the typical structural organization of fine-textured soil. The organo-mineral soil matrix is composed of quartz grains (a), clay minerals (b), organic coatings on mineral surfaces (c), amorphous, particulate organic matter (e) and organic tissues (g). In the upper left corner, the highly connected pore space between mineral grains is illustrated, where fungi (d) frequently associated with roots and bacteria (f) are active. As an example of biotic mixing, an earthworm cast (h) is drawn on the right side. The hotspots of biological activity are locations where carbon sources are available for the microbiome, living in pores of appropriate size. Mobile organic and mineral compounds may diffuse through the connected pore space within the rigid skeleton of mineral grains, leading to a heterogeneous organo-mineral soil matrix. The drawing is not meant to be true to scale to better illustrate the relevant components (Graphics: Lisa Vogel, www.lisavogel-illustration.de)

molecules by exudation or after hyphal decomposition, can be considered as another mechanism of biotic mixing (Rillig & Mummey, 2006). Bacteria, archaea and fungi are virtually ubiquitous in soils as long as pores are large enough to accommodate their size. The materials produced by soil fauna or roots diffusing or percolating through the pore network are bound sooner or later to be used by these organisms for their sustenance. It should be emphasized that all of the above processes are reliant on flows, transports and movements that, by definition, can take place only through soil pores, in turn creating, modifying and rearranging them.

The picture that eventually emerges from the combination of these various processes is that of a heterogeneous organo-mineral soil matrix, illustrated schematically in Figure 2. The resulting architecture is reflected by the spatial configuration of primary pores between particles, variably cemented by organic molecules and pervaded by a secondary pore network at a higher hierarchical level produced by well-known processes such as root growth, faunal activity, swell–shrink dynamics and freezing–thawing cycles. If exposed to mechanical stress, this organo-mineral soil matrix disintegrates into fragments along zones of relative weakness. When increasing the stress, they are further partitioned into smaller fragments of increased internal coherence. This is exactly what we observe when we isolate aggregates using various standard methods of wet- and dry-sieving to study them for their size distribution, stability or internal constituents. In this picture, aggregates that are produced by sieving are zones of different density and coherence produced by mixing processes as described above.

A significant aspect of this picture of soil architecture is that none of the processes on which the focus comes naturally in that context is hypothetical. Ample experimental evidence exists concerning all of them. For example, in subsoils where bioturbation is limited, Kautz (2015) has observed a clear gradient in organic matter content close to macropores generated by roots and earthworms. In a Luvisol, Hoang et al. (2016) found this same pattern to be more pronounced for the soil material around earthworm channels as compared to old root channels. Similarly, based on visualization of bacteria in soil thin sections, Nunan, Wu, Young, Crawford, and Ritz (2003) found an increase of bacterial densities close to large pores in the subsoil, unlike in the topsoil where mixing by bioturbation and/or tillage is much more prevalent. Lehmann, Kinyangi, and Solomon (2007) concluded from the spatial distribution and quality of organic compounds in chunks of soil subjected to spectroscopic analysis that these organic compounds are stabilized by mobile microbial metabolites.

For mature soils, the resulting architecture, which is assumed to be in some steady state or in a very slowly evolving state, reflects the local site conditions in terms of the major factors of soil formation according to Jenny (1941). This is why soil architecture is so closely linked to functional characteristics and why we should put substantial scientific effort into understanding its formation, stability and resilience. In general, except for some agricultural interventions, this architecture is found to be surprisingly stable in terms of its macroscopic properties, whereas understanding its microscopic dynamics remains a formidable scientific challenge. Some important soil functions, such as the turnover and stabilization of organic matter, depend on this dynamic. This is why we need to consider soil as a whole, including the transport processes and pathways required for internal dynamics of soil architecture.

## 4 | A CRITICAL ANALYSIS OF AGGREGATES AS FUNCTIONAL UNITS

The holistic view described in the previous section is in contrast to the idea of aggregates as functional units that are formed in situ by some self-organized process. The term “aggregation,” which is frequently used to characterize the state of soil structure, indeed suggests the presence of an aggregation process in the sense of some agglutination of smaller building blocks, such as mineral grains and organic matter, to form larger units. Following this idea, a widespread conception today is that macroaggregates are formed around particulate organic matter (POM) acting as an initial kernel of aggregate formation. Fuelled by available carbon sources, microbes and especially fungi produce binding agents that increase cohesion between POM and mineral particles to form macroaggregates. In the course of further decomposition, low-molecular-weight organic compounds are increasingly produced, having a high affinity to mineral surfaces, strengthening the binding forces locally. This leads to the formation of microaggregates within macroaggregates as postulated by Six et al. (2004) and the idea of a characteristic life cycle of aggregates that are constantly formed anew and disintegrate again. This turnover of aggregates is considered to be of central importance for carbon cycling in soil. A considerable body of literature is based on this conception and a number of models have been recently suggested and developed to simulate this process of aggregate formation related to carbon cycling in soil (Segoli et al., 2013; Stamati et al., 2013; Wang et al., 2019b).

It is very notable that aggregate cycling envisaged from this perspective does not involve any explicit reference to pores, the rhizosphere, their spatial organization or their temporal dynamics. The presence of pores of different sizes, implicitly assumed in this conceptual framework, appears to be a mere outcome of the coagulation of soil particles by microorganisms and their products. The notion of intra- and interaggregate porosity, which is frequently used to characterize the pore space, can be seen as a by-product of this perspective. It reflects the view that there is a separable inside and outside of aggregates considered as distinct functional units. Given that mixing and transport processes are driving structure formation, this approach is misleading. However, unfortunately, microscopic processes of structure formation do not lend themselves to direct observation in situ. This is why we need to rely on a “presumptive trial” based on observable phenomena to infer the processes involved. This is carried out in the following:

### 4.1 | Imaging soil structure

Using imaging tools to visualize undisturbed soils, distinct and separable structural units, such as micro- and macroaggregates, are hardly ever observed. This is true for 3D imaging based on modern X-ray tomography but also in the classical field of soil micromorphology, based on the analysis of thin sections. Indeed, the terms “micro-” and “macroaggregate” are virtually absent in the micromorphological literature although these methods operate at exactly the same spatial scale as that of micro- and macroaggregates. In this respect, Or et al. (2021) have recently pointed out very perceptively that “the common notion of inter-aggregate macroporosity is probably rooted in tilled soil structure” since “natural soil aggregates are seamlessly embedded in the surrounding soil matrix, whereas tillage-produced fragments are often loosely packed and form inter-fragment spaces.” This clearly contradicts the view of aggregates as distinct functional units, which requires that they are surrounded by some other material (or pores) to be distinct.

### 4.2 | Mobility of aggregate constituents

The skeleton of mineral grains within soils is rather rigid. Except for swelling/shrinkage and freezing/thawing processes, mineral particles are hardly mobile on their own, as postulated by the aggregate turnover concept. Another exception is the translocation of dispersed clay particles to deeper soil horizons during pedogenesis of, for example, Luvisols. Among the constituents of aggregates the most mobile one is organic matter in the form of DOC. As shown by Miltner, Bombach, Schmidt-Brücken, and Kästner (2012), stabilized SOM originates to a considerable degree from soil microorganisms in the form of small particulate SOM (i.e., cell residues) that might be mobile in the soil solution as well. In their recent opinion paper, Lavallee, Soong, & Cotrufo (2020) discuss DOC that may reach mineral surfaces via diffusion as a major source for the formation of organo-mineral complexes. This provides the glue between mineral grains and leads to a heterogeneous soil matrix according to the holistic approach suggested above. However, there is also larger particulate organic matter found within compact (macro) aggregates (Tisdall & Oades, 1982). Although the clustering of mineral particles around organic debris is unlikely due to their reduced mobility, a highly efficient process for this type of mixing is bioturbation, especially by earthworms. It has been shown that in a temperate deciduous forest, earthworms with a biomass of 10 g dry weight $m^{-2}$ managed to incorporate the annual litter fall of 5 t $ha^{-1}$

into the soil (Schaefer & Schauermann, 1990). This bioturbation also triggers microbial activity and further decomposition of organic matter within the casts and by this contributes significantly to the formation of the heterogeneous soil matrix.

## 4.3 | Internal structure of aggregates

The existence of aggregates as functional units and the postulated formation process based on organic kernels suggest some internal pattern of constituents. Having this hypothesis in mind, Lehndorff et al. (2021) analysed the inner structure of a large number (60) of microaggregates extracted from Luvisols with different clay contents. They used electron probe microanalysis (EPMA) for elemental mapping and found a clear correlation between plant detritus and microbial organic matter. However, beyond this, no spatial organization could be found at all. The authors finally concluded "that well-established macro-scale correlations between contents of pedogenic oxides and clay minerals with soil organic matter storage do not apply to soil microaggregates." This confirmed a previous study of Voltolini, Taş, Wang, Brodie, and Ajo-Franklin (2017), who could not find any structural pattern within microaggregates (≈250 μm) of two different soils using X-ray microtomography.

## 4.4 | Formation of organo-mineral complexes and microaggregates

It is undisputed today that the sorption of organic compounds on mineral surfaces is considered to be key to explaining the stability of the soil matrix (or aggregates). This sorption happens on mineral surfaces at the nanometre scale and provides the glue between clay and silt particles (Totsche et al., 2018). Recently, Huang et al. (2020) demonstrated how onion-like layers of organic coatings are formed on mineral surfaces within a couple of days when organic compounds are available in the form of DOC. They also showed that the quality of these layers is highly sensitive to the presence of microorganisms and their metabolic activity. This is in agreement with the findings of Lehmann et al. (2007), who found a random patchy distribution of carbon deposits within microaggregates of different soils using infrared (FTIR) and near-edge X-ray absorption (NEXAFS) spectroscopy. They found a spatial correlation between aliphatic and aromatic carbon forms with clay minerals and concluded that the dominant process in carbpn stabilization is adsorption of previously mobile organics on mineral surfaces rather than occlusion of organic debris by adhering clay particles. All this indicates that mobile organic matter may impregnate the rigid skeleton of mineral grains to increase mechanical stability, rather than mineral grains arranging themselves around organic compounds to form distinct aggregates.

## 4.5 | Aggregation process in vitro

There were attempts to reproduce the process of aggregation in laboratory experiments looking at suspensions or homogeneous mixtures of different constituents. In such artificial mixtures, agglomeration of these constituents is observed at pretty short time scales (Pronk, Heister, Ding, Smalla, & Kögel-Knabner, 2012; Rabbi, Minasny, McBratney, & Young, 2020). De Gryze, Six, and Merckx (2006) and Peng, Zhu, Zhang, and Hallett (2017) used rare elements to mark aggregates of different size to monitor how quickly these markers are found in other aggregate sizes classes. Also, in these experiments the observed time scales were found to be very short, in the range of weeks to months. However, these experiments are performed on repacked soil, which is repeatedly exposed to drying and subsequent wet sieving. In another microcosm experiment, Bucka, Kölbl, Uteau, Peth, and Kögel-Knabner (2019) used mixtures of mineral grains with POM and DOC incubated at constant water potential to avoid any effects of wetting-drying cycles. They could demonstrate the formation of water stable macroaggregates after only 4 weeks of incubation. This effect was more pronounced for added POM as compared to DOC due to the growth of biofilms on POM particles. In any case, they found that the composition of the obtained aggregates reflects the original composition of the mixture. This confirms that the observed aggregates do not differ from the bulk material in the sense of forming distinct functional units. All these experiments confirm that organic matter in concert with microbial activity is highly effective in increasing the cohesion between soil particles. However, it is by no means obvious how to transfer the findings to the dynamics of soil structure within natural soil.

## 4.6 | Age of organic carbon within aggregates

The age of organic matter found in microaggregates is pretty old, most of it is older than about 300 years (Balesdent, Chenu, & Balabane, 2000; Guggenberger & Haider, 2002). This indicates that microaggregates are rather cold spots that are stable over a very long time. This is in contrast to the turnover times in the range of weeks or months as measured in the laboratory experiments based on homogeneous mixtures and previously isolated aggregates cited above.

A key conclusion of all these observations is that aggregates isolated by dismantling the soil cannot be considered as functional units, and that by adopting the aggregate concept the conclusions that are drawn may be unconsciously biased in that direction. If we focus on all the observable phenomena from very different perspectives, such as the morphology of the 3D pore network, the fabric of the organo-mineral soil matrix, the quality of organic matter and binding agents, we must come to a conclusion that it is inappropriate to study soil architecture as an assembly of aggregates, just as it is inadequate to infer the function of a building from a pile of the rubble resulting from its destruction, an analogy along the lines of what Walter Kubiëna wrote many years ago.

It appears much more appropriate that the contribution of soil architecture to soil functioning is addressed by analysing the formation of pores, in which most processes take place. The heterogeneity of solid constituents in between these pores also depends to a large degree on the morphology of the pore system and various mixing processes brought about by water flow, molecular diffusion and bioturbation. Examples of implementing this approach are becoming more and more frequent. For example, Kravchenko, Guber, et al. (2019) showed that the propensity of roots from different vegetation covers to form new pores in a size range optimal for microbial carbon processing (30–150 μm) mainly explains their divergent soil carbon stocks.

## 5 | IMPLICATIONS FOR MODELLING SOIL FUNCTIONS

In the next few years, as demands intensify to better understand the link between the architecture of soils and the various functions and services that we expect them to fulfil, soil research will need to continue shifting its attention to a range of processes that cannot be fully assessed at the scale of soil fragments or aggregates. These include first and foremost the different biotic and abiotic processes that contribute to the creation of pores of various sizes. In terms of the biotic factors, the zone of highest biological activity is the rhizosphere and the soil pore space associated with it, where the vast majority of energy in the form of carbon sources is provided and processed by soil biota. Research should be increasingly directed toward pore formation and functioning in the rhizosphere as well as to the physical framework, enabling mixing processes, such as diffusion of DOC and bioturbation. Both processes are under-represented in current research agendas. Moreover, the importance of soil architecture for physical protection and related long-term storage of soil organic matter should be explored from the perspective of the pore space. The same is true for processes sensitive to redox conditions such as denitrification. Today it is possible to quantify distances inside the soil matrix with respect to the pore network, which can be related to diffusion lengths for organic compounds, exoenzymes or oxygen (Kravchenko et al., 2018; Rohe et al., 2021; Schlüter, Zawallich, Vogel, & Dörsch, 2019). This pore network can be characterized in terms of pore size, with implications for the accessibility for different organisms and the dynamic distribution of water and gases. This can and should be performed without disturbance of the natural soil architecture, because disturbance will alter the connecting paths and distort flows, in the worst case misrepresenting the actual drivers of observed phenomena. Current models of denitrification based on the aggregate concept as proposed by Ebrahimi and Or (2018) could be easily translated to a pore perspective by changing the aggregate size distribution to a distribution of distances of any location within the soil matrix to the nearest air-filled pore. This would account for the fact that aggregates are not necessarily surrounded by air-filled pores at their original location in the undisturbed soil, as implied by the aggregate perspective. Moreover, the pore perspective allows one to consider how distances to the air-filled porosity change with changing water saturation. Based on the more holistic approach suggested here, we can describe soil architecture and its dynamics, including its impact on the turnover of organic matter, by invoking features that are directly observable in undisturbed soil, that is, the hierarchical pore geometry of soil and the chemical heterogeneity of the soil matrix. We need not rely on a process of aggregate formation that is not observable and for which the underlying mechanisms are not readily obvious.

The recent article by Meurer et al. (2020) provides a very enlightening example of how a model concept based on aggregates may turn towards a pore perspective for practical and scientific reasons. These authors' aim was to model the dynamic interactions between soil structure and the storage and turnover of soil organic carbon (SOC). At the beginning of their article, they argue that "the aggregated structure of soil is known to protect SOC from decomposition and, thus, influence the potential for long-term sequestration. In turn, the turnover and storage of SOC affects soil aggregation, physical and hydraulic properties and the productive capacity of soil." They then set out to develop a new computational model of the "dynamic feedbacks between soil organic matter (SOM) storage and soil physical properties (porosity, pore size distribution, bulk density and layer thickness)." In the process of developing this model, they first performed a sensitivity analysis and also investigated parameter identifiability using a synthetic dataset. This was done because, following Juston, Andrén, Kätterer, and Jansson (2010) and Luo, Wang, and Sun (2017), they argue that the data usually available from field experiments to test models of SOM storage and turnover may be insufficient to uniquely identify the parameters of even the simplest models. "Such problems of parameter non-identifiability or equifinality (Beven, 2006) may introduce considerable uncertainties into model predictions under changing agro-environmental conditions." As a result of their sensitivity and parameter identifiability analysis, Meurer et al. (2020) decided to focus on the dynamics of the soil pore space, and invoked the term of aggregation solely to refer to the generation of additional pore space in soil associated with the presence of organic matter. Based on empirical observations, they assumed a linear relationship between this aggregation pore volume and the volume of SOM. Thus, Meurer et al. (2020) write, "individual soil aggregates are not considered as explicit entities in this model" and, as Kuka, Franko, and Rühlmann (2007) had earlier, they propose a strictly pore-based model instead. A similar approach was followed by Falconer et al. (2015), who showed that SOM dynamics was regulated by accessibility determined by the soil pore network, as well as the way organic matter and microorganisms are arranged and can move within the pore space. This did not require an a priori assumption about protection of organic matter within aggregates.

In order to carry out a research programme based on the proposed holistic approach, it is clear that interdisciplinary research will be essential, at a much larger scale than in the past, and involving disciplines that have not had a tradition of collaborating together. There have been many such calls for interdisciplinary research in the last decade (e.g., Cayuela, Clause, Frouz, and Baveye, 2020). Erktan, Or, and Scheu (2020) in their very good recent review of the literature on the effect of the physical structure of soil on trophic interactions among organisms "unable to deform the soil," describe possible future ways for interdisciplinary and more quantitative research merging soil physics and soil food web ecology. This type of joint research, extended to include organisms such as earthworms that modify soil pores, will have to become central in the research. Soil physicists will have to work hand in hand with soil ecologists and plant scientists, in particular, to make the research agenda move forward. Like any interdisciplinary endeavour, this one will not be easy, and will be undoubtedly slowed down by all the usual impediments to such efforts, including some due to the current training of soil scientists, overemphasizing monodisciplinary specialization (Baveye & Wander, 2019). Yet one should perhaps find hope in the fact that soil microbiologists and (bio)chemists have been able to work together increasingly in the last decade on the fate of SOM. The same might now happen with other disciplines.

## 6 | CONCLUSIONS

The architecture of soils in terms of the spatial arrangement of a hierarchical pore network and the various mineral and organic components is key for an improved understanding of soil functions. A critical scientific challenge is to understand how this architecture is formed and continuously reshaped to bring about soil functions such as carbon storage, nutrient cycling, providing the habitat for an enormous functional biodiversity, water storage and the degradation of contaminants.

In this paper we propose a holistic approach for the formation and functionality of this architecture. It is based on the soil's hierarchical pore network and the rhizosphere as the major pathways and locations where organic matter is supplied to a heterogeneous organo-mineral soil matrix that is mainly formed by mobile organic compounds and mixing processes brought about by diffusion and bioturbation. This view contrasts with the approach centred around the formation of aggregates as basic building blocks and functional units of soil architecture, which has been increasingly developed during the last two decades.

Because we do not have the technical tools to directly observe the formation and dynamics of soil architecture in situ we need to rely on observable phenomena to draw conclusions on the key processes of structure formation. We do this based on available imaging methods and characteristics of soil organic matter. The holistic approach we recommend, in conclusion, clearly mandates that we consider soils in their undisturbed spatial configuration and not dismantled into aggregates or fragments, in which case much of the soil pore space no longer subsists.

After such a shift in perspective, soil volumes sampled by various sieving protocols are considered as local zones of different densities and different internal coherence, and we need to sacrifice the idea of some self-organized process of hierarchical aggregate formation, which, until now, has never been observed in natural, that is, undisturbed, soils. Such a shift in perspective should not be a huge leap either for those who focus their research on aggregates. In their often-cited review, Six et al. (2004) very aptly noted that studies often use "aggregate measurements as surrogates of the, in itself, complex soil matrix."

We are convinced that the increasing development of imaging technologies to quantify the spatial structure not only of the pore network but also of the mineral and organic components relative to this pore network will pave the way towards the proposed holistic approach explored in interdisciplinary teamwork of soil scientists.

## ACKNOWLEDGEMENT

Open access funding enabled and organized by Projekt DEAL.

## AUTHOR CONTRIBUTIONS

**Hans-Joerg Vogel:** Conceptualization (lead). **María Balseiro-Romero:** Conceptualization (supporting); writing-review & editing (equal). **Alexandra Kravchenko:** Conceptualization (equal); writing - original draft (equal); writing-review & editing (equal). **Wilfred Otten:** Conceptualization (equal); writing - original draft (equal); writing-review & editing (equal). **Valerie Pot:** Conceptualization (supporting); writing-review & editing (equal). **Steffen Schlueter:** Conceptualization (supporting); writing-review & editing (equal). **Ulrich Weller:** Conceptualization (supporting); writing-review & editing (equal). **Philippe Baveye:** Conceptualization (equal); writing - original draft (equal); writing-review & editing (equal).

## DATA AVAILABILITY STATEMENT

Data sharing not applicable - no new data generated.

## ORCID

*Hans-Jörg Vogel* https://orcid.org/0000-0003-2404-9485
*Maria Balseiro-Romero* https://orcid.org/0000-0003-0831-3899
*Alexandra Kravchenko* https://orcid.org/0000-0001-5920-927X
*Philippe C. Baveye* https://orcid.org/0000-0002-8432-6141

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**How to cite this article:** Vogel, H.-J., Balseiro-Romero, M., Kravchenko, A., Otten, W., Pot, V., Schlüter, S., Weller, U., & Baveye, P. C. (2022). A holistic perspective on soil architecture is needed as a key to soil functions. *European Journal of Soil Science*, *73*(1), e13152. https://doi.org/10.1111/ejss.13152