



# Natural and managed soil structure: On the fragile scaffolding for soil functioning

Dani Or<sup>a,b,\*</sup>, Thomas Keller<sup>c,d,\*\*</sup>, William H. Schlesinger<sup>e</sup>

<sup>a</sup> Swiss Federal Institute of Technology ETH, Department of Environmental Systems Science, Universitätsstrasse 16, CH-8092 Zürich, Switzerland

<sup>b</sup> Desert Research Institute, Division of Hydrologic Sciences, 2215 Raggio Parkway, Reno, NV, 89512, USA

<sup>c</sup> Swedish University of Agricultural Sciences, Department of Soil & Environment, Box 7014, SE-75007 Uppsala, Sweden

<sup>d</sup> Agroscope, Department of Agroecology & Environment, Reckenholzstrasse 191, CH-8046 Zürich, Switzerland

<sup>e</sup> Cary Institute of Ecosystem Studies, Millbrook, NY, 12545, USA

## ARTICLE INFO

### Keywords:

Soil structure  
Soil organic carbon  
Tillage  
No-till  
Soil aggregates  
Land use

## ABSTRACT

Soil structure in natural systems is a product of complex interactions between biological activity, climate and soil minerals that promote aggregation and accumulation of biopores. In arable lands, the management of soil structure often requires the mechanical fragmentation of hardened soil to improve seedbed, control weeds and bury plant residue. Despite difficulties in defining and quantifying soil structure, its critical role is evidenced by loss of productivity when natural structure is perturbed (e.g. compaction) and the long history of tillage in agriculture. To overcome persistent ambiguities among scientific disciplines regarding definition and function of soil structure, we propose a framework for distinguishing managed and natural soil structure based on their different formation processes and functions. Natural soil structure preserves ecological order and legacy that promotes biopore reuse, stabilizes foodwebs and protects soil organic carbon (SOC). The contribution of net primary productivity of natural lands to soil structure forming processes makes it a useful (surrogate) metric of soil structure. The benefits of managed soil structure for crops are quantified indirectly via comparisons with no-till farming under similar conditions. The levels and trends of SOC are useful metrics for the status of natural and managed soil structure. The systematic consideration of soil structure state in natural and arable lands using suitable metrics is a prerequisite for rational decisions related to land management and ensuring sustainable functioning of a fragile and central resource such as soil.

## 1. Introduction

Soil structure is an important trait that emerges from biological activity including biopores formed by plant roots and earthworms and aggregations of soil particles by biopolymers and hyphae (Tisdall and Oades, 1982). A different type of soil structure results from the mechanical breakup and loosening of soil by tillage operations. Soil structure is fragile and easily disrupted: decades of natural structure formation can be undone in an instant by the passage of a heavy farm implement. Traditional definitions of soil structure are biased towards characterization of soil structure in agricultural lands, primarily focusing on the favorable arrangement of soil constituents with respect to their agronomical functions (Dexter, 1988). The extreme sensitivity of

soil structure to constituent arrangement, and the centrality of soil structure in the functioning of natural lands call for a broader view and unifying concepts of soil structure. We offer here a tentative definition of soil structure as “the spatial arrangement and binding of soil constituents and the legacy of biological agents that support physical, chemical and biological functions in soils”. We emphasize the importance of visible spatial organization (solids and pores) and invisible traits (mechanical bonds and biological legacy) of soil structure.

Soil structure management by tillage is an old art (Whitney, 1925) whose benefits and necessity often rely on local experience and qualitative measures. Soil tillage is probably the largest geo-engineering activity on Earth. Considering the global extent of arable land (14 million km<sup>2</sup>) and a mean tillage depth of 0.15 m (removing the area of no-till),

\* Corresponding author at: Desert Research Institute, Division of Hydrologic Sciences, 2215 Raggio Parkway, Reno, NV, 89512, USA.

\*\* Corresponding author at: Swedish University of Agricultural Sciences, Department of Soil & Environment, Box 7014, SE-75007 Uppsala, Sweden.

E-mail addresses: [dani.or@env.ethz.ch](mailto:dani.or@env.ethz.ch) (D. Or), [thomas.keller@slu.se](mailto:thomas.keller@slu.se) (T. Keller).

<sup>1</sup> These authors contributed equally.

<https://doi.org/10.1016/j.still.2020.104912>

Received 27 July 2020; Received in revised form 15 November 2020; Accepted 11 December 2020

Available online 25 December 2020

0167-1987/© 2020 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

we estimate a tilled soil volume of 1840 km<sup>3</sup>/yr. This value exceeds by two orders of magnitude the total of all engineering earthworks on Earth (Supplementary Table S1). For comparison with the natural process of soil bioturbation by plant roots and earthworms (Haff, 2010), we find a bioturbated soil volume of 960 km<sup>3</sup>/yr (Supplementary Table S1). It is astonishing that such significant global activity (i.e. tillage) rests on a limited quantitative framework for gauging its direct benefits (Huggins and Reganold, 2008). The rapid expansion of conservation tillage of the past few decades (presently comprising 12.5 % of the arable land surface; Kassam et al., 2019) demonstrates that, for some regions and crops, farmers can do well without conventional tillage. Moreover, the projected intensification of agriculture for feeding a rapidly growing global population (Tilman et al., 2011) and associated risk of soil structure degradation (Keller et al., 2019) add urgency to define and quantify the benefits of tillage practices. Growing concerns over the role of tillage in greenhouse gas emissions and soil carbon storage (Reicosky et al., 1995; Houghton, 1999; Post and Kwon, 2000; Poeplau et al., 2011) add new dimensions to tillage decisions beyond short-term agronomic return.

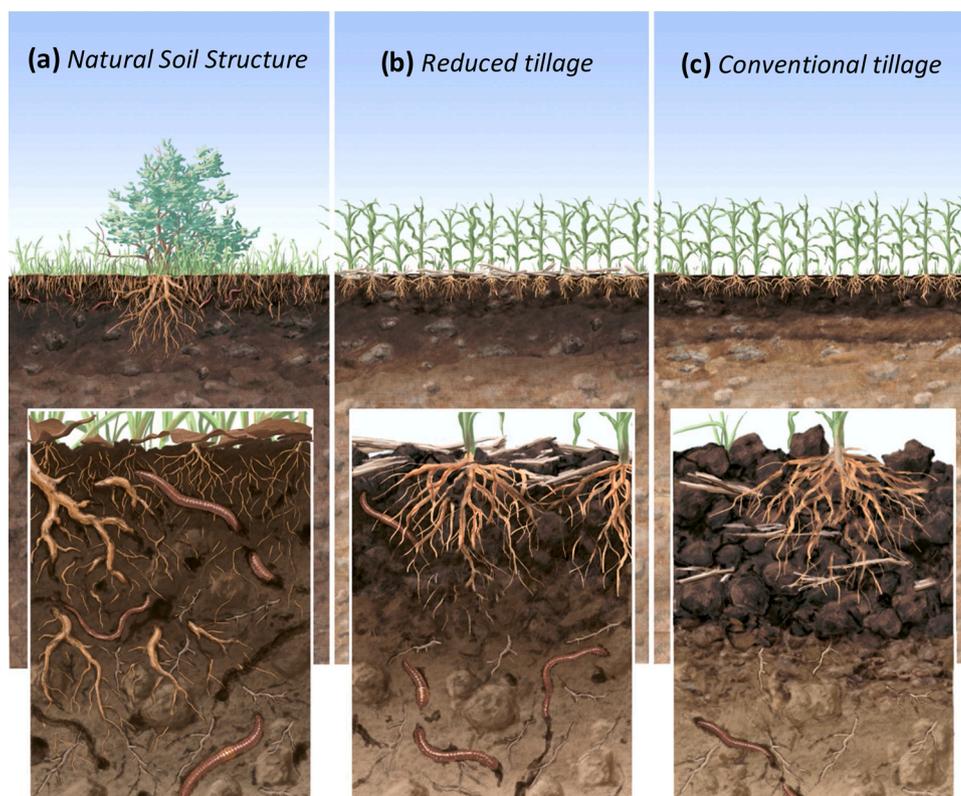
An important first step towards demystifying soil structure and developing informed expectations regarding its role and management is to make a distinction between natural and managed soil structure. We define natural soil structure as *the cumulative ecological legacy and soil constituent architecture by natural aggregation and bioturbation that support soil functioning under given climatic conditions*. Managed soil structure by tillage is defined here as *the breakup and arrangement of soil constituents to support uniform and favorable conditions for crop seeds and root zones to maximize yields*. Tillage aims to break up hardened soil towards reducing mechanical impedance, enhancing soil-seed contact, reducing weed competition, burying plant residues and improving transport properties without excessively harming soil ecological traits (Fig. 1).

The foregoing discussion suggests that the goals and benefits of tillage are considerably different from the ecosystem services provided by natural soil structure. Some of these differences are qualitatively expressed in terms of biogeochemistry (Schlesinger and Bernhardt, 2013), SOC accumulation (Schlesinger, 1990), soil hydrology (Lange

et al., 2009; Rabot et al., 2018), and the crop yields of arable lands. Even under managed soil structure, undisturbed biological activity may persist below (and within) the tilled layer and contribute to land productivity (Cresswell and Kirkegaard, 1995). Conservation tillage practices offer soil management ranging from reduced tillage to no-till, where structure disturbance is more similar to natural soil structure and may offer benefits under certain conditions (Pittelkow et al., 2015b). The primary goal of this study is to propose a framework for distinguishing soil structure in natural and managed ecosystems with potential metrics commensurate with their respective roles in natural or arable lands. We review key features of soil structure, seek to quantify the benefit of soil structure managed by tillage, and characterize dynamic aspects of soil structure following perturbations due to land use change or soil management.

## 2. Characteristics of natural and managed soil structures

A large literature is devoted to quantifying the critical links between soil biological activity and soil structure (Lynch and Bragg, 1985; Jastrow and Miller, 1991; Oades, 1993; Niemeyer et al., 2014; Rabot et al., 2018). Biological activity over long time scales transforms the characteristics and mineralogy of soil parent material and contributes to soil formation, and is thus considered a primary soil-forming factor (Jenny, 1941). Over shorter time horizons of years to decades, biological agents transform and organize soil constituents through trophic preferences and life cycles. The cumulative signatures of these activities give rise to a structure that supports stable food webs and offers ecological templates for future life cycles (Verboom and Pate, 2006; Rabot et al., 2018; Colombi et al., 2017; Landl et al., 2019). In contrast to the gradual and nuanced soil structure formed by biological processes, the top layer of arable soil is subjected to abrupt mechanical fragmentation by tillage (Whitney, 1925; Dexter, 1979; Hadas, 1997). The annual tillage ritual is often driven by the relatively rapid collapse of the loose soil structure by wetting-drying cycles (Ghezzehei and Or, 2000), compaction by farm machinery (Andersson and Håkansson, 1966), weed and pest control



**Fig. 1.** A sketch of natural and managed soil structure characteristics. (a) Natural soil structure is shaped by soil-fauna-vegetation-climate feedbacks (accumulation of biopores and invisible soil aggregation). (c) Managed (tilled) soil structure is characterized by mechanical fragmentation of the top layer and subsequent coalescence and consolidation of the loose structure (certain biological activity is maintained at the undisturbed subsurface). (b) No-till and reduced tillage management fosters higher biological activity that conventional tillage but lacks the vegetation diversity and soil organic carbon accumulation of natural soil under similar conditions.

and preparation of a seedbed for the next crop (Håkansson and von Polgár, 1984; Hadas, 1997).

Despite considerable differences in the formation and functions of natural and managed soils (Fig. 1), agronomic experience shows that tillage is effective in promoting crop growth. An unfortunate source of confusion is the similar appearance and size distributions of tillage-produced soil fragments and biologically-formed aggregates (Dexter, 1988; Hadas, 1997; Or and Ghezzehei, 2002). Despite reference to these as aggregates, fragments and natural aggregates are mechanically and ecologically different (Fig. 2). Soil fragments are weak and coalesce upon wetting (Or and Ghezzehei, 2002). In contrast, natural aggregates are embedded in the soil matrix; they tend to be stable and biogeochemically active (Tisdall and Oades, 1982; Lynch and Bragg, 1985; Tisdall, 1994; Jastrow et al., 1998). The acquired mechanical stability is a product of aggregate formation processes with organic residues incorporated by biological activity including binding and stabilization by biopolymers, and particle enmeshing by hyphae and fine roots (Six et al., 2002, 2004; Rabot et al., 2018; Ghezzehei and Or, 2000).

### 2.1. Natural soil structure

The close links between biological activity and soil binding by embedded SOC, proliferation of legacy biopores, and formation of stable food webs offer glimpses of how natural soil structure promotes soil ecological functioning. Evidence suggests that plant roots preferentially exploit and reuse existing biopores (Cresswell and Kirkegaard, 1995; Watt et al., 2006; Colombi et al., 2017; Landl et al., 2019). Biopores act as biological hotspots that may persist across years and decades (Hagedorn and Bundt, 2002). Recent studies have elucidated how soil pores and organic carbon jointly interact to mediate decomposition rates (Kravchenko and Guber, 2017; Lucas et al., 2019). Anecdotal evidence suggests that natural soil structure not only promotes SOC accumulation (Reicosky et al., 1995; Poeplau et al., 2011), but also allows for preservation of spatial ecological traits including legacy rhizobionomes preserved in favorable locations that provide a roadmap for future roots (Garbeva et al., 2008; Poudel et al., 2019). Avoidance of mechanical disruptions permits accumulation of biopores (Verboom and Pate, 2006; Wuest, 2001; Rabot et al., 2018; Lucas et al., 2019) and the persistence of habitats formed by macrofauna that contribute to increased diversity

of soil organisms (de Bruyn, 1997; Chan, 2001) and preserving beneficial fungal networks (mycorrhiza). The bulk effects of biological activity, such as increased macro-porosity (Valentine et al., 2012) and higher levels of SOC, modify soil transport properties and enhance water retention and gas exchange that, in turn, promote biological activity. Evidence suggests that a stable and mature soil structure in natural ecosystems supports ecological functioning by promoting root growth and efficient exploration of soil volumes populated by beneficial bacteria and fungi, with new roots capitalizing on legacy microbiome, nutrients and biopores.

Despite these observations, the centrality of soil aggregates as hot spots for biological activity (Haynes and Swift, 1990), biogeochemical processes (Schlesinger and Bernhardt, 2013), and their significance to soil structure have been questioned recently (Kravchenko et al., 2019; Rabot et al., 2018). This debate could be partially linked to the confusion between soil aggregates and fragments (Fig. 2). Natural soil aggregates are seamlessly embedded in the surrounding soil matrix, whereas tillage-produced fragments are often loosely packed and form inter-fragment spaces. Hence, the common notion of inter-aggregate macroporosity is probably rooted in tilled soil structure, whereas natural aggregates become apparent only after mild disruption of a sampled soil volume (Tisdall and Oades, 1982; Oades and Waters, 1991; Six et al., 2002). The process and life cycle of an aggregate may span years to decades (Kay, 1990; Jastrow et al., 1998). Empirical correlations between aggregate stability and soil productivity and functioning (Six et al., 2002, 2004) reflect the role of aggregates as stable biological hotspots in the soil's ecological hierarchy (Wang et al., 2019a, b).

The amounts and changes (trends) in SOC reflect a delicate balance between plant-derived carbon inputs, decomposition by biological activity, and the internal accumulation of SOC as binders for soil structure across several hierarchical levels (Haynes and Swift, 1990). The importance of SOC-laced soil structure becomes evident following significant land use changes from natural to managed land that disrupt these delicate structures and the balance of processes that maintain them. Such transitions are accompanied by significant losses (or accumulation) of SOC over decades to century (Post and Kwon, 2000; Poeplau et al., 2011) as will be elaborated in Section 3. Although the complex processes that give rise to specific SOC levels have not yet been resolved, SOC is an important index that enables assessment of the

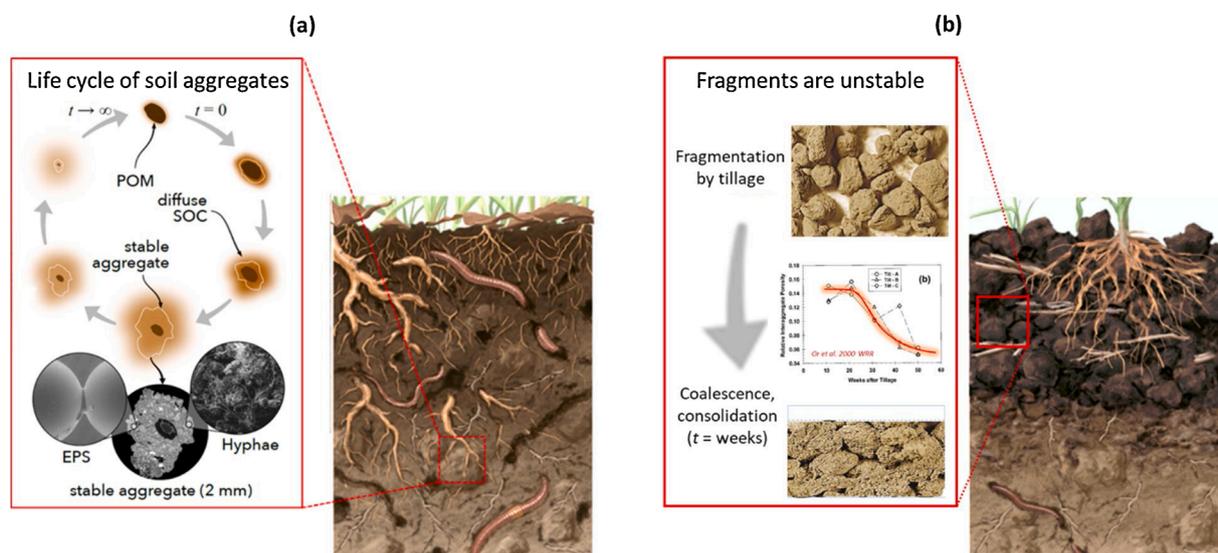


Fig. 2. Soil aggregates and fragments may look similar but are formed by different process and have different properties. (a) Soil aggregation is stimulated by biological activity with biopolymers and hyphae that stabilize and bind soil particles (the inset reflects a hypothetical aggregate life cycle, from Ghezzehei and Or, 2020, in preparation); (b) soil fragments form by mechanical forces of tillage, they tend to be mechanically weak and coalesce upon wetting with macroporosity collapsing within a single season (see insert from Or et al., 2000). The different formation mechanisms impart different mechanical properties, arrangement in the soil body, and ecological functions for aggregates and fragments.

stability and ecological effectiveness of soil structures (and potential attainment of functional steady state). In essence, we propose to expand the proposition of Schmidt et al. (2011) for considering the rate of change of SOC and its long-term levels as an indicator of the state of soil structure and function.

### 2.1.1. Metrics of natural soil structure

In the consideration of potential metrics for assessing the status of soil structure, we often invoke the standard hydro-mechanical traits (similar to those used for assessing managed soil structure), including water and gas transport metrics (saturated hydraulic conductivity, gas diffusivity, and infiltration capacity), water storage and mechanical penetration resistance. These metrics are useful because they are measurable and provide a basis for systematic comparisons. Because defining target values for natural soil structure is of limited value, we may use these metrics for comparisons of soil structure state across biomes, or in comparisons to tilled soil (Fig. 3). Metrics associated with biological activity (microbial biomass, earthworm biomass and abundance) are strongly reduced in tilled soil, whereas mechanical impedance is often similar in managed and natural soil structure. The differences reflect that soil tillage aims at optimizing mechanical impedance for root growth, but not specifically promoting soil biological activity. Certain soil structural features are specific to natural soil such as the proliferation of soil biopores (Wuest, 2001; Lucas et al., 2019), and the abundance and diversity of soil macrofauna. Hence, their levels could serve as specific metrics for soil structure. In addition, we could reinterpret the well-established metric of water-stable aggregates to account for the fraction of natural aggregates within a soil volume (to distinguish them from unstable fragments) and thus the degree of natural soil structure that remains in tilled and fragmented soil.

The development of soil structure under stable natural vegetation shows NPP as a critical parameter determining soil structure in different biomes (Dunne et al., 1991; Faticchi et al., 2020). NPP reflects the soils' potential for supporting biological activity; it affects carbon inputs and long-term SOC balance. Studies have shown links between NPP and natural soil structure development. For example, higher saturated hydraulic conductivity or surface infiltration capacity (see also Fig. 3), have been attributed to cumulative effects of vegetation, particularly the increase in biopores formed by decaying roots (Dunne et al., 1991; Lange et al., 2009; Thompson et al., 2010; Wuest, 2001; Niemeyer et al., 2014; Lucas et al., 2019). The myriad links between vegetation, NPP and

soil structure have not been widely discussed due to the dominance of soil structure in the context of agricultural soils and tillage (Or, 2019). It is precisely this gap linking vegetation and soil structure and indirectly soil hydraulic properties that motivated Faticchi et al. (2020) to propose systematic consideration of vegetation effects on natural soil structure and soil hydraulic parameterization with consequences for local and global hydrologic fluxes.

## 2.2. Managed (tilled) soil structure

The basic tenets of Cato the Elder regarding soil management from *De agri cultura* (160 BC) "What is it to till the land well? It is to plow well. What next? To plow. What is third? To manure" (Olson, 1945) have not changed much over the millennia. Certain aspects of desired soil structure may vary with soil type, crop and climatic regions, yet the main goal remains similar – creation of favorable agronomic conditions for the crop and elimination of competition from weeds. Considering the success of no-till in many parts of the world, it is reasonable to ask what are the direct benefits of tillage? How can we quantify these benefits objectively and systematically?

### 2.2.1. Goals and desired traits of managed soil structure

Tillage disrupts the past "ecological legacy" and presents seedlings and crop roots with a homogenized soil environment with limited ecological cues for the expanding roots. Yet, experience shows that tillage offers significant benefits ranging from creation of favorable tilth with reduced mechanical impedance, to uniform conditions across the field, reduced competition with weeds, deeper and faster incorporation of plant residue, and pathogens control (Watt et al., 2006). Seedbed preparation and homogenous conditions are critical to uniform germination and the ultimate success of crops (Collis-George and Hector, 1966; Håkansson and von Polgár, 1984; Collins et al., 1984; Brown et al., 1996). On balance, the advantages presented by natural soil structure are partially compensated by mechanically favorable and uniform conditions of tilled soils. Average target values, optimal ranges and thresholds for selected properties of managed soil structure are summarized in Table S2. Interestingly, no target values for biological properties of tilled soils are reported in the literature, highlighting the narrow aims of tillage that are not strongly guided by biological traits.

It is instructive to consider the role and function of the undisturbed subsoil below the tilled layer and its understudied contribution to

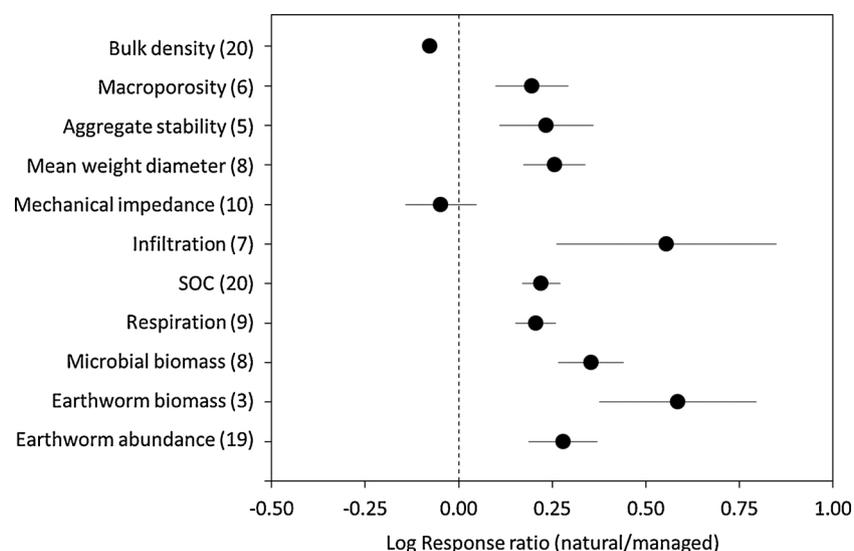


Fig. 3. Metrics of natural soil structure relative to managed soil structure. Data are from paired studies (Supplementary Table S3) that compare metrics from natural and managed soil structure at the same location (to remove potential biases due to climate, soil type or measurement methods). Numbers in parentheses indicate the numbers of paired studies.

agriculture. While this soil domain remains largely undisturbed, it may not function in a similar way as natural soil under native and diverse vegetation and fauna, due to the presence of annual monoculture with agrochemicals and fertilization inputs. Moreover, the presence of a compacted plow layer creates a mechanical and hydrological discontinuity not found under natural soil conditions (Dexter, 1986). Nevertheless, within this minimally disturbed layer biopores develop and accumulate (Kirkegaard and Lilley, 2007; Lucas et al., 2019) and roots may access water and nutrients (McCallum et al., 2004; Watt et al., 2006). To realize the crops' full potential, the untilled subsoil must remain mechanically accessible to crop roots (Dexter, 1991; Cresswell and Kirkegaard, 1995). This places significant constraints on sustainable agro-mechanical operations, namely avoidance of compaction of the untilled subsoil – a risk projected to increase with agricultural intensification (Keller et al., 2019).

### 2.2.2. Quantifying the benefits of managed soil structure (tillage)

The long history of continuous practice at massive scales with a limited empirical basis makes soil tillage “a commonly practiced art, but a neglected science” (to paraphrase Keey, 1972). The expansion of conservation agriculture (Kassam et al., 2019) with demonstrated benefits in certain climatic regions and crops (Pittelkow et al., 2015b) raises questions regarding the direct benefits of conventional tillage. Considering Human Allocated Net Primary Production (HANPP) under different land use practices (Haberl et al., 2007; Krausmann et al., 2013) suggests that native land with natural soil structure supports higher ecosystem NPP levels than arable lands. The differences have been attributed in part to a richer soil ecology, naturally balanced carbon and nutrient cycles, and diverse vegetation self-selected for soil and climate. This is supported by analyses of land productivity potential (Tilman et al., 2011; Foley et al., 2011) that create the impression that arable lands are less productive than natural (untilled) lands. The difference in productivity could be partially attributed to the inherent annual cycle of crops that grow during part of the year, with considerable investment in building new roots and shoots and only part of the plant harvested for yield. The notion that arable lands are less productive than the original native lands is debatable considering crop yields selected for maximum biomass or dry matter production (i.e., where yield is close to NPP). For example, sugar beet or corn for silage, where crop yields may reach 20–30 tons/ha (dry matter) similar or higher than potential NPP of native vegetation. Bradford et al. (2005) have shown that agriculturally derived NPP in the Great Plains of the USA often exceeds native vegetation NPP. The point being that tillage (despite its many limitations) does not necessarily reduce land productivity relative to natural lands

supporting native vegetation, particularly in the context of modern agronomic practices with exogenous human inputs such as irrigation and fertilization (Smith et al., 2014).

### 2.2.3. No-till as a reference frame for evaluating the benefits of tillage under similar conditions

A potentially useful reference frame for evaluating the direct benefits of tillage for arable lands is a comparison of crop yields (and other traits) for tilled and no-till under similar soils, climatic conditions and crops (Huggins and Reganold, 2008; Soane et al., 2012; Powlson et al., 2014). This appears to be the closest comparison where tillage is the primary difference between these land management practices. No-till often results in reduction in crop yields of about 10 % on average relative to tilled soil (Pittelkow et al., 2015a, b; Fig. 4). Among the expected benefits of no-till are the stimulation of ecological networks, increased soil organic carbon, and improved soil water retention and storage (Huggins and Reganold, 2008; Powlson et al., 2014; Kassam et al., 2019). The results in Fig. 4 indicate that the crop performance under no-till is strongly dependent on the crop type and climate. The greatest benefits of no-till occur under rainfed agriculture in arid regions (Pittelkow et al., 2015a). Although not described in detail, we expect differences between crops (Fig. 4a) to reflect the sensitivity of different crops to seed placement and germination uniformity (Collis-George and Hector, 1966; Brown et al., 1996). Minute differences in seed placement depths due to nonuniform crop residues in no-till (Conceição et al., 2016) and in moisture conditions (Håkansson and von Polgár, 1984) could affect crop yields. No-till appears less favorable in humid climates (Fig. 4b) where soil aeration is important and higher soil density under no-till may limit soil gas transport (Ben-Noah and Friedman, 2018; Colombi et al., 2019), and where crop residues may make it difficult to control pathogens (Watt et al., 2006). Additionally, crops sensitive to soil mechanical impedance or those that invest in belowground tubers tend to perform worse under no-till that generally presents higher mechanical impedance (Valentine et al., 2012; Martínez et al., 2016). The trends emerging from comparative studies show that no-till may not be suitable for all conditions (Pittelkow et al., 2015a), suggesting that conventional tillage may offer certain advantages in carefully managed intensive agriculture where chronic yield losses associated with no-till are not acceptable economically.

From climate change mitigation perspective, it has been shown that no-till has not resulted in significant soil carbon accumulation even after a decade of crop residue return, except at the very top soil layer (Baker et al., 2007; Angers and Eriksen-Hamel, 2008; Powlson et al., 2014). One reason could be that carbon inputs into the soil (i.e. roots) do not

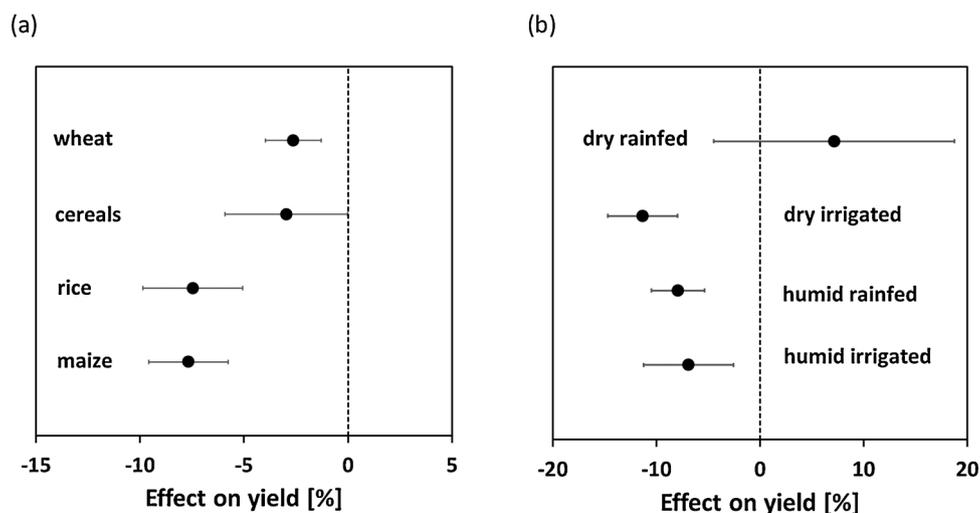


Fig. 4. Crop yield impact of no-till relative to conventional tillage systems. Difference in crop yield (in %;  $100 \times [\text{Yield}_{\text{NT}} - \text{Yield}_{\text{T}}] / \text{Yield}_{\text{T}}$ , where T is conventional tillage and NT no-till) for (a) different crops and (b) different climates. Redrawn from the global meta-analyses of Pittelkow et al. (2015b).

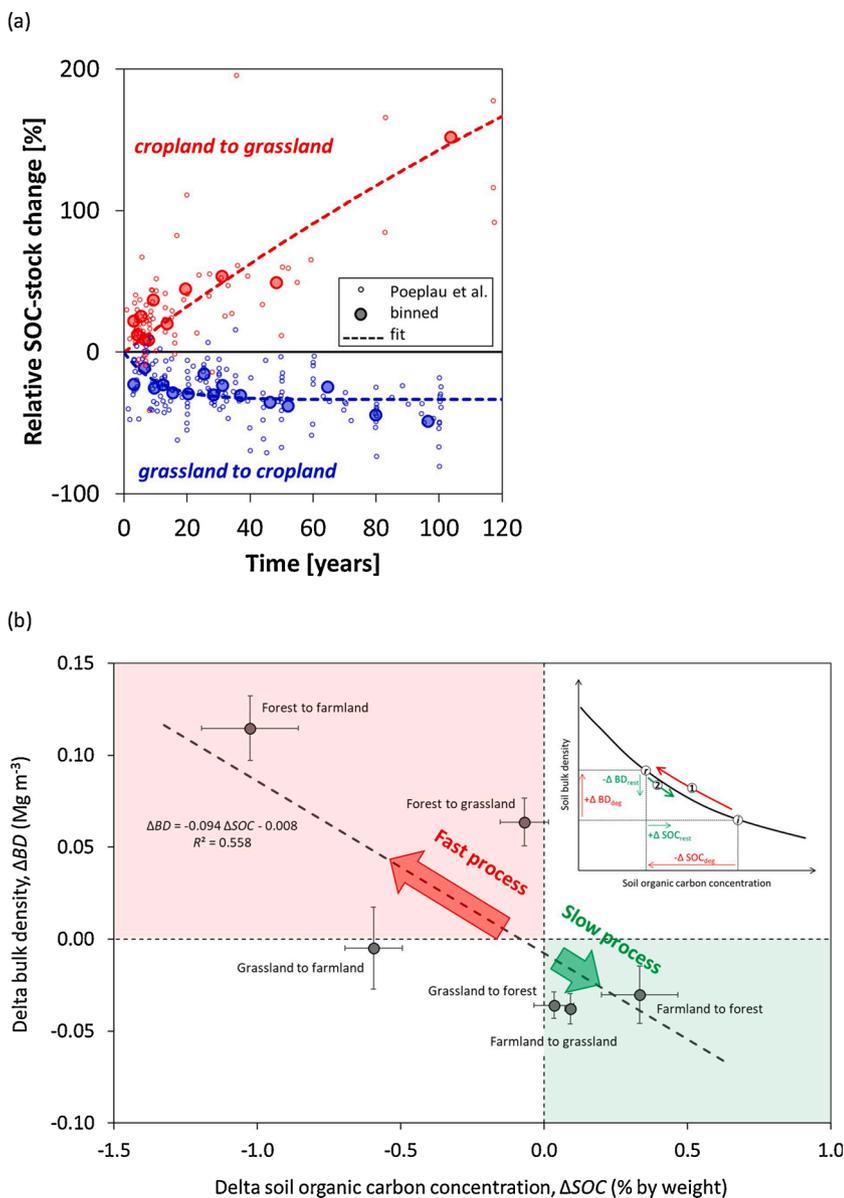
change much, whereas harvested parts of crops are removed from the field irrespective of tillage practices. It is also possible that the extremely slow rates of SOC accumulation in response to changes in soil management (Houghton, 1999; Poeplau et al., 2011) and inter-annual variability make it difficult to detect changes in SOC. The persistent response of SOC levels to changes in land management (particularly a rapid decline in conversion of natural to tilled) provides an important clue for the crucial role of soil structure and the adverse impacts of mechanical disruptions for soil ecology and its ability to store organic carbon (Reicosky, 1997). Hence, differences in soil management should be evaluated not only by their impacts on yield, but also considering their long-term effects captured by integrative ecological metrics such as SOC.

### 3. Aspects of soil-structure dynamics and soil functioning

Soils are living systems with their internal structure dynamically adjusting to management, climate, and disturbance legacy. Among the most revealing examples for the role of soil structure in ecosystem functioning are the consequences of abrupt land use change (e.g. forest to arable land conversion), natural disturbances (fire, desertification or climate change) and unintended consequences of land management (e.g.

soil compaction). These abrupt changes trigger a cascade of impacts that may either lead to a new equilibrium soil state, or gradually revert to pre-disturbance state. The prediction of a soil stable state and its trajectory is far from simple, yet ample evidence of persistent changes in the state of SOC with changes in soil management has been well-documented (Supplementary Fig. S1; Houghton, 1999; Post and Kwon, 2000; Poeplau et al., 2011). Moreover, soil systems may attain different stable states under similar climate, soil and vegetation cover depending on management and disturbance history (Robinson et al., 2017, 2019). For practical applications, the rates of change and processes that dominate the attainment of new soil equilibria (or reverting to pre-disturbance state) are of particular interest.

The potential usefulness of SOC levels and dynamics as metrics of ecosystem functioning (Schmidt et al., 2011) is supported by observations of SOC dynamics following land-use conversions (Houghton, 1999; Post and Kwon, 2000; Poeplau et al., 2011). Often, the response of SOC levels to land-use conversion is asymmetric with rapid SOC loss for conversion of natural to tilled soil, relative to slow accumulation and long equilibration times following the abandonment of tillage (Fig. 5a, Supplementary Fig. S3; Novara et al., 2011). Ledo et al. (2020) have shown that SOC increases under perennial crops in comparison to



**Fig. 5. Changes in soil organic carbon concentration (SOC) and bulk density due to land use change.** (a) Relative change in SOC following land use change: degradation (grassland to cropland; blue) reaches a new steady-state within a decade or two, whereas restoration from cropland to grassland is a slower process (SOC levels steady-state is not reached even after a century); data from Poeplau et al. (2011). (b) Change in soil bulk density (BD) as a function of the change in SOC, revealing that the loss (increase in BD, decrease in SOC) is larger than the gain (decrease in BD, increase in SOC), which is associated to the different time scales for degradation (faster) and restoration (slower); data from Deng et al. (2016). The conceptual inset in (b) illustrates impacts of land use change on SOC and BD with ① representing soil degradation following forest to arable land conversion, and ② soil restoration from arable land to forest. Soil degradation (SOC loss, increased BD) is faster than restoration, with differences in absolute changes for a given time period (red and green arrows represent similar periods).

annual crops, attributing the trend to absence of mechanical disturbance by tillage in perennial crops. These studies paint a consistent picture of the effects of introduction or abandonment of tillage on SOC trends.

Tillage results in a homogenization of SOC within the tilled layer, while SOC accumulates near the surface under no-till (Reicosky et al., 1995). Meta-analyses of data from conventional tillage and no-till (Angers and Eriksen-Hamel, 2008) show no significant differences in soil SOC accumulation, contrary to expectations in terms of soil carbon sequestration under no-till (Powlson et al., 2014). Nevertheless, several studies show a gradual increase in SOC stocks under no-till, albeit differences between tillage systems become detectable only after several decades after conversion (Angers and Eriksen-Hamel, 2008; Haddaway et al., 2017).

Hence, the challenge for using SOC levels and dynamics as diagnostic metrics for soil management and ecological functioning are the exceedingly slow changes that span decades, while soil structure management decisions and disturbances occur at much shorter time scales. We thus propose to supplement SOC measurements with soil structure metrics that respond rapidly to soil disturbances at short time scales, such as changes in soil macroporosity (preferably expressed as biopores), mechanical impedance or bulk density. Despite many limitations and lack of sensitivity to soil pore architecture, soil bulk density has been used and reported extensively for soil structure characterization. The availability of concurrent information on SOC and soil bulk density motivated the analysis presented in Fig. 5b, to address rapid and precursory changes in soil structure state, reflected in abrupt changes in bulk density and the ensuing adjustments in SOC levels that may take decades to be manifested (Fig. 5a). The results also point to a strong relationship between SOC and bulk density that links SOC response to changes in soil structure, highlighting the usefulness of SOC as an integrative measure of soil structure state (Supplementary Fig. S2). The nonlinear synergy between SOC and soil structure is also manifested by the large decrease in bulk density with increasing SOC that exceeds predictions from linear mixing of organic matter and solids with their respective densities. Finally, the impact of land use change summarized in Fig. 5 suggest that soil structure degradation occurs and is manifested at shorter times relative to the slower and longer path of soil structure restoration. The different pathways for soil structure degradation and restoration highlight the urgent need for more inclusive and ecologically sensitive metrics for soil structure (other than bulk density), for example, quantifying rates of biopore accumulation or loss.

The dynamic nature of soil structure and its influence on soil function are reflected in trends and equilibrium levels of SOC (and associated changes in soil bulk density). The sensitivity of SOC to tillage operations (Supplementary Fig. S4; Reicosky et al., 1995) and the rate of attainment of new equilibria following land use or soil structure perturbation (Fig. 5), make SOC monitoring a promising metric for comparing the consequences of soil management, land use and disturbances for both natural and managed soil structures. However, the usefulness of SOC monitoring must be placed in the context of land use practices to calibrate expectations for SOC levels for natural and tilled soils (for certain soil and climatic conditions).

#### 4. Summary and outlook

A central theme of this study is the distinction between natural and managed soil structure, a critical step towards disentangling past confusion and enabling a rational path for quantifying desired soil structure states and their potential contributions to ecosystem services. The centrality of stable structure to soil ecosystem services becomes abundantly clear following land use conversion with the introduction (or cessation) of tillage. The conversion of native grassland to arable land invariably leads to rapid decline in SOC levels within a decade with subsequent stabilization at a new soil structure state determined by climate and land management.

Globally, soil tillage is the largest land engineering operation on

Earth, yet tillage is a neglected science. The expansion of no-till practices challenges the need for tillage; however, systematic evaluation of crop yields and other metrics suggest that no-till is not universally beneficial, and no-till adaptation must be tailored to crop, soil and climate conditions. Seedbed and sowing uniformity play a critical role in crop yields and may be a decisive factor in the success of tillage. A “strategic” application of minimum tillage may result in numerous benefits (Conyers et al., 2019) despite conflicts with the philosophical ideal of zero disturbance. The term “managed soil structure” does not preclude natural contributions within disturbed soil volumes and in the undisturbed subsurface, with no-till practices further blurring the lines between the binary classification of natural versus managed soil structure.

The services rendered by natural soil structure are quantitatively indecipherable, yet mounting evidence suggests that stability and legacy effects of biological activity result in an ecological road map for future vegetation. Roots favor growth into existing biopores and potentially benefit from legacy microbial communities. The cumulative effects of biological activity lead to increased soil stabilization by organic carbon deposited by biological agents. The formation of ecological aggregates is an example that underlies the traditional use of water-stable aggregates as a measure of soil health. Aggregates and soil fragments formed by tillage may look similar but have vastly different functions, which may contribute to the confusion and debate related to the existence and relative importance of soil aggregates.

A certain degree of overlap in the values used to characterize natural and managed soil structures does not reflect similar roles. Classical metrics often focus on hydrologic functions (infiltration, water retention, diffusion) and plant related conditions (aeration, low mechanical impedance) guided by desired traits of managed soil structure. The overlap in characterization methods and metrics, and the lumping of aggregates and fragments have hindered progress in this important area. We propose to expand the range of metrics by including SOC levels and dynamics (trends) as an integrator of soil structure on its ecological functioning. Additionally, the distinction between natural and managed soil structures requires consideration of long-term vegetation cover (NPP) of natural lands as an important factor that feeds structure-forming biological processes. Evidence suggests that the development of natural soil structure is linked with vegetation density, thus allowing this remotely sensed variable to be an indirect metric of soil structure in natural lands. Ability to include soil structure in the characterization of natural landscapes is an important step towards the quantification of their functioning as ecohydrological units, and contributes to better representation of soil hydraulic and transport properties in Earth system models.

Improved understanding of the nature and role of soil structure in arable lands is critical for rational guidance of tillage operations with their agronomic, environmental and climatic consequences. There is a need to demystify the benefits and role of no-till relative to tillage practices within the spectrum of land management options. Clearly, for some regions and crops, no-till offers an environmentally and economically sound solution. On the other hand, sweeping rejection of conventional tillage where no-till performs poorly is a disservice to farmers and to the needs of a rapidly growing global population in need for efficient food production systems.

A rigorous and universal definition of soil structure remains elusive, however, the proposed framework for disentangling biases surrounding this important soil trait paves the way for adopting new metrics suitable for managed and natural lands, and placing the representation of soil structure on quantitative and predictive scientific basis.

#### Declaration of Competing Interest

The authors have no conflict of interest involving this study and the findings reported in this paper.

## Acknowledgements

Ideas and concepts for this work evolved from an International Exploratory Workshop on "Quantifying the role of biophysical processes in soil structure dynamics" held 14-15 April 2016 in Zürich, Switzerland. The workshop received financial support from the Swiss National Science Foundation (SNF) through grant no. IZ32Z0\_164150, and was organized and hosted by Thomas Keller and Dani Or. Thomas Keller acknowledges financial support from the Swedish Farmers' Foundation for Agricultural Research (Stiftelsen Lantbruksforskning, SLF) through grant no. O-19-23-309. The study benefited greatly from discussions with Margaret McCully (CSIRO, Australia), Teamrat Ghezzehei (University of California Merced, U.S.) and Paul Hallett (University of Aberdeen, U.K.). We thank Fabian Rüdy for artwork presented in Figs. 1 and 2, and Peter Lehmann and Daniel Breitenstein (ETH Zurich, Switzerland) for their assistance with various aspect of the study.

## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.still.2020.104912>.

## References

- Andersson, S., Håkansson, I., 1966. Strukturodynamiken i matjorden. En fältstudie (with English summary). *Grundförbättring* 19, 191–228.
- Angers, D.A., Eriksen-Hamel, N.S., 2008. Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. *Soil Sci. Soc. Am. J.* 72, 1370–1374.
- Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration – what do we really know? *Agric. Ecosyst. Environ.* 118, 1–5.
- Ben-Noah, I., Friedman, S.P., 2018. Review and evaluation of root respiration and of natural and agricultural processes of soil aeration. *Vadose Zone J.* 17 doi:10.2136/vzj2017.06.0119.
- Bradford, J., Lauenroth, W., Burke, I., 2005. The impact of cropping on primary production in the U.S. Great Plains. *Ecology* 86, 1863–1872. <https://doi.org/10.1890/04-0493>.
- Brown, A.D., Dexter, A.R., Chamen, W.C.T., Spoor, G., 1996. Effect of soil macroporosity and aggregate size on seed-soil contact. *Soil Tillage Res.* 38, 203–216.
- Chan, K.Y., 2001. An overview of some tillage impacts on earthworm population abundance and diversity - Implications for functioning in soils. *Soil Tillage Res.* 57, 179–191.
- Collins, G., Stibbe, E., Kroesbergen, B., 1984. Influence of soil moisture stress and soil bulk density on the imbibition of corn seeds in a sandy soil. *Soil Tillage Res.* 4, 361–370.
- Collis-George, N., Hector, J.B., 1966. Germination of seeds as influenced by matric potential and by area of contact between seed and soil water. *Aust. J. Agric. Res.* 4, 145–146.
- Colombi, T., Braun, S., Keller, T., Walter, A., 2017. Artificial macropores attract crop roots and enhance productivity on compacted soils. *Sci. Tot. Environ.* 574, 1283–1293.
- Colombi, T., Walder, F., Büchi, L., Sommer, M., Liu, K., Six, J., van der Heijden, M.G.A., Charles, R., Keller, T., 2019. On-farm study reveals positive relationship between gas transport capacity and organic carbon content in arable soil. *Soil* 5, 91–105.
- Conceição, L.A., Barreiro, P., Dias, S., Garrido, M., Valero, C., Marques da Silva, J.R., 2016. A partial study of vertical distribution of conventional no-till seeders and spatial variability of seed depth placement of maize in the Alentejo region, Portugal. *Precision Agric.* 17, 36–52.
- Conyers, M., van der Rijt, V., Oates, A., Poile, G., Kirkegaard, J., Kirkby, C., 2019. The strategic use of minimum tillage within conservation agriculture in southern New South Wales, Australia. *Soil Tillage Res.* 193, 17–26.
- Cresswell, H.P., Kirkegaard, J.A., 1995. Subsoil amelioration by plant-roots - the process and the evidence. *Soil Res.* 33, 221–239.
- De Bruyn, L.A.L., 1997. The status of soil macrofauna as indicators of soil health to monitor the sustainability of Australian agricultural soils. *Ecol. Econom.* 23, 167–178.
- Dexter, A.R., 1979. Prediction of soil structures produced by tillage. *J. Terramech.* 16, 117–127.
- Dexter, A.R., 1986. Model experiments on the behaviour of roots at the interface between a tilled seedbed and a compacted sub-soil. III. Entry of pea and wheat roots into cylindrical biopores. *Plant Soil* 95, 149–161.
- Dexter, A.R., 1988. Advances in characterization of soil structure. *Soil Tillage Res.* 11, 199–238.
- Dexter, A.R., 1991. Amelioration of soil by natural processes. *Soil Tillage Res.* 20, 87–100.
- Dunne, T., Zhang, W., Aubry, B.F., 1991. Effects of rainfall, vegetation, and microtopography on infiltration and runoff. *Water Resour. Res.* 27, 2271–2285.
- Faticchi, S., Or, D., Walko, R., Vereecken, H., Young, M.H., Ghezzehei, T.A., Hengl, T., Kollet, S., Agam, N., Avissar, R., 2020. Soil structure is an important omission in Earth System Models. *Nat. Commun.* 11, 522.
- Foley, J., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. *Nature* 478, 337–342.
- Garbeva, P., van Elsas, J.D., van Veen, J.A., 2008. Rhizosphere microbial community and its response to plant species and soil history. *Plant Soil* 302, 19–32.
- Ghezzehei, T.A., Or, D., 2000. Dynamics of soil aggregate coalescence governed by capillary and rheological processes. *Water Resour. Res.* 36, 367–379.
- Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzer, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M., 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proc. Natl. Acad. Sci. U.S.A.* 104, 12942–12947.
- Hadas, A., 1997. Soil tillage - the desired soil structural state obtained through proper soil fragmentation and reorientation processes. *Soil Tillage Res.* 43, 7–40.
- Haddaway, N.R., Hedlund, K., Jackson, L.E., Kätterer, T., Lugato, E., Thomsen, I.K., Jørgensen, H.B., Isberg, P.-E., 2017. How does tillage intensity affect soil organic carbon? A systematic review. *Environ. Evid.* 6, 30. <https://doi.org/10.1186/s13750-017-0108-9>.
- Haff, P.K., 2010. Hillslopes, rivers, plows, and trucks: mass transport on Earth's surface by natural and technological processes. *Earth Surf. Process. Landforms* 35, 1157–1166.
- Hagedorn, F., Bundt, M., 2002. The age of preferential flow paths. *Geoderma* 108, 119–132.
- Håkansson, I., von Polgár, J., 1984. Experiments on the effects of seedbed characteristics on seedling emergence in a dry weather situation. *Soil Tillage Res.* 4, 115–135.
- Haynes, R.J., Swift, R.S., 1990. Stability of soil aggregates in relation to organic constituents and soil water content. *J. Soil Sci.* 41, 73–83.
- Houghton, R.A., 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus* 51B, 298–313.
- Huggins, D., Reganold, J., 2008. No-Till: the quiet revolution. *Sci. Am.* 299, 70–77.
- Jastrow, J.D., Miller, M., 1991. Methods for assessing the effects of biota on soil structure. *Agric. Ecosyst. Environ.* 34, 279–303.
- Jastrow, J.D., Miller, R.M., Lussenhop, J., 1998. Contributions of interacting biological mechanisms to soil aggregate stabilization in restored prairie. *Soil Biol. Biochem.* 30, 905–916.
- Jenny, H., 1941. Factors of Soil Formation: a System of Quantitative Pedology. Republished in 1994. Dover Publications, New York, USA.
- Kassam, A., Friedrich, T., Derpsch, R., 2019. Global spread of conservation agriculture. *Int. J. Environ. Studies* 76, 29–51.
- Kay, B.V., 1990. Rates of change of soil structure under different cropping systems. *Adv. Soil Sci.* 12, 1–41.
- Keey, R.B., 1972. *Drying – Principles and Practice*. Pergamon Press, Oxford, New York.
- Keller, T., Sandin, M., Colombi, T., Horn, R., Or, D., 2019. Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. *Soil Tillage Res.* 194, 104293.
- Kirkegaard, J.A., Lilley, J.M., 2007. Root penetration rate – a benchmark to identify soil and plant limitations to rooting depth in wheat. *Aust. J. Exp. Agr.* 47, 590–602.
- Krausmann, F., Erb, K.H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzer, C., Searchinger, T., 2013. Global human appropriation of net primary production doubled in the 20<sup>th</sup> century. *Proc. Nat. Acad. Sci. U. S. A.* 110 (25), 10324–10329. <https://doi.org/10.1073/pnas.1211349110>.
- Kravchenko, A.N., Guber, A.K., 2017. Soil pores and their contributions to soil carbon processes. *Geoderma* 287, 31–39.
- Kravchenko, A., Otten, W., Garnier, P., Pot, V., Baveye, P.C., 2019. Soil aggregates as biogeochemical reactors: not a way forward in the research on soil-atmosphere exchange of greenhouse gases. *Global Chang. Biol.* 25, 2205–2208. <https://doi.org/10.1111/gcb.14640>.
- Landl, M., Schnepf, A., Uteau, D., Peth, S., Athmann, M., Kautz, T., Perkonis, U., Vereecken, H., Vanderborght, J., 2019. Modeling the impact of biopores on root growth and root water uptake. *Vadose Zone J.* 18, 180196. <https://doi.org/10.2136/vzj2018.11.0196>.
- Lange, B., Lüschner, P., Germann, P., 2009. Significance of tree roots for preferential infiltration in stagnic soils. *Hydrol. Earth Sys. Sci.* 13 (10), 1809–1821.
- Ledo, A., Smith, P., Zerihun, A., Whitaker, J., Vicente-Vicente, J.L., Qin, Z., McNamara, N.P., Zinn, Y.L., Llorente, M., Liebig, M., Kuhnert, M., Dondini, M., Don, A., Diaz-Pines, E., Datta, A., Bakka, H., Aguilera, E., Hillier, J., 2020. Changes in soil organic carbon under perennial crops. *Global Change Biol.* 00, 1–11. <https://doi.org/10.1111/gcb.15120>.
- Lucas, M., Schlüter, S., Vogel, H.J., Vetterlein, D., 2019. Soil structure formation along an agricultural chronosequence. *Geoderma* 350, 61–72.
- Lynch, J.M., Bragg, E., 1985. Microorganisms and soil aggregate stability. *Adv. Soil Sci.* 2, 134–170.
- Martínez, I., Chervet, A., Weisskopf, P., Sturny, W.G., Etana, A., Stettler, M., Forkman, J., Keller, T., 2016. Two decades of no-till in the Oberacker long-term field experiment: Part I. Crop yield, soil organic carbon and nutrient distribution in the soil profile. *Soil Tillage Res.* 163, 141–151.
- McCallum, M.H., Kirkegaard, J.A., Green, T.W., Cresswell, H.P., Davies, S.L., Angus, J.F., Peoples, M.B., 2004. Improved subsoil macroporosity following perennial pastures. *Aust. J. Exp. Agr.* 44, 299–307.
- Niemeyer, R., Fremier, A., Heinse, R., Chávez, W., DeClerck, F., 2014. Woody vegetation increases saturated hydraulic conductivity in dry tropical Nicaragua. *Vadose Zone J.* 13 <https://doi.org/10.2136/vzj2013.01.0025>.
- Novara, A., Gristina, L., La Mantia, T., Rühl, J., 2011. Soil carbon dynamics during secondary succession in a semi-arid Mediterranean environment. *Biogeosci. Discuss.* 8, 11107–11138. <https://doi.org/10.5194/bgd-8-11107-2011>.

- Oades, J.M., 1993. The role of biology in the formation, stabilization and degradation of soil structure. *Geoderma* 56, 377–400.
- Oades, J.M., Waters, A.G., 1991. Aggregate hierarchy in soils. *Aust. J. Soil Res.* 29, 815–828.
- Olson, L., 1945. Cato's views on the farmer's obligation to the land. *Agric. History* 19 (3), 129–132.
- Or, D., 2019. The tyranny of small scales – on representing soil processes in global land surface models. *Water Resour. Res.* 55.
- Or, D., Ghezzehei, T.A., 2002. Modeling post-tillage soil structural dynamics: a review. *Soil Tillage Res.* 64, 41–59.
- Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015a. Productivity limits and potentials of the principles of conservation agriculture. *Nature* 517, 365–368.
- Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X., van Groenigen, K.J., Lee, J., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015b. When does no-till yield more? A global meta-analysis. *Field Crops Res.* 183, 156–168.
- Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemael, B., Schumacher, J., Gensior, A., 2011. Temporal dynamics of soil organic carbon after land-use change in the temperate zone – carbon response functions as a model approach. *Global Change Biol.* 17, 2415–2427.
- Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: processes and potential. *Global Change Biol.* 6, 317–327.
- Poudel, R., Jumpponen, A., Kennelly, M.M., Rivard, C.L., Gomez-Montano, L., Garrett, K.A., 2019. Rootstocks shape the rhizobiome: rhizosphere and endosphere bacterial communities in the grafted tomato system. *Appl. Environ. Microbiol.* 85, e01765–18.
- Powlson, D., Stirling, C., Jat, M., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. *Nat. Clim. Change* 4, 678–683.
- Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H.J., 2018. Soil structure as an indicator of soil functions: a review. *Geoderma* 314, 122–137.
- Reicosky, D., 1997. Tillage-induced CO<sub>2</sub> emission from soil. *Nutr. Cycl. Agroecosyst.* 49, 273–285.
- Reicosky, D.C., Kemper, W.D., Langdale, G.W., Douglas, C.L., Rasmussen, P.E., 1995. Soil organic matter changes resulting from tillage and biomass production. *J. Soil Wat. Conserv.* 50, 253–261.
- Robinson, D.A., Panagos, P., Borrelli, P., Jones, A., Montanarella, L., Tye, A., Obst, C.G., 2017. Soil natural capital in Europe; a framework for state and change assessment. *Sci. Rep.* 7, 6706.
- Robinson, D.A., Hopmans, J.W., Filipovic, V., van der Ploeg, M., Lebron, I., Jones, S.B., Reinsch, S., Jarvis, N., Tuller, M., 2019. Global environmental changes impact soil hydraulic functions through biophysical feedbacks. *Global Change Biol.* 25, 1895–1904.
- Schlesinger, W.H., 1990. Evidence from chronosequence studies for a low carbon-storage potential of soils. *Nature* 348, 232–234.
- Schlesinger, W.H., Bernhardt, E.S., 2013. *Biogeochemistry: an Analysis of Global Change*, 3rd ed. Elsevier. 688 pp.
- Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P., Weiner, S., Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. *Nature* 478, 49–56.
- Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant Soil* 241, 155–176.
- Six, J., Bossuyt, H., Degryze, S., Deneq, K., 2004. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res.* 79, 7–31.
- Smith, W.K., Cleveland, C.C., Reed, S.C., Running, S.W., 2014. Agricultural conversion without external water and nutrient inputs reduces terrestrial vegetation productivity. *Geophys. Res. Lett.* 41, 449–455. <https://doi.org/10.1002/2013GL058857>.
- Soane, B.D., Ball, B.C., Arvidsson, J., Basch, G., Moreno, F., Roger-Estrade, J., 2012. No-till in northern, western and south-western Europe: a review of problems and opportunities for crop production and the environment. *Soil Tillage Res.* 118, 66–87.
- Thompson, S., Harman, C., Heine, P., Katul, G., 2010. Vegetation-infiltration relationships across climatic and soil type gradients. *J. Geophys. Res.* 115, G02023 <https://doi.org/10.1029/2009JG001134>.
- Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. *Proc. Nat. Acad. Sci. U. S. A.* 108, 20260–20264.
- Tisdall, J.M., 1994. Possible role of soil microorganisms in aggregation in soils. *Plant Soil* 159, 115–121.
- Tisdall, J.M., Oades, J.M., 1982. Organic matter and water stable aggregates in soils. *J. Soil Sci.* 33, 141–163.
- Valentine, T., Hallett, P., Binnie, K., Young, M., Squire, G., Hawes, C., Bengough, G.A., 2012. Soil strength and macropore volume limit root elongation rates in many UK agricultural soils. *Ann. Bot.* 110, 259–270. <https://doi.org/10.1093/aob/mcs118>.
- Verboom, W.H., Pate, J.S., 2006. Bioengineering of soil profiles in semiarid ecosystems: the 'phytotarium' concept. A review. *Plant Soil* 289, 71–102.
- Wang, B., Brewer, P.E., Shugart, H.H., Lerdau, M.T., Allison, S.D., 2019a. Soil aggregates as biogeochemical reactors and implications for soil-atmosphere exchange of greenhouse gases—a concept. *Global Change Biol.* 25, 373–386.
- Wang, B., Brewer, P.E., Shugart, H.H., Lerdau, M.T., Allison, S.D., 2019b. Building bottom-up aggregate-based models (ABMs) in soil systems with a view of aggregates as biogeochemical reactors. *Global Change Biol.* 25, e6–e8. <https://doi.org/10.1111/gcb.14684>.
- Watt, M., Kirkegaard, J.A., Passioura, J.B., 2006. Rhizosphere biology and crop productivity – a review. *Aust. J. Soil Res.* 44, 299–317.
- Whitney, M., 1925. *Soil and Civilization – a Modern Concept of the Soil and the Historical Development of Agriculture*. Van Nostrand-Reinhold, New York, USA.
- Wuest, S.B., 2001. Soil biopore estimation: effects of tillage, nitrogen, and photographic resolution. *Soil Tillage Res.* 62, 111–116.