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Lessons of a landmark 1991 article on soil structure: Distinct precedence of non-destructive assessment and benefits of fresh perspectives in soil research[1]

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Abstract
In 1991, at the launch of a national symposium devoted to soil structure, the Australian Society of Soil Science invited Professor John Letey to deliver a keynote address, which was later published in the society's journal. In his lecture, he shared the outcome of his reflection about what the assessment of soil structure should amount to, in order to produce useful insight into the functioning of soils. His viewpoint was that the focus should be put on the openings present in the structure, rather than on the chunks of material resulting from its mechanical dismantlement. In the present article, we provide some historical background for Letey's analysis, and try to explain why it took a number of years for the paradigm shift that he advocated to begin to occur. Over the last decade, his perspective that soil structure needs to be characterized via non-destructive methods appears to have gained significant momentum, which is likely to increase further in the near future, as we take advantage of recent technological advances. Other valuable lessons that one can derive from Letey's pioneering article relate to the extreme value for everyone, even neophytes, to constantly ask questions about where research on given topics is heading, what its goals are, and whether the methods that are used at a certain time are optimal.

Introduction

From the 1950s to the 80s, the topic of soil structure attracted considerable attention amongst soil scientists in Australia, and the scientific literature contains many frequently-cited contributions on the subject by Australian researchers of that era (e.g., Emerson, 1959, 1967; Rose, 1961; Tisdall and Oades, 1979, 1982). In this context, the Australian Society of Soil Science decided in 1991 to hold a national symposium devoted entirely to soil structure, a proposal that was received enthusiastically by most eminent local experts, who accepted to present their work at the event. The organization of the symposium, and the subsequent publication of conference papers in the then *Australian Journal of Soil Research*, was entrusted to the Victorian branch of the society whose president, Dr. Pichu Rengasamy, was keen on asking an international scientist to deliver a keynote lecture. He and his colleague, Dr. Ken Olsson, with the endorsement of the organization committee, proposed to invite Professor John Letey, of the University of California at Riverside, for that purpose.

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In many ways, this invitation was a bold move. Professor Letey was a very prominent soil scientist, and frequently delivered keynote addresses at national or international meetings, so in that sense his selection was a no-brainer. However, until then, he had written very little on soil structure *per se*. He mentioned the topic in a book chapter on the physical properties of soils (Letey, 1977) and in an abundantly-cited review article on the response of soils to sodic and saline conditions (Shainberg and Letey, 1984). For a number of years, he collaborated with several researchers on the effect that addition of polymeric soil conditioners could have on soil dispersion and water infiltration (Aly and Letey, 1988, 1990; Helalia and Letey, 1988a,b; Ben-Hur et al., 1989; Nadler and Letey, 1989), and in that context he dealt briefly with aggregate stability (Helalia and Letey, 1989). In a celebrated article (Letey, 1985) in which he promoted the now popular notion of "non-limited water content" (NLWR), the extent to which he dealt with soil structure, which he mentions in passing only twice, was to write that "the traditionally measured soil physical properties such as bulk density, aggregate stability index, texture, etc., may not be the most helpful in judging the productivity potential of a soil". Aside from this remark, he had not proceeded in any detail to a critical analysis of the concepts of soil structure and aggregate stability, or of their measurement. Nevertheless, Drs. Rengasamy and Olsson were keen to get his opinion on the topic. In particular, they were excited about the NLWR, and were interested to hear Professor Letey's views about its "possible use to quantify the effects of sodicity on soil structure so that a distinction could be made between sodic and saline soils".

In characteristic fashion, Professor Letey not only enthusiastically accepted the invitation, but also rose to the challenge of an assignment that for many other researchers would have been incredibly daunting: delivering a keynote address on a topic on which he had hardly worked at all, in front of an audience encompassing many of the world's foremost experts on the topic. He took time to reflect carefully about what soil structure meant, and nurtured his reflection not primarily through an exhaustive review of the existing literature, but largely on the basis of his own, very extensive, practical experience with plant-soil relationships. As a result, he came up during his address on "The study of soil structure—Science or art?", as well as in the ensuing article (Letey, 1991), with a perspective that others, in particular several soil micromorphologists, had already implicitly adopted, but had never argued for logically nor articulated clearly as a crucial paradigm shift. His perspective, which for some must have appeared initially to come out of nowhere, took some time to sink in, as is evinced by the fact that his article qualifies as a proverbial "sleeping beauty" in scholarly publishing, i.e., a publication that is very seldom cited for years, and then all of a sudden either starts being cited at a steadily rising rate or serves as a key foundation for articles that are themselves heavily cited. Thirty years onward, there are still two very different, conceptually conflicting perspectives among soil scientists about soil structure, yet the fact that Letey's (1991) article and some of the publications following in his footsteps are referenced more and more frequently might be construed as evidence that the paradigm shift he advocated is gradually happening and gaining momentum.

In that general context, the primary objectives of the present article are to provide some background information on views similar to those presented by Professor Letey, which had manifested implicitly in the soil science literature prior to 1991, to analyse in detail his contribution to the debate and explain to what extent his perspective was much ahead of its time, and to outline how significant technological progress over the last two decades has helped make Letey's (1991) views increasingly implementable and relevant in practice. Since the recent article by Vogel et al. (2021) provides a snapshot of the current status of the paradigm shift related to the structure/architecture of soils, the present article attempts to complement the picture by emphasizing the historical context of this shift as

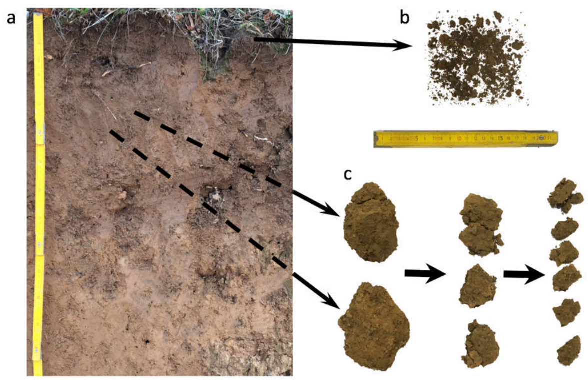

Figure 1. (a) Profile of a soil located in Grignon (France) and classified alternatively as an Orthic Luvisol (FAO classification) or Hapludalf (U.S. Soil Taxonomy). (b) Round-shaped aggregates, of biological origin, are easily identified in the surface (Ah1) horizon. (c) Aggregates of progressively smaller sizes obtained by breaking down, by hand, large chunks of soil initially dislodged from the profile with a knife. (Modified from Kravchenko et al., 2019)

well as the chronology of its evolution over the last 3 decades. We also briefly discuss where the research on soil structure/architecture appears to be headed at this juncture, and what lessons can be drawn from Letey's (1991) landmark article about the practice of soil science in general.

State of the art before 1991

Early in the development of soil science, soil surveyors realized that in order to describe soil profiles in place and to identify key structural elements in pits dug especially for that purpose, they had to use a sharp knife to refresh the profiles and eliminate possible artefacts due to the digging. Another, key use for this implement was to help identify structural elements that otherwise could not be revealed. At the soil surface, characteristic features like earthworm fecal pellets or shrinkage cracks could be easily spotted without the use of a knife, but further down in the profiles, experience showed that it was necessary to poke into the soil with a knife to dislodge from the bulk matrix chunks of material whose size and shape could then be described according to an agreed-upon nomenclature, and be taken into consideration to classify soils or formulate hypotheses concerning their genesis (Figure 1).

By the late 1980s, this procedure had persisted, unabated, nobody apparently having found a better, less intrusive alternative. To date the method has evolved into the widely used Visual Examination of Soil Structure (VESS) as an on-farm, practical methodology to evaluate soils (e.g., Franco et al. 2019). Over the years, disruption of the soil matrix had also become the standard protocol in the laboratory to characterize the physical "structure" of soils and of the chunks, referred to as "aggregates", into which a soil sample is broken down. Several experimentalists had demonstrated that by imparting increasing levels of mechanical energy to soil samples to dismantle them, and after careful sieving, one obtained aggregates of progressively smaller sizes and, conversely, of increasing stability (Tisdall and Oades, 1982; Dexter, 1988; Oades and Walters, 1991), an observation that had led to the development of a theory of the hierarchical spatial organisation of aggregates in soils. The stability of these aggregates was commonly assessed by immersing them abruptly in an aqueous solution or by subjecting them to artificial rainfall. As a result, the degree of stability of aggregates brought to the laboratory had become a routine procedure to characterize the stability of soil structure *in situ*.

In parallel with this approach toward soil structure based on the dismantlement of soils into aggregates, some researchers adopted early on a very different conceptual viewpoint. Motivation to do so may have come in part from one of the giants of soil science, Walter L. Kubiëna, who in his celebrated treatise on soil micromorphology 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, 1938). The context of this comment was the tradition of archiving pulverized soil samples in national repositories of soil information, a practice that Kubiëna strenuously opposed. Shortly after the publication of Kubiëna's book, researchers like Redlich (1940) and Russell (1941) began to focus on the pore space in soils, rather than on aggregates. Russell (1971) summarized this perspective as follows: "from the point of view of crop production, the term soil structure may be used to cover a group of properties largely concerned with the pore-space distribution in the soil. […] The fundamental problems in soil structure management are therefore concerned with the creation of structural pores, and their stabilization when formed". This focus on pores made it mandatory to try to describe soils in their undisturbed or a least minimally disturbed state, e.g., after the slow impregnation of soil samples with resin. During the 70s and 80s, significant research by soil physicists and soil micromorphologists dealt with the description of the pore space in 2-dimensional images of thin sections of resin-impregnated soil blocks, and with the quantification of their geometry and distribution, in particular using an Image Analysis Computer, the Quantimet (since 2014 a trademark of Leica Microsystems CMS GmbH), previously developed by geologists for similar purposes (e.g., Jongerius et al., 1972; Murphy et al., 1977; Bouma et al., 1979; Ringrose-Voase and Bullock, 1984). In the couple of years preceding the Australian symposium, a significant development occurred in this field, in that various groups around the world (e.g., Ai et al., 1988; Vaz et al., 1989; Phogat and Aylmore, 1989; Grevers et al., 1989; Warner et al., 1989; Anderson et al., 1990) independently pioneered the use of either γ–ray or X-ray computed tomography (CT) to describe the distribution and geometry of pores in 3 dimensions in undisturbed soil samples. The instruments either developed by these researchers specifically for that purpose or available to them in hospitals generally had a coarse resolution, of the order of one or two millimetres, which allowed only macropores to be visualized (e.g., Joschko et al., 1991), but nevertheless this was in many ways a major breakthrough.

At the time of the 1991 symposium in Australia, the two different approaches to the description of soil structure, based on aggregates or the pore space, seem to have coexisted without significant argument, at least none reported on in the literature. The presentation of Passioura (1991) is a good example of the apparent attitude of many in those days, whose considerations about soil structure involved both aggregates and pores, viewed implicitly as two sides of the same coin, regardless of the fact that the identification of the former required by definition that soils be disturbed whereas measurement of the second imperatively forbade any kind of disturbance.

Letey's (1991) contribution

In sharp contrast with what could be construed as a "laissez-faire" attitude toward the two different perspectives on soil structure, Letey (1991) pointed out that the isolation and characterization of aggregates is artificial and effectively destroys much of the structure that one purports to describe. He also argued that the fact that this characterization depends on arbitrary choices that need to be made by observers (e.g., in terms of the energy imparted to soil samples to dismantle them, or the chemical composition of the water used in assessments of aggregate stability) transforms it into an art form, and is not acceptable from a scientific perspective, which was intimately associated in his view to the requirement of unambiguous, objective measurements. In his words, referring to the dismantlement of soils into aggregates and to the subsequent measurement of their stability, "all these measurements made by soil physicists related to soil structure tend to be dependent upon the method of measurement and have relatively little to do with soil structure".

To alleviate this problem, Letey (1991) recommended that the structure of soils be approached by focusing squarely and solely on the pore space. For the first time, this was a clear statement that the two approaches to the structure of soils, which until then had been construed as two sides of the same coin, should not be viewed as such, and that only the approach that did not require heavy disturbance of soils made much operational sense. He illustrated the practical significance of this shift by considering the use of a cationic polysaccharide (guar) to improve the architecture of soils subjected to irrigation with saline water. He showed that in this case, the effect of guar on aggregate stability was small or even negligible, whereas its effect on the stability of the pore network and on the infiltration rate of soils was significant. Letey justified his radical shift in perspective by invoking Kubiëna's (1938) appealing architectural analogy of a soil dismantled into aggregates with a "pile of debris". He also argued that many of the functions of soils on which human societies have come to depend result from processes that take place largely if not solely within soil pores. He

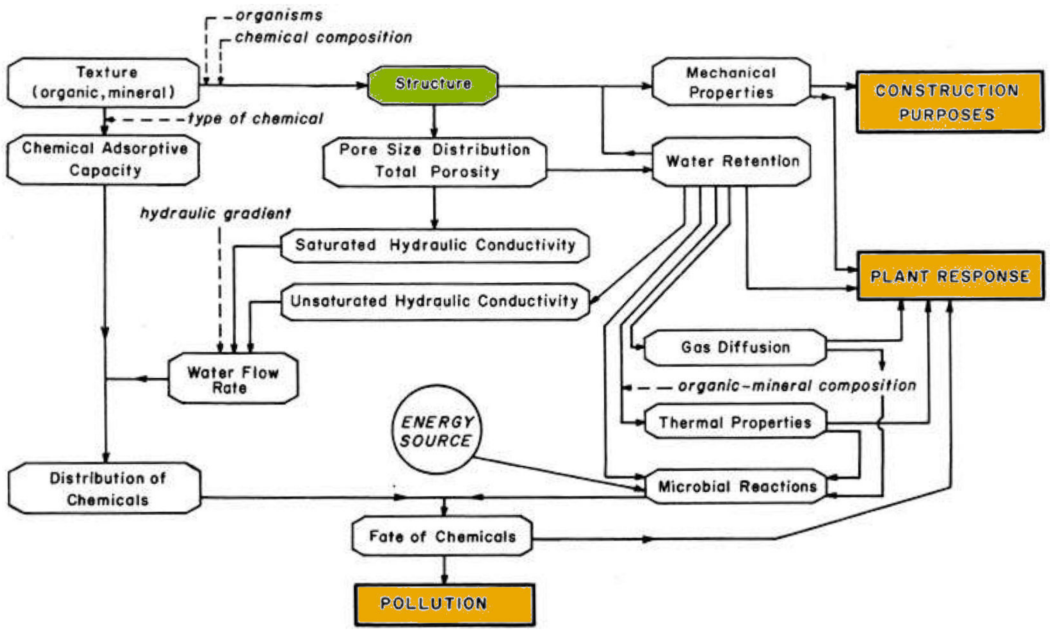

Figure 2. Interrelationships among soil physical properties, according to Letey (1977). (Modified from Letey, J. (2010), Summary of my career, unpublished notes).

had made that point already in 1977 in a chapter on the physical properties of soils (Letey, 1977). In a diagram accompanying his text (reproduced in Figure 2), he linked soil structure indirectly to three functions that soils render, namely the prevention of pollution by regulating the movement of chemicals, crop production via the supply of nutrients and water to plants, and the mechanical support to buildings[2].

The reference by Letey (1991) to Kubiëna's pile of debris viewpoint is occasionally misunderstood, and sometimes even considered derogative or offensive by steadfast advocates of the aggregate concept. One might argue on the contrary that the connection of soil structure with architecture that it establishes is in fact a very rich analogy, from which one can derive significant insight. To study the structure and functionality of a building, no one with a right mind would recommended that it first be demolished. The notion is clearly preposterous. Everyone can readily understand that chunks of demolished walls would not provide any valuable information about what a building looked like originally. For example, it would be difficult to an art historian attempting to characterize the architecture of buildings erected in France in the high Middle Ages to determine from a pile of debris whether they came from a castle or from a cathedral (Baveye, 2006). In both cases, the same building materials may have been used, including the same type of binding agent (cement, lime, clay, or mixtures of them, as the case may be). What differentiates a castle from a cathedral is the volume and relative organisation of the rooms, the size and shape of openings (doorways, windows). These characteristics can vary widely from one building type to another and determine, e.g., how many people can occupy comfortably each room, how easy it is to move from one room to another, how much light gets in, how easy it is to heat each of them when the weather turns cold. Clearly, none of these features depends uniquely on the building blocks

[2] The diagram of Figure 2 is interesting, parenthetically, in another respect as well, in connection with the extensive research carried out over the last 30 years to develop so-called "pedotransfer functions" (Wösten et al., 2001). These functions correlate empirically an array of hard-to-measure parameters, like the hydraulic conductivity or the water retention capacity, to readily measured parameters like the texture and the bulk density. From Letey's (1977) perspective, clearly visualized in Figure 2, any relationship between, e.g., the hydraulic conductivity and texture, necessarily has to account explicitly for the pivotal role of the structure of soils. The practical consequences of this fundamental observation have been reviewed recently by Fatichi et al. (2020).

of which the walls are made. By and large, one could have exactly the same architecture whether a building were made of stones, bricks, wood, or even soil.

Pursuing the same line of thought, one could take the architectural analogy one step further than Letey (1991) did. If one had to paint the inside of a building, one would never estimate the amount of paint needed by considering the total surface area of all the individual bricks or stones making up the building. One would start instead from the actual, much smaller surfaces of walls and ceilings in place. In other words, the surface properties of a building cannot be approached at all solely from the perspective of its constituents. This perspective, applied to soils this time, may implicitly have accounted for Kubiëna's adamant opposition to the storage of pulverized samples of soil in soil repositories. The intent behind storing soils under these conditions was (and still is) presumably to obtain a homogenized material that could be subjected later (sometime years later) to wet-chemistry or spectroscopic analyses of their properties. For a very long time, this was standard practice in soil chemistry, and is manifested, e.g., by the direct link that, following tradition in this respect, Letey established in Figure 2 between the "chemical adsorptive capacity" of soils and their texture. The pioneering work of Mokady and Bresler (1966), echoed by Boast (1973), however demonstrated that the cation exchange capacity (CEC) that actually matters in applications, i.e., the *effective* CEC of soils in their undisturbed, often partially water-saturated state, can differ appreciably from the one assessed using traditional chemical methods. This discrepancy may be due, e.g., to the occlusion by amorphous coatings of part of the reactive surfaces, or to thin adsorbed water films in unsaturated soils limiting access to the exchange complex (Baveye, 2012)). For most practical purposes, therefore, and in analogy to the painter story, one should modify the diagram of Figure 2 to make the CEC of soils, and indeed most properties affecting their ability to retain chemicals, dependent on the architecture of soils, instead of just their texture. As wisely suggested by one of the reviewers of the present article, this type of analysis could be extended beyond soil chemistry, to all the functions that soils fulfil. Just like the grinding of a pocket watch and the determination of its elemental composition would shed no light whatsoever on its function, so it goes as well for soils.

In spite of these severe shorcomings, the demolition of a building could nevertheless yield some insight into the properties of the "gluing" material used to put the walls together. If a particularly strong kind of cement was used, the chunks of walls that would result after the building is torn down would likely tend to be relatively large, whereas if soil and a little bit of lime were used, as was often the tradition in old stone buildings, the extremely sturdy walls while intact would likely crumble down easily when demolished, with very few fragments of walls left intact. To a large extent, the same could be said about soils: by breaking down a soil artificially into progressively smaller chunks and by subjecting them to standard stability tests, one can obtain information about how strongly bound together mineral particles are in them by various types of cementing agents, e.g., humic substances, metal or Fe/Al oxides and hydroxides, bacterial or archaeal exopolymers, or fungal hyphae. A considerable amount of instructive 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 that are involved (see, e.g., detailed review in Totsche et al., 2018; Vogel et al., 2021). In theory, knowledge about the nature and strength of cementing agents gluing chunks of soil may help to some extent understand how resilient the soils are to environmental influences (e.g., raindrop impacts, root penetration, susceptibility to erosion). However, practically, to move beyond mere speculation and verify experimentally the role of cementing agents in this context, requires that one could keep track of where in the original architecture aggregates were located, and therefore to which conditions they were subjected, so that these conditions could be replicated in the laboratory, under controlled conditions. However, that mandatory requirement has so far never been carried out.

This quick overview of Letey's (1991) insightful architectural analogy, inspired by Kubiëna (1938), would not be complete without mentioning its intrinsic limitation. Indeed, even though analogies can often be extremely useful, it is crucial not to get too bogged down in them, beyond the point where they cease to match exactly the reality under study. In soils, this limit is reached when, instead of just snapshots at a fixed instant, one envisages the evolution of soils over time. Indeed, unlike with buildings generally, a key characteristic of the architecture of soils is that it is *dynamic*, i.e., changes over time under the influence of an array of processes. Intrinsically, even when they do not contain 2:1 clay minerals, most soils have a tendency to shrink and swell when their moisture content changes, which normally modifies the geometry and connectivity of the pore space. In addition, the activity of soil fauna, in particular earthworms (e.g., Joschko et al., 1991; Capowiez et al., 1998; Bottinelli et al., 2015; Balseiro-Romero et al., 2020), but also larger animals like rabbits, moles, gophers that burrow into soils, is known to lead to major alterations of pores. Under some circumstances, the impact of raindrops at the soil surface can cause noticeable damage to soil architecture, dislodge and disperse fine particles, and eventually lead to the formation of crusts, restricting water movement (e.g., Bielders et al., 1996). Finally, the presence and metabolic activity of different types of microorganisms (algae in surface biocrusts, bacteria, archaea, fungi) can alter the properties of the pore space and change not only the hydrology but also the chemical reactivity of soils. Mainly because of technological limitations, the 4-dimensional dynamical measurements needed to carry out research on the effect of these various processes on architecture dynamics have been very few until now (see review in Baveye et al., 2018), so that many questions remain to be answered, let alone addressed, at this stage.

But aggregates are real and informative, aren't they?

To proponents of the aggregate perspective, Letey's (1991) statement that the isolation and characterization of aggregates was artificial must have taken them aback, and probably continues to do so to this day. Indeed, as illustrated in Figure 1, in many soils in temperate zones with high contents of organic matter in their top horizon, occasionally referred to by the term of "humipedon" (e.g., Zanella et al., 2018), it takes almost no effort at all to make the soil matrix crumble. The natural aggregates that result in these horizons are of clearly biogenic origin, linked with the activity of various soil fauna groups that deposit casts and faecal pellets of different sizes and shapes depending on the organisms (Figure 3). Such faecal materials are dominant features especially in organic soil layers containing fragmented organic tissues ingested and released by different species such as Diptera larvae, Oribatidae mites, Colembola, and enchytraeids. In mineral soils, casts from earthworms and woodlice pellets are common features. Earthworms, in particular, can be very efficient in structure formation and maintenance, by mixing soil constituents and depositing cast material. At high earthworm activity, especially in tropical grasslands, large parts of the soil volume may consist of earthworm casts of different ages (Lavelle, 1988). Schaefer (1990) has shown that in a temperate deciduous forest, earthworms with a biomass of 10g dry weight/m^2 managed to incorporate the annual litter fall of 5 t/ha into the soil. In some thin section images of soils, earthworm casts are so densely packed that individual casts can hardly be distinguished anymore.

Extensive research by soil ecologists over the last decades has documented in detail how different groups of organisms create aggregates of different sizes. Among soil-dwelling organisms, small-size fauna (mites, springtails, and some enchytraeids) typically producing aggregates of less than a mm in diameter (biomicrostructure), medium-size fauna (endogeic and epigeic earthworms, large enchytraeids, and small macroarthropods) resulting in aggregates of between 1 and 4 mm in diameter (biomesostructure), and large-size fauna (anecic earthworms and some endogeic earthworms, woodlice) yielding aggregates larger than 4 mm in diameter (biomacrostructure) (Zanella et al., 2018). If one includes organisms like ants, termites, and some insect larvae, whose activity is only partially in the soil, the picture becomes relatively complex, and the organisms that have an effect on soil architecture can be classified, following Bottinelli et al. (2015) into bioturbators *sensu stricto*, soil aggregate re-organizers, and mineral weathering agents.

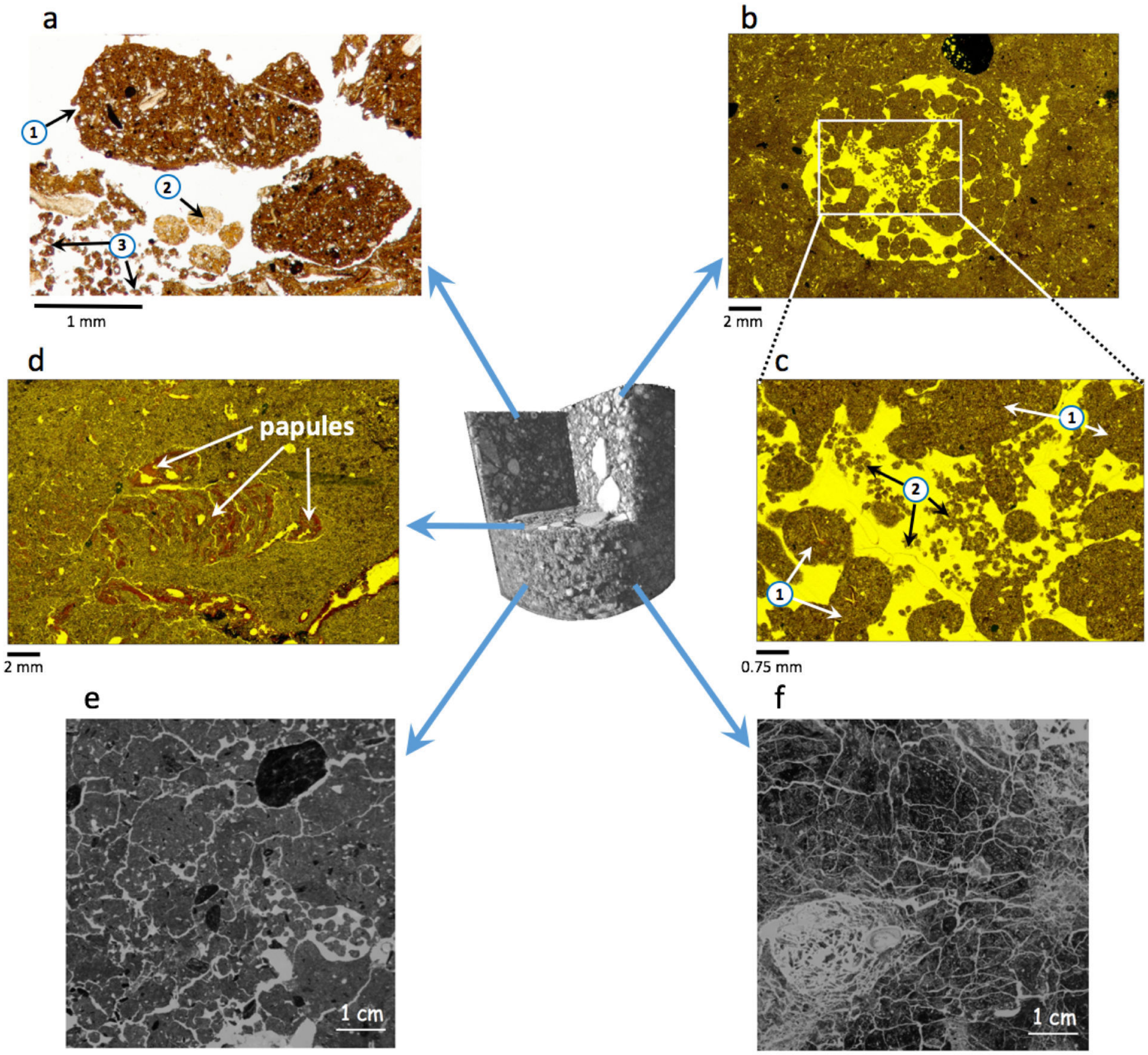

Figure 3. Illustrative examples of the types of "natural" aggregates that one identifies routinely in thin sections obtained from resin-impregnated, undisturbed soil samples: (**a**) Cast material of earthworms (1), diptera larvae (2) and enchytraids (3) in the top horizon of a clay loam forest soil characterized by high activity of earthworms; (**b**) and enlarged portion in (**c**) Earthworm hole in a Luvisol (Paris Basin, France), partially filled with coalesced large earthworm faecal pellets (1) along with mesofaunal excrements (2); (**d**) Infilling with stacked crescent-like layers with papules (i.e., fragments of laminated clay coatings) formed by an earthworm; (**e**) Mamillated vughs resulting from the packing of recent and coalescent earthworm dejections at 5 cm depth in an untilled soil; (**f**) Development of shrinkage cracks at 30 cm depth in a forest soil (Neoluvisol ruptic) near Clermont-en-Argonne (France) due to the presence of smectite. [Picture credits: Dr. Otto Ehrmann (a), Professor Ophélie Sauzet (b,c,d), and Dr. Nicolas Bottinelli (e,f). Information on the soil in images b,c, and d, are available in Sauzet et al. (2016, 2017)].

In Oxisols in tropical regions, surface horizons also tend to crumble readily into small aggregates, but in this case they are not predominantly of biogenic origin. These aggregates, referred to as pseudo-sands or pseudo-silts depending on their overall diameter, are constituted chiefly of kaolinite mixed with Fe- or Al-(hydr)oxides, and contain varying amounts of organic matter. They are, as a rule, extremely stable; by definition, pseudo-sands are not dispersible in water even after being shaken vigorously for 16 hours. Martinez and Souza

(2020) recently reviewed the literature on the genesis of pseudo-sands in Brazilian Oxisols, and attribute these aggregates to the following processes: (i) residual accumulation of pedogenic Fe- and/or Al-(hydr)oxides that cement kaolinite particles together; (ii) linkages between Fe- and/or Al-(hydr)oxides, kaolinite, and organic matter, which increase cohesive forces among clay particles and create pore space; (iii) mechanical fracturing of mineral materials by long-term wetting-drying and erosion-deposition cycles; and (iv) long-term bioturbation that reduces the size and increases the physical stability of aggregates.

Abiotic processes, such as soil moisture changes or freezing/thawing cycles, can also have an effect on the creation of natural aggregates, sometimes labelled as "physicogenic" (Jouquet et al., 2009). This can take place in surface horizons, but is especially significant deeper in soil profiles, in a part of the soils that is occasionally referred to as the "copedon" (see figure 18 in Zanella et al., 2018). Shrinkage of soil during severe desiccation leads to the formation of cracks and the alignment of minerals particles during the retreat of water menisci. Although this process is often associated with soils with a high content of swelling 2:1 clay minerals, most soils swell and shrink to some extent, including highly weathered tropical soils and organic soils, and can produce cracks if their desiccation is extreme enough. Once cracks form and while they stay open, dust and small soil particles tend to fall in them, which explains the frequent observation that during repeated wetting and drying cycles, desiccation cracks are mostly formed at the same locations, leading to polyhedric aggregates at multiple hierarchical levels in the dry state having sharp edges and planar faces once detached from the rest of the soil matrix. Another cause of crack formation in the soil matrix, not only vertically but also horizontally, is related to freezing, and subsequent thawing (e.g., Chamberlain and Gow, 1979; Viklander, 1998).

Aside from aggregates that result from natural processes, either biotic or abiotic, various authors (e.g., Russell, 1971; Or et al., 2021) have also argued that chunks of soil that can readily be identified when soil samples are broken apart are man-made, and result from tillage operations. Fracture and break up of soil by tillage is an essential operation of conventional agricultural practices to decrease bulk density and provide weed control, as well as improve aeration and the penetration of roots. The soil matrix is regularly disturbed by mechanical forces brought about by different types of machinery. For a time at least after each tillage operation, identifiable soil chunks persist down to a certain depth related to the type of machinery used (e.g., plow depth), and soil architecture is composed of those fragments and larger pores in between. In this last 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 "[n]atural soil aggregates are seamlessly embedded in the surrounding soil matrix, whereas tillage-produced fragments are often loosely packed and form inter-fragment spaces."

Undoubtedly, the fact that under some circumstances, soils seem to readily break down into what was or at least appeared to be natural aggregates caused significant resistance to the perspective advocated by Letey (1991). This probably explains why many soil researchers continued for a long time to systematically dismantle soils to study their structure, and spent time developing various theories to account for the genesis and dynamics of these aggregates (e.g., Totsche et al., 2018). Nevertheless, strictly speaking, the fact that the disturbance needed to produce aggregates is in some cases very slight does not change the fact that this disturbance is absolutely required, otherwise one cannot identify these aggregates. Therefore, in order to study the response of aggregates to changes in their undisturbed environment, one would have to be able to first find out precisely where aggregates were located in the original soil, and subsequently to replicate on them in the laboratory the same types of boundary conditions that they experienced in situ. The title of a recent article (Koestel et al., 2021) suggests that the first step is already possible at this stage. However, in the body of that article, the authors concede that they have not yet been able to achieve their goal. One should remain optimistic, nevertheless, and assume that this condition might become reality in the next few years, pending the development of novel tracking and pattern recognition algorithms. Unfortunately, the latter condition, of replicating natural conditions in the laboratory, is not only entirely unfeasible at the moment, but it does not seem realistic to expect that one shall be able to fulfil it any time soon (Kravchenko et al., 2019).

Steadily growing acceptance of Letey's perspective over time

The fact that Letey (1991), rather bluntly, referred to the traditional approach to soil structure as a form of art rather than as science may have offended some people, and may have resulted in some resistance from the old guard. Clearly, though, an additional and key reason why Letey's (1991) perspective did not convince people initially has to do with the fact that, in several respects, Letey's thinking was at least a decade if not two ahead of his time. Indeed, compared to the ease with which a soil could be dismantled into aggregates and their stability be assessed, the fastest ways available practically in the early 90s to get detailed, quantitative data about the properties of the pore space in soils, via the measurement of the moisture retention curve (e.g., Hassink et al., 1993) or by using a mercury intrusion porosimeter, were still considerably slower. And the information provided by these methods was not necessarily of great value. In either case, provided one accepted a number of assumptions, one could obtain the overall size distribution of pores, but no information whatsoever about their specific properties or spatial arrangement relative to one another within a soil sample. In addition, both of these methods suffer from a potentially severe overestimation of the volume of small pores due to connectivity-related ink-bottle and sample size effects (e.g., Moro and Böhni, 2002). By contrast, the different methods developed by soil micromorphologists yielded much more pertinent data, but, because they required the very slow impregnation of soil samples with resin, were even less suited for routine measurements of a large number of soil samples, especially when one attempted to obtain a 3-dimensional perspective on soil pores by working painstakingly with parallel thin sections (e.g., Cousin et al., 1996).

By the late 90s, X-ray CT was being used by an increasing number of researchers and was attracting significant attention, but nevertheless remained a very cumbersome technique to adopt. Either one had to get extremely lucky and gain access to beam time at one of the few synchrotron facilities around the world that had the required equipment (e.g., rotating stage, detector panel) to carry out CT measurements, or one had to use medical cat scan equipment whenever patients were not around, which generally meant that measurements had to be carried out during weekends, and even then often in the thick of the night. In addition, the resolution that could be achieved with these different facilities allowed researchers to visualize pores that were slightly smaller than the macropores that could be seen with the X-ray and γ–ray scanners available a decade earlier, but not tremendously smaller than that.

The situation changed dramatically soon after the turn of the millennium, as table-top X-ray computed tomography (CT) scanners became commercially available and increasingly common in soil science laboratories, enabling researchers to observe the geometry of the pore space at suitably fine resolutions. Various mathematical techniques were also devised to extract from three-dimensional CT images a wealth of quantitative information about the tortuosity, connectivity, and topology of the pore space (Perret et al., 1999; Pierret et al., 2002; Vogel et al., 2010). These technological and computational advances progressively persuaded researchers that the observation of soil architecture in undisturbed soil samples was becoming straightforward enough to be used in practice, and allowed one to address all kinds of practical questions. A number of these researchers started routinely citing Letey (1991) as an early advocate of the perspective they were increasingly adopting.

Notable amongst the publications along this vein is an article by Young et al. (2001) in which the authors again questioned "the use of aggregates as indicators of structure" and assessed possible alternatives to characterise the structural heterogeneity of soils without having to severely disturb it first. A further charge against traditional aggregate size distribution and stability measurements was made three years later by Wander (2004), who quoted Letey (1991), and by Young and Crawford (2004), who did so as well in connection with a criticism of the hierarchical model of soil structure proposed by Tisdall and Oades (1982). According to Young and Crawford (2004), this model "has been consistently misinterpreted as providing evidence for the existence of discreet, experimentally [manipulatable] aggregates rather than as a qualitative description of the aggregated hierarchical nature of the soil system in terms of the linkages between the architecture of the habitat and biological functioning. Over the past decade, this conceptual model has been used as an excuse to develop a wide variety of tests that purport to quantify the stability of soil ecosystems […] but in reality tell us little about the functioning of soil and more about the tests used". This last remark definitely echoes Letey's (1991) viewpoint.

Since the early 2000s, Letey's (1991) article has been cited increasingly by researchers working on soil architecture. Even if the total number of its citations remains relatively modest, several of the articles that have reiterated its message have, contrastedly, been cited extensively. The articles by Young et al. (2001), Wander (2004), and Young and Crawford (2004), for example, have according to Google Scholar been cited respectively 213, 470, and 839 times so far. Perhaps the most significant statistics relates to the number of articles in recent years that have relied on computed tomography in one of its forms to study the architecture of soils in their

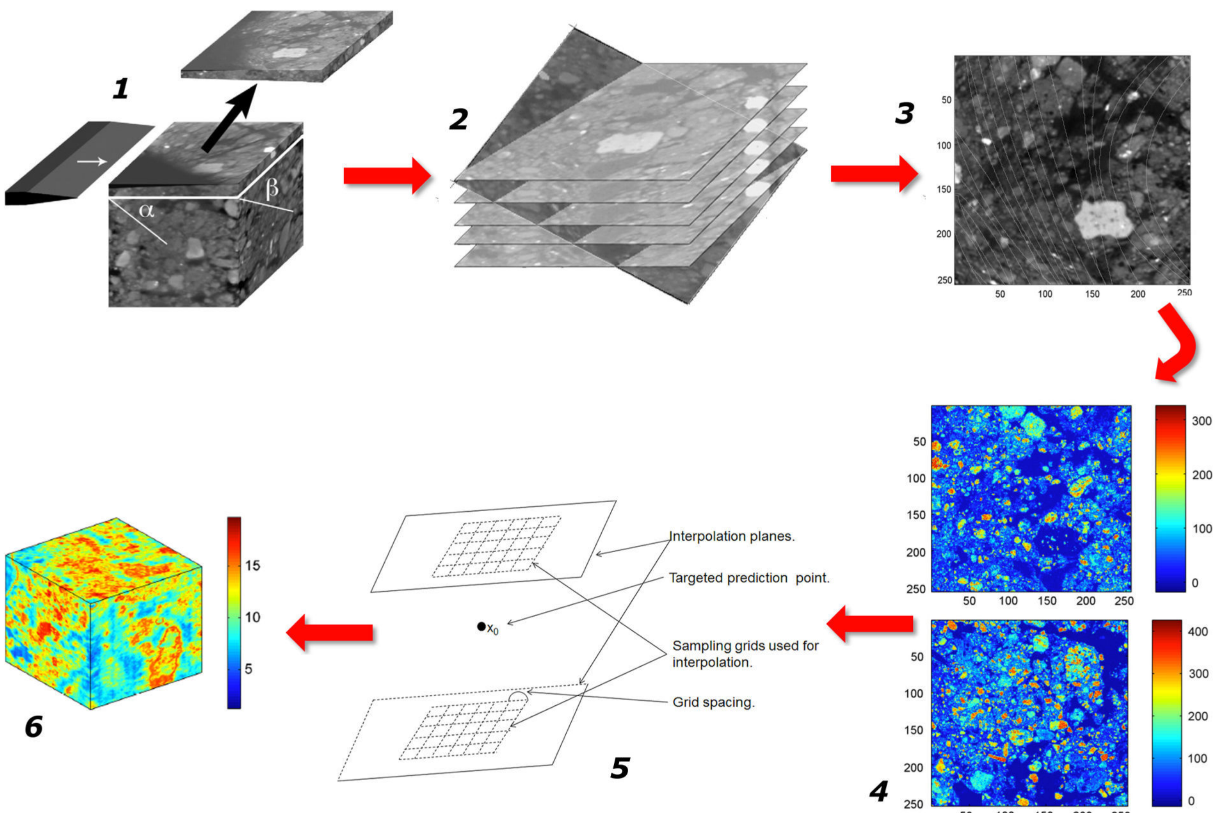

Figure 4. Schematic diagram of the successive steps in the 2D–3D interpolation method proposed by Hapca et al. (2011, 2015). (1) Illustration of a typical method to isolate a layer from a soil cube, with a microtome blade. The cut may be at angles α and β with the *x*–*y* plane in the *x* and *y* directions, respectively, resulting in layer surfaces that are not strictly parallel to each other, (2) rotation of the chemical analysis plane within the 3D CT image, (3) Reconstituted CT image of the soil surface. The dotted lines correspond to the limits of the different masks applied to the successive layers during the zonation process, (4) Spatial distribution, measured with SEM–EDX, of silicon in the top and bottom soil surfaces of an individual slice through the soil sample, (5) schematic representation of the interpolation layers and the corresponding sampling grids for the selection of the interpolation points, (6) 3D prediction of the silicon distribution in the soil sample. (Reprinted from Baveye et al., 2018, with permission).

undisturbed state. In 2020, again according to Google Scholar, 385 articles alluded to "computed tomography" and "soil structure". As of the writing of this article, on September 29, 2021, just 9 months into the year, 505 articles have already alluded to the same topics in 2021, again according to Google Scholar. Few of them cited Letey (1991) explicitly. Many did not even cite the articles that later espoused his message. But clearly, the idea that it is best to rely on non-destructive methods to characterize the architecture of soils has come a long way, and appears to be well accepted worldwide.

Current state-of-the-art and future prospects

At the time Letey (1991) wrote his article, the methods then available to describe soil structure made it logical to oppose a perspective that focused on dismantling soil samples into aggregates, to one that focused on the pore space in undisturbed soil samples. The rapid development of X-ray CT technologies after the turn of the century put this duality into sharper contrast, by allowing researchers to characterize the pore space at increasingly finer resolutions. Yet, it is only in the last few years that technology and the mathematical treatment of available data have progressed to the point of permitting a more holistic perspective on soil architecture that goes beyond Letey's (1991) vision, as described in detail in Vogel et al. (2021).

This evolution has been greatly catalysed by the development of computational techniques that allow information from different sources to be combined. Hapca et al. (2011, 2015) proposed a method to register 2-dimensional quantitative chemical information obtained, e.g., using energy-dispersive X-ray spectroscopy, with 3-dimensional data about soil pores derived from X-ray μCT images (Figure 4). This research can be extended to a wide range of (bio)chemical parameters, as well as microbiological ones. The article by Schlüter et al. (2019) is an excellent example of the type of work that is unfolding in this area. Using a combination of X-ray μCT, fluorescence microscopy, scanning electron microscopy and nanoSIMS, these authors were able to study the distribution of bacteria in a soil, and to show that they have a preference toward foraging near macropore surfaces and near fresh particulate organic matter. In a similar manner, Juyal et al. (2019, 2020) combined X-ray CT with biological thin sections to elucidate the impact of pore architecture on bacterial distribution in soil. This research shows that it is possible at this stage not only to characterize the geometry, topology, and connectivity of the pore space in undisturbed soils, but also to obtain concomitantly a wealth of 3-dimensional data about pore interfaces and the (bio)chemical and microbiological features of the soil matrix. This type of holistic perspective should prove particularly useful at a time when there is an urgent need to be able to describe quantitatively better than we currently do the functions (e.g., water storage and provisioning to plants, aquifer recharge, nutrient cycling) that soils fulfil, to assess their resilience to environmental stressors, and to predict in what measure they will still be fulfilled in years to come, as climate keeps changing (Baveye et al., 2020).

An objection that is sometimes levied against the non-destructive description of soil architecture, and especially that using X-ray CT scanners, is that these machines allow us to have access to some of the pore space in soils, but not to all of it, and therefore the picture they provide may be misleading. It is indeed correct that since CT scanners necessarily have to operate at a set resolution, uniquely determined by the size of the sample and the respective locations of the X-ray source and the detector array, pores whose size is smaller than the voxel size of the resulting images become invisible. This property of CT images is well known and has been abundantly discussed already (e.g., Baveye et al., 2017). It is not necessarily a drawback with regard to the characterization of soil architecture, however. Indeed, depending on what research question one is addressing, one does not absolutely need to have thorough and exhaustive information at all scales about the geometry of pores. For example, if one is interested in using repeated 3D CT images to describe how earthworms modify the architecture of soil samples over time, as various authors have done (e.g., Capowiez et al., 1998; Balseiro-Romero et al., 2020), soil samples need to be sufficiently large to accommodate several worms, which means that the resolution at which they are scanned has to be relatively coarse, of the order of 10s or even hundreds of microns. At this resolution, one can clearly identify the pores that earthworms are creating in the soil, and most of the pre-existing ones that are modified by the activity of the earthworms. To understand how the geometry and connectivity of pores in soils affects the propagation of fungi, one would logically use CT images with a resolution of a few microns, which enables the visualization of pores that are large enough to allow the penetration of hyphae. To study the movement of bacteria and a fortiori viruses in soils, or the microscale structure of organo-mineral complexes, one would get images at a considerably higher resolution, which can be obtained in correspondingly minute samples or, with modern CT equipment, in computationally-isolated subsamples within larger soil cores. In other words, the type of question one wants to address determines at what spatial scale it is relevant to visualize the architecture of soils. Even if in principle, complete knowledge of the geometry of pores, all the way down to nanometric sizes, would be ideal, it is sufficient for most purposes to be able to zero in on a range of pore sizes that make sense for a particular situation. However, to date, the role that pores of various sizes fulfil in soil functioning is not quantitatively understood, and this needs to be urgently addressed (Baveye et al., 2020), in addition to the quest to improve technology.

Another criticism that proponents of the aggregate approach occasionally levy against the non-destructive description of soil architecture is that, unlike the dismantlement of soils into aggregates and the subsequent measurement of their stability, the quantitative description of soil architecture using, e.g., X-ray computed tomography, requires access to expensive equipment that not every soil science laboratory or research institution possesses. The criticism is well taken. Even in relatively rich countries, many institutions do not have CT equipment dedicated to soil research. Instead of using this as an argument against the non-destructive measurement of soil architecture, it might be a better strategy to take advantage of it to try to convince administrators and managers of research institutions and funding agencies that CT scanners are fast becoming essential pieces of equipment in soil science. In developing countries, this approach would be fruitless, in all likelihood, for lack of financial resources but perhaps international global collaborations among researchers could still make it possible for soil samples to be scanned. Or perhaps various countries could sponsor shared laboratory facilities in which CT equipment would be available to researchers across borders, just like nowadays synchrotron facilities around the world can be accessed by scientists from countries that lack such expensive facilities.

To some extent, a similar situation occurred in soil science roughly 30 years ago, with a different type of equipment. Up until the 1980s, flame atomic absorption spectrometry (Flame AAS or FAAS) was the standard technique in soil chemistry to quantify the concentration of particular chemical elements in soils. Measurements were carried out one element at a time, and required a lengthy calibration for each one of them separately. Another method existed, which was known to be vastly better in a number of respects, but it was used only by a privileged few in the soil science community who were fortunate to have access to the required equipment, which at that juncture was very onerous. Inductively coupled plasma-atomic emission spectrometry (ICP-AES), developed in the 60s, had by then become extremely popular in (generally wealthier) chemistry departments, but not in soil testing laboratories. Compared to the older FAAS technique, ICP-AES is generally free from matrix and inter-element artefacts, and its emission mode presents the enormous advantage that it enables the simultaneous and fast measurement of the concentration of major (Na, K, P, Ca, and Mg) and trace (Fe, Cu, Zn, Mn, Pb, Cd, Co, Cr, Ni, V, Ti, Al, Sr, and Ba) elements (Dahlquist and Knoll, 1978). Slowly but surely, in the 80s and early 90s, soil testing laboratories and soil science departments began purchasing ICP-AES machines, and as that trend intensified, these machines became progressively more affordable, which had a snowball effect. By the mid-90s, it was clear that ICP-AES was destined to entirely supplant the far less versatile FAAS method. Nowadays, it is even common for soil laboratories to own or have easy access to second- or third-generation machines, in which ICP is coupled with optical emission spectrometry (ICP-OES), laser ablation (LA-ICP), or mass spectrometry (e.g., ICP-MS or time-of-flight ICP-MS). The cost of these machines has dramatically decreased since they were introduced. Likewise, it is not hard to imagine that as more soil- or geoscience research institutions decide to purchase X-ray CT scanners to make them available to their personnel, the price of these machines will decrease rapidly in the near future, and their use will become routine.

Just like with ICP-AES, it is very likely that in the next few years, soil science researchers will have access to second- and third-generation CT equipment that will be vastly superior to anything we have at the moment, at a cost that will allow far more research groups to purchase them. The review article by Baveye et al. (2018) mentions a number of advances achieved by physicists in the last few years, like laser-wakefield accelerators not much larger than a shoebox yet producing synchrotron-quality, nearly mono-chromatic (single energy) tunable X-ray beams, that are paving the way for new, vastly better equipment in the not very distant future.

As this sophisticated equipment becomes available to soil scientists, it will be crucial not to lose track of what the key questions are that we are trying to answer with it. To ensure that soils are resilient enough to cope with the severe environmental changes that one can expect in the coming decades, we need to be able to predict how their key dynamic properties, like the hydraulic conductivity, water retention capacity, as well as mechanical and thermal properties, are going to be affected. According to Figure 2, this means that we imperatively need to understand how the structure or, rather, the architecture, of soils is going to evolve over time under the effect of, among other things, changing rainfall patterns, enhanced microbial activity due to rising temperatures, and increasing demands for food production. Letey's (1991) recommendation in this context, and his key message, is that we are not likely to make much progress toward that goal unless we look at soils as they are in nature, *with their architecture left undisturbed*, we characterize soils in that state, and we come up with mathematical relationships or models that relate specific aspects of the soil architecture (e.g., the geometry and connectivity of the pore space) to environmental stressors.

Two additional valuable lessons from Letey's legacy

Even though the key message of Letey's (1991) article undoubtedly relates to the scientific study of soil architecture, we would be missing an invaluable opportunity if we did not also point out worthy lessons that Letey (1991) provides us in at least two other respects, which one might consider are equally important. Both have to do with the fact, alluded to already in the introduction, that Professor Letey was by no means a world expert on soil structure at the time he accepted the invitation to deliver the keynote address that eventually led to his 1991 article. He mentioned in his talk and article that he had lectured about soil structure to generations of students in his soil physics course at UC Riverside, so that he was undoubtedly aware of the extensive literature on the topic. Nevertheless, for anyone who thinks that only those who have carried out extensive research on a topic know it in enough depth to write a comprehensive review and come up with interesting insight, the notion that Professor Letey could have accepted an invitation to deliver a keynote lecture on soil structure would be anathema. However, there is an entirely different way of looking at this. The fact that he had not worked extensively on the topic clearly meant that he did not have any vested interest in promoting or defending any particular approach, and that, starting from a clean slate, he could let his reflection go wherever he believed it needed to go. He was what one might describe as an "honest broker", potentially able to shed a new, entirely unbiased light on an old question, and he did just that.

Given the impact of his cogitation, one might consider that Letey's (1991) example would be well worth emulating, not just in soil science but in every discipline. Every year, thousands of Ph.D. students spend countless hours reading and analysing in great detail the literature related to the topic of their research, and writing a comprehensive review that typically constitutes the first chapter of their dissertation. Then, after the latter is successfully defended, it ends up in a library where it only accumulates dust and is promptly forgotten. Very few of the bibliographical chapters these dissertations contain end up getting published, because nowadays the prejudice is still strong against a young researcher publishing a review article, even if assisted by his/her faculty supervisor, especially if their research on the topic is a new endeavour for both. To a large extent, this regrettable prejudice, which most probably has kept treasures hidden or has discouraged some people from doing as good a job on this aspect of their research as they could have, does not apply just to early career researchers, but also discourages more seasoned researchers from stepping outside the strict confines of their narrow specialty, to explore new grounds. And yet, experience has shown occasionally in several disciplines that those coming afresh to a topic, and providing a new perspective on it, could come up with extremely valuable insights, which veterans of the field, with years of experience but little distance from it had not thought about, most likely because they had "their nose on the black board", as used to be said about teachers. As George Orwell put it at one point, "To see what is in front of one's nose needs a constant struggle". Prototypical examples of the insight that can come from having a certain distance from things have been provided repeatedly by the famous Indian-born physicist Subrahmanyan Chandrasekhar, who during his whole career switched fields on purpose periodically, with the result that his career can be divided into distinct periods. In each one, he would exhaustively study the literature in a specific area, publish several papers in it, most often containing significant breakthroughs, and eventually write a book summarizing his perception of the major concepts in the field. He would then move on to an entirely different field for the next decade and repeat the pattern, with immense success. One of these successive episodes earned him a Nobel Prize in physics in 1983, for his studies on the physical processes important to the structure and evolution of stars.

Yet, the usefulness of stepping out of one's area of specialty is not the only "extra" lesson that can be drawn from Letey's (1991) article. There is another part of what Letey did that is extremely valuable, and deserves to be emulated as well. Indeed, he could have taken a safe road for his keynote address, and carried out the type of review of the literature that many people come up with, i.e., a long sequence of "who-did-what-when" with a few sprinkled thoughts on the evolution of our knowledge on the topic. Instead, he endeavoured to reflect carefully on what researchers working on soil structure were doing, why they were doing it that way, which questions they were trying to answer in the process, what problems they were experiencing, and whether there could be a better way to go about the whole endeavour. These fundamental questions seem essential in any discipline, to ensure that the research move in the most meaningful direction at all times. And yet, there is a minuscule number of articles in the soil science literature that carry out this type of reflection, perhaps because of a reluctance on the part of many researchers to stir up controversy by pointing out implicitly that some of their colleagues are heading the wrong way in their respective field of research. Regardless of how one feels in that respect, it would be hard to argue against the view that articles reflecting on the state-of-the-art, questioning currently accepted dogmatic views, and eventually suggesting a better way to do things, are extremely valuable for the advancement of knowledge.

In this respect, there is an interesting similarity between the influence of Letey's reflection on soil structure, and what happened in statistics right after the second World War. At that stage, two philosophically distinct approaches battled for supremacy in this field and, consequently, statisticians were divided in two opposite camps, with the "frequentist" camp largely dominating the "Bayesian" one in practical applications, in spite of the adhesion to the latter camp of eminent researchers like the physicist Erwin Schrödinger, the geophysicist Harold Jeffreys, or the economist John Maynard Keynes. A condensed matter physicist at Johns Hopkins, Richard T. Cox, who had previously published nothing on the topic, decided to approach the debate on the foundation of probability and statistics from an entirely novel angle by asking for the first time a very basic question. He wondered abstractly what would be the most rigorous way to draw inferences in situations where knowledge is incomplete, given a set of simple rules, based in logic, that should apply to any kind of inference, whether under uncertainty or not. The conclusion of his groundbreaking reflection, known as the celebrated Cox theorem, is the crucial proof that the "algebra of probable inference" necessarily has to correspond to the Bayesian perspective. Cox's (1946) original article on the topic did not get a single citation for 16 years, and the seminal book he later wrote (Cox, 1961) did not fare much better initially, until another physicist started praising them (Jaynes, 1963, 2003), and Good (1966) did likewise in the field of artificial intelligence. Cox's work is now considered revolutionary in the field of probability theory (Tribus, 1969, 2002; Baierlein, 2004), and the substantial theoretical legitimacy it has conferred to Bayesian statistics is widely acknowledged to have contributed to its impressive rise to prominence in the last few decades.

Take-home message

In his landmark article, inspired partly by an architectural analogy due to Kubiëna (1938), Letey (1991) advocated for a radical paradigm shift in the research on soil structure, away from the then routine dismantlement of soils into aggregates. He suggested that, in order to understand the functioning of soils, it made much more sense to focus on their pore space. Because this message was years if not decades ahead of the technology available at the time to characterize the pore space, it was not immediately heeded. In fact, it took a good twenty years for it to be followed. Since, however, the notion that the architecture of soils needs to be studied via non-destructive methods, like X-ray computed tomography or resonance magnetic imaging, has become increasingly accepted and implemented in research all over the world. Not only do these non-destructive methods allow the geometry, topology, and connectivity of soil pores to be characterized at a variety of scales, relevant to a wide range of research questions, but in addition, this information can now be combined with spatial data on (bio)chemical and microbiological properties of soils. This provides a unique, holistic perspective on the ability of soils to fulfil a number of crucial functions and services (Vogel et al., 2021). As research intensifies in that context, it is reasonable to hope that within the next few years, we are going to be able to better understand how we can manage soils so that they can continue to fulfil these functions/services, in spite of looming threats caused by climate change.

As a corollary to this key message, Letey's (1991) article also bears valuable lessons concerning the conduct of research in soil science, and specifically about the usefulness of the type of "fresh look" that someone who is not an expert in a given field may have on it upon dedicated study. Too often, it seems in soil science, we are reluctant to publish in-depth reviews in fields to which we have not contributed over an extended period of time. Letey's (1991) example demonstrates that from a fresh, neophyte look in which one methodically asks probing questions about the objectives of the research, the assumptions made, and the methods used, extremely useful insight can sometimes result, with long-lasting impact.

Data Availability and Conflict of Interest Statements

No new data were generated during the research reported in this article. Furthermore, the authors declare that they have no conflicts of interest concerning this research.

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