Physical and Hydrological Processes in Soils Under Conservation Tillage in Europe

19

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Abstract

Soil structure is core to many physical soil properties important for sustainable crop production. Aggregate formation and size distribution are related to the pore system, which in turn affects air and water flow. Additionally, soil physical deterioration such as compaction and superficial sealing or crusting derives from poor structural stability, leading to a decrease in infiltration, hydraulic conductivity, and changes in water retention. Consequently, aggregate stability has been used as an indicator of soil structure and soil health. Factors controlling aggregate formation and breakdown are various and operate at different scales. In Europe, it is worthwhile to distinguish among the boreal, temperate, and Mediterranean biogeographic regions as regards as climate concerns. Agricultural practices play an important role at the field scale affecting variables such as the organic matter content, biological activity (roots, earthworms, hyphae, microorganisms, etc.), physical and chemical properties that can induce dispersion or flocculation and of course the mechanical disruption of tillage. However, effects of land use and soil management are soil-specific as the interaction of controlling factors is complex and can lead to site-specific dominant processes.

Keywords

Soil structure · Tillage · Porous system · Aggregates · Organic matter · Soil management

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19.1 Introduction

19.1.1 Soil Structure: Core to Soil Physical Properties

Soils are complex porous media composed of solid, liquid and gaseous constituents. Soil structure is the aggregation of soil particles (sand, silt, clay and organic matter) into granules, crumbs or blocks. Inorganic and organic constituents are bound together forming aggregates and leaving voids in between, which constitute the porous system. Soil structure is the shape that the soil takes based on its physical, chemical and biological properties, regulating the soil-water cycle and sustaining a favourable rooting medium for plants (Kibblewhite et al. 2008). Despite the rigidity of the term, soil structure is dynamic, with cyclical aggregate breakdown and new aggregation, depending on many factors. Aggregate stability is an indicator of soil quality, as in well-structured soils with stable aggregates, water and air have no physical impediment to flow. On the contrary, soils with poor structure have unstable aggregates that break easily into smaller particles, reducing the pore space and its connectivity, inducing numerous problems including waterlogging and oxygen deficits for plant roots and other organisms (Batey 2009; Morris et al. 2010).

There are many factors influencing aggregate dynamics. These factors are from the soil itself (e.g. organic matter, clay, sand and salts content), the environment in which it develops (e.g. climate or topography) and the land use it is subjected to (e.g. forestry, pasture or cereal cropping). Therefore, soil structure and the physical properties which depend on it are soil- and site-specific. Thus, conservation tillage will have different effects on soil physical properties and, in turn, how these influence agricultural production, depending as well on the geographical location.

Conservation tillage (CT) is a term that includes a range of practices that compared to conventional tillage reduce ploughing depth, number of passes or disturbed surface; does not turn over the soil or even drills seeds directly into the undisturbed soil (with the exception of the furrow to place the seed). Farmers around Europe adopt these CT practices in a flexible way, adapting the technology to local conditions and their own personal preferences, resulting in many different farming approaches. Depending on the tillage practice, the environment and the combination of practices of the system in which it is applied, the impacts on the soils' physical and hydrological properties vary.

In Europe, conservation tillage, in any of its forms, is applied in 22.14% of its 102,535,310 ha of arable land, but this percentage varies greatly across regions (EUROSTAT 2010). Another estimate reported that CA is practised on 22.7 Mha, representing 25.8% of arable land in Europe (Kertész and Madarász 2014; Soane et al. 2012). EUROSTAT (2010) data analysis shows that Bulgaria is leading the adoption of conservation tillage, with 55.81% of its arable land. Cyprus, Germany, Czech Republic, the United Kingdom, France, Spain, Austria, Luxemburg, Switzerland and Finland are all above the European average. When focusing on no tillage, the European average that is under this practice is only 3.44% (3,527,214.66 ha). Finland is leading the adoption of no tillage with 7.25% of the arable land, and Romania, Estonia, Spain, Denmark, Italy, Poland and the United

Kingdom are above the European average. In the case of no tillage, Cyprus and Bulgaria have some of the lowest adoption rates. These adoption rates and their variability show that the adoption of conservation agriculture (CA) practices are complex decisions influenced not only by land suitability but also by sociocultural and economic factors.

Any of the conservation tillage (CT) practices reduces the mechanical breakdown of the soil aggregates and the machinery load on the soil. Therefore, aggregates have more time to establish stronger bonds and become more resistant to other disturbances. By reducing the number of field operations, CT also decreases the number of passes of heavy machinery through the field and therefore decreases the risk of soil compaction, whereas in conventionally ploughed fields, below the plough layer, compaction can lead to the formation of a plough pan, which constitutes a physical barrier for root development and water flow. Furthermore, the benefits of CT on soil structure stability increase with the adoption of CA systems, including surface protection and crop rotation. This is because these practices add organic matter and increase soil biological activity, which are aggregation agents that contribute to a more stable soil structure.

19.1.2 Soil Structure and Aggregate Dynamics

Research advances have developed our understanding of soil structure and aggregate dynamics and how they are affected by numerous factors that vary geographically, including tillage practices.

Tisdall and Oades (1982) introduced the importance of soil organic matter (SOM) in the aggregation process. They proposed a hierarchical model in which larger aggregates are formed by smaller aggregates. Moreover, they stated that each aggregate size had its own major binding agent. Indeed, the effectiveness of binding agents depends on their own dimensions in relation to the voids and particles they have to bridge (Kay 1990 cited in Jastrow and Miller 1997). The nature of the aggregation agents leads to differences in aggregate stability. Thus, roots and fungal hyphae are the major binding agents for macroaggregates (>250μm diameter), whose labile characteristics explain why macroaggregates break down into smaller particles easier than microaggregates (<250μm diameter), which are bound together by more recalcitrant organic matter or more stable aggregation agents.

Further development of the hierarchical model helped to relate soil structure to the carbon cycle, in a process that follows organic residue decay, successive integration in soil, occlusion in soil aggregates and sorption to clay minerals (Golchin et al. 1994), which represent consecutively increasing carbon sequestration potential. Afterwards, it was shown that microaggregates form inside macroaggregates (Angers et al. 1997). Since the latter provides physical protection from microbial attack of fresh organic matter, giving it time to establish chemical or physico-chemical bonds with clay particles or more stable organic compounds (Balabane and Plante 2004).

Time is precisely what conservation tillage provides, by avoiding mechanical disturbance, therefore allowing the development of more stable aggregates. On the contrary, macroaggregate turnover rates in cultivated land are only between 5 and 33 days (Plante and McGill 2002a, b). Even the hierarchical model highlighted the vulnerability of macroaggregates to tillage, since their binding agents are labile. More recently, the disruptive effects of tillage have been ratified by other researchers, proving that tillage disturbance increases macroaggregate turnover and carbon mineralisation (Six et al. 1998). Notwithstanding the generally accepted slower turnover rates in microaggregates, Virto et al. (2010) found similar ages of organic matter from within silt-size microaggregates and from outside those silt-size microaggregates, therefore questioning the understanding of turnover rates of this aggregate fraction, which would be much quicker than previously thought.

Besides, the major influence of organic matter in aggregate dynamics, aggregate formation and breakdown is a complex process influenced by many other factors. Even the authors of the hierarchical model highlighted that organic matter becomes the major bonding agent only in soils where other binding agents are absent. Amézketa (1999) showed there are many intrinsic or extrinsic factors affecting soil aggregate stability in different soils, making it a site- and soil-specific property. Among the binding agents are calcium carbonate, calcium sulfate (gypsum), silica, iron or aluminium oxides, clays and organic matter. In turn, their effects can be influenced by the soil solution electrolyte concentration, clay mineralogy, the nature of the organic compounds, climate, time (or ageing), roots, soil microbes, edaphofauna and agricultural management (i.e. tillage, irrigation, organic matter amendments, crop type and crop rotation, chemical amendments, etc.). Additionally, aggregate stabilization factors have interactions. For example, in an experiment in Argentina investigating the interaction between water regimes and vegetation, the results showed that aggregate stability was higher under wet and dry cycles with vegetation compared to the same moisture conditions in sterile soil (Taboada et al. 2004). Therefore, the importance of the synergies among CA practices, including soil surface protection with crop residues or cover crops, and crop rotation and diversification becomes apparent.

Across Europe, different soils and locations have distinct combinations of aggregation agents, which might be dominated by one particular agent. Cementing compounds are major aggregation agents in different soils; for example, Regelink et al. (2015) described the importance of Fe-(hydr)oxides in Austria, Czech Republic and Greece, and Boix-Fayos et al. (2001) stressed the importance of calcium carbonate in Spain. Furthermore, clay mineralogy has been studied by Norton et al. (2006), through soils of a range of clay types and under a range of land uses. They discovered that under cultivation, kaolinitic (1:1 clays, less reactive) soils had greater aggregate stability than in illitic or smectitic soils (2:1 clays, more reactive) but that kaolinitic clays associated with iron oxides, provided the stability that might be resistant even to land use change. However, the importance of studying the aggregation of distinct clay types stemming from the same soil has been emphasised, to avoid interferences of other aggregation agents; thus, Virto et al. (2008) and Fernández-Ugalde et al. (2013) showed that microaggregates tend to form in the more reactive 2:1 clays than kaolinite-type clays (1:1 type) or quartz. In the same soil, the latter were more abundant in non-aggregated particles.

Aggregate dynamics depend also on aggregate breakdown, which is not exclusively linked to organic matter decay. The disruptive processes that lead to aggregate breakdown also include physico-chemical dispersion, slaking, differential swelling and the impact of mechanical forces (Le Bissonnais 1996). Physico-chemical dispersion occurs in soils containing high concentrations of monovalent cations such as sodium from sodium chloride salt deposits. They act as dispersants between clay particles, whereas polyvalent cations, such as calcium, act as flocculants. Physico-chemical dispersion leads to aggregates breaking down into elemental particles. Several researchers observed that soil management history influenced clay dispersibility (Kay and Dexter 1990; Curtin et al. 1994, and Watts 1996, cited in Amézketa 1999). Furthermore, slaking disrupts aggregates during wetting due to forces generated by trapped air; it occurs at the same time as differential swelling, whose origin is influenced by the diverse expanding behaviours among soil compounds when moist. As a result of slaking and differential swelling, aggregates break into smaller aggregates. Finally, mechanical disruption occurs when external forces impact on soil aggregates, such as the "splash effect" from raindrops or the impact from tillage. According to soil composition, some soils, for example, saline soils rich in sodium, are naturally more vulnerable to any of these aggregate disruptive processes, and therefore they have to be treated with special care "during" agricultural land use (Rengasamy and Olsson 1991).

19.1.3 The Porous System

In parallel to aggregates, the soil structure is characterised by its voids or porous system. The pore system defines air and water flows through the soil and organisms' habitat. The formation of pore networks operates across many spatial scales. Earlier porous system models were based on textural properties, but these simplistic models have developed to include more realistic concepts such as pore connectivity and pore tortuosity. Logically, the pore system is linked with soil aggregate size distribution and vice versa (Lipiec et al. 2007).

Therefore, as a consequence of soil aggregation following a hierarchical model, a hierarchy in the pore system also exists. Accordingly, Elliott and Coleman (1988) described four pore sizes linked to the aggregate hierarchy which was further developed through hydraulic modelling, leading to the distinction of three categories with several subcategories as presented in Kutílek (2004):

- Macropores can either be formed by roots and earthworms resulting in stable pores; by cracking of swelling clays that shrink when the soil dries out; or by tillage, with their location limited by depth and their dynamics evolving throughout the growing season. In general, macropore size or diameter (typically $>250\mu m$) enables water to drain quickly at field capacity and to provide a path for macroarthropods.

- Micropores, also known as capillary pores, have a size or diameter (typically <250 μm) small enough to retain water at field capacity. In this category, there are inter-aggregate pores, big enough to be inhabited by nematodes, and a matrix of intra-aggregate pores. The pores within macroaggregates may be inhabited by small nematodes, protozoa and fungi, whereas the micropores within microaggregates may be around 1μm and inhabited mostly by bacteria.
- Submicroscopic pores (typically <30 μm) are so small that they restrict continuous water flow and cannot be inhabited by microorganisms.

19.1.4 Methods to Study Soil Structure

Traditionally soil structure has been defined through aggregate size distribution and aggregate stability tests. Tests include sieving through a series of decreasing mesh sizes. Dry or wet soil samples can be used. According to the purpose of the research, the chosen method will vary: dry sieving is used mainly in relation to wind erosion, whereas wet sieving is related to rain and runoff erosion, infiltration and formation of surface seals. It is important to note that the method highly influences the results, making it impossible to separate one from another (Nimmo 2005). Additionally, if the method requires wetting, the manner in which it is performed (quick wetting, slow wetting, in vacuum or through vapour) also produces slaking and differential swelling, which disrupts the soil aggregates and influences the results (Nimmo 2005). In any case, indexes have been developed to compare soils, the most widely used is the mean weight diameter (MWD), defined as the sum of the weighted mean diameters of all aggregate classes. The idea behind it is that the bigger the stable aggregate size, the more stable the soil itself (Nimmo 2005).

Another commonly used index is the water-stable aggregates (WSA), which is the proportion of dry sieved aggregates that resist water disruption. Barut and Celik (2017) found that on a clay soil in Turkey, under all tillage strategies, WSA increased in depth and that no tillage had greater WSA than conventional tillage (38.52% and 28.09%, respectively), whereas Sheehy et al. (2015) found the greatest difference in MWD between no tillage and conventional tillage on a silt clay soil (0.28 and 0.58 mm, respectively), whilst on clay soil the differences were not always statistically significant.

Nonetheless, Young et al. (2001) attributed the lack of a mathematical link between soil structure and soil functions to research being too focussed on aggregate stability. Furthermore, he questioned the use of aggregate stability as an indicator, stressing the absence of information about spatial and temporal heterogeneity. Instead, he proposed a focus on topology, which is the three-dimensional soil structure, or where the aggregates and pores locate themselves in the soil continuum. Some of the available technologies to study soil structure and its related properties include in situ methods such as environmental scanning electron microscopy (ESEM), nuclear magnetic resonance (NMR), ground-penetrating radar (GPR), electromagnetic induction (EMI) and proximal or remote sensing and ex situ methods such as sequenced thin sections, X-ray or gamma-ray computed tomography and electrical resistivity tomography (ERT). Developments of these new technologies make it possible to look at the topology (e.g. connectivity of pore space) in undisturbed soils. However, these technologies are still constricted in terms of detectable soil features, required sample size, penetrating depth, spatial resolution, temporal frequency, cost (Lin 2012) and sample preparation time requirements, when required.

An additional barrier that has to be overcome is the diverse focus of different sub-disciplines when studying soil structure. Traditionally, the focus was either on the solid matrix (pedology), the pore system (soil hydrology) or the habitats and interfaces (soil biology and biogeochemistry) (Lin 2012). Nowadays, the concept of soil architecture relates the solids with the pores and the interfaces within and between them (Lin 2012). Whether the concept of soil architecture is different from the soil structure or not, the integration of the three components (solid, pores and interfaces) is necessary for a better understanding of the link between these physical properties and physical, chemical and biological soil functions.

19.2 Conservation Tillage Effects in European Biogeographic Regions

19.2.1 Mediterranean Region

The Mediterranean climate is characterised by hot summers, mild winters and specifically irregular rainfalls and drought risk. Moreover, rainfall during the warmer season occurs in intense events (cold front), which, combined with the land topography and soil properties, leads to high risk of erosion for the whole region. Nonetheless, the rainfall irregularity and the uncertainty of water availability during the growing season are the main risks farmers confront in rainfed crop production.

Due to its climatic characteristics, the soils in the Mediterranean region have lower soil organic carbon (SOC) and higher content of soluble components. As the rainfall is lower than in other European regions, biomass production also decreases, which leads to a reduction in organic inputs. Additionally, higher temperatures enhance microorganism activity, producing greater organic matter mineralisation, which contributes to lower soil organic matter contents in soils. This affects soil physical and hydrological properties, as organic matter enhances soil aggregation and water holding capacity. Furthermore, a less percolating climate means that more soluble components remain in the soil. Depending on the parent material, soils contain calcium carbonate and salts. In this case, aggregate stability and breakdown depend on the particular chemical compound, and as mentioned earlier, calcium carbonate is a cementing agent, whereas salts, such as sodium chloride, are dispersants. Additionally, low rainfall and high evapotranspiration values can result in the formation of calcium carbonate crusts, which are physical barriers that influence water flows, root growth and the overall land suitability for agricultural practices.

Conservation tillage (CT) has been introduced mainly in the rainfed systems because of its potential to reduce fuel consumption and labour. It is generally viewed by farmers and promoted by agricultural extension institutes as a way to reduce the investment in a system in which yield, and therefore investment return, is not always assured. Thus, CT is used among other measures of cost reduction such as lower fertilization rates, lower seeding densities and in general less field operations. Furthermore, predominantly it is used in a flexible manner, alternating no tillage with minimum tillage and even conventional tillage, according to farmers' assessment of tillage needs to manage soil compaction or weed infestation. However, farmers who have adopted no tillage for economic reasons have seen some benefits in terms of soil physical and hydrological properties.

One of the main soil health benefits of CT is that it increases soil structural stability because of the reduction of mechanical disruption and the increase in soil organic matter (SOM). Evidence for this under Mediterranean conditions has been found in Greece (Sidiras et al. 2001) and in Spain for different soil types, with loam and clay textures and with calcium carbonates (Hernanz et al. 2002; Álvaro-Fuentes et al. 2008; Apesteguía et al. 2017). Also in Spain, Plaza-Bonilla et al. (2013) studied the effects of no-tillage adoption on soil aggregation on a chrono-sequence in a loam Typic Xerofluvent (Soil Taxonomy, 1994). Starting from conventional tillage, they compared soil properties after 1, 4, 11 and 20 years of conservation agriculture (CA) practice. The results showed a high correlation between water-stable aggregates and SOC. They also found that after 11 and 20 years of no tillage, the proportion of large water-stable aggregates was greater than those found in conventional tillage plots and even those from plots after only 1 or 4 years of no-tillage adoption. However, these differences were restricted to the surface soil layer (0–5 cm). Deeper (5–10 cm) layers only showed differences after 20 years of no-tillage adoption, and at increased depths, no statistically significant differences were found. Thus, no-tillage benefits on soil aggregation are a function of time and soil depth.

Soil compaction is one of the major barriers that prevent farmers from no-tillage adoption. Field operations with heavy machinery, animal grazing and the lack of reiterated soil loosening by tillage can lead to compaction. However, better soil aggregate stability permits higher load strength providing the soil with higher resistance to compaction. When comparing no-tillage systems with conventional tillage systems, soil compaction is a function of soil moisture and time since the ploughing event. Results of bulk density analysis in a variety of soil textures are shown in Table 19.1. Penetration resistance values in these studies, when performed, correlate with bulk density values. Karamanos et al. (2004) report bulk densities dynamics for the growing season, concluding that after 5-month no-tillage duration, bulk density became the lowest but similar to conventional tillage values. Nonetheless, the overall results show that, although in some cases bulk density decreases under no tillage, in general, bulk density is greater in no-tillage fields.

Bescansa et al. (2006) attributed the higher bulk density values to a reorganisation of the soil structure and pore system. They studied soil porosity, and results showed an increase of pores below 9μm, resulting in greater soil water content in no-tillage

Table 19.1 Topsoil bulk density values for different soil textures and tillage systems in the European Mediterranean region

Country	Soil texture	Sample depth (cm)	Bulk density (kg m^{-3}) No tillage	Conventional tillage	Reference
Spain	Clay	0–5	1.69–1.78	1.50–1.55	Apesteguía et al. (2017)
Spain	Clay	0–3	1.05–1.20	1.04–1.13	Ordóñez Fernández et al. (2007)
Greece	Silty clay	0.5–3	1.31–1.48	1.09–1.16	Cavalaris and Gemtos (2002)
Greece	Clay loam	0–30	1.27	1.37	Karamanos et al. (2004)
Spain	Clay loam	0–15	1.62	1.52	Bescansa et al. (2006)
Italy	Sandy clay	0–45	1.42	1.16	De Vita et al. (2007)
Spain	Sandy clay loam	0–20	1.51–1.64	1.25–1.33	Pelegrin et al. (1990)
Spain	Sandy loam	0–5	0.91–0.95	1.04–1.05	Gómez-Paccard et al. (2015)

fields, compared to conventional tillage, which had bigger pores with lower water holding capacity. These results are consistent with higher porosity under conventional tillage but greater water content in no-tillage soils as presented in Cavalaris and Gemtos (2002), De Vita et al. (2007) and Pelegrin et al. (1990). When soil water content is linked to wheat yield, De Vita et al. (2007) found that it depends on rainfall during the growing season (from November to May); if it is below 300 mm, no tillage, due to its increased soil water holding capacity, presents higher yields, whereas in wetter years, conventional tillage performed better.

A particular case is presented by Gómez-Paccard et al. (2013) for a sandy loam Paleoxerult during the water excess period. In this case, no tillage had greater porosity and exhibited higher water content at saturation, saturated hydraulic conductivity and water infiltration rates, compared to conventional tillaged plots that even presented waterlogging problems.

Greater cumulative infiltration rates have also been reported in Greece (Papayiannopoulou et al. 2008). Generally, this phenomenon is attributed to greater pore connectivity and vertical macroporosity generated by roots and earthworms. Studies have also shown greater earthworm populations in conservation tillage fields, but the correlation between earthworms population and increased macroporosity is difficult to establish and has only been done qualitatively. Tarolli et al. (2019) presented an interesting microtopography soil study where no tillage presented greater surface roughness, including more concavities and tortuous surface water flows, potentially enhancing water infiltration and reducing runoff, which is especially desirable in intense but scarce rainfall events in Mediterranean rainfed fields.

19.2.2 Atlantic and West Continental Regions

The climate in the Atlantic region is influenced by the ocean, resulting in mild winters, relatively fresh summers and rainfall distributed throughout the year, whereas the continental region has contrasting temperatures and rainfall values between the summer and the winter months. These contrasting effects are stronger the further away from the coastline, whilst the western part is still influenced by the Atlantic Ocean. Topographically, the European Plain covers Belgium, the Netherlands, Germany, Denmark, Poland and Russia and is intensively farmed by commercial agriculture.

In this region, farmers' concerns about compaction and weed management increase, as the climate becomes more humid and soil workability is compromised. Additionally, farmers include potatoes and sugar beet in their crop rotations along with cereals and leguminous plants. Harvest of those tube crops involves higher soil disturbance; additionally, crop establishment seems to fail under no-tillage conditions. These concerns are depicted in a preference for minimum tillage, also known as reduced tillage or mulch tillage, rather than no tillage, which has low adoption rates.

Accordingly, to intensive land use and agricultural practices, research interest has focused on structural stability, the formation of plough pans and soil strength against heavy machinery load. In general, the same trends as those in the Mediterranean region are seen in terms of bulk density increase under CA practices compared to conventional tillage (Tebrügge and Düring 1999; Dexter et al. 2008; Czyz and Dexter 2009; Vogeler et al. 2009; Rücknagel et al. 2017; Schlüter et al. 2017). These studies were performed mainly on silt loam or loam sand soils developed from loess in Germany and Poland, after reduced tillage was performed up to 25 years. Nonetheless, Vogeler et al. (2009) saw a change in the increased bulk density values in the surface layers after a period of 5 years, presenting similar values to conventional tillage, and at the end of the experiment even reversing the situation, although the subsuperficial layers, at 20 cm depth, were still presenting higher compaction in the reduced tillage plots.

Equally, the structural changes of soils due to the adoption of conservation tillage, which are shown as higher bulk densities, lead to lower total porosity (Schlüter et al. 2017) or macroporosity (Tebrügge and Düring 1999) but higher soil water content in the surface layers (Czyz and Dexter 2008, 2009). Gruber et al. (2011) found higher water content in no-tillage fields during the spring but slightly lower water content during the autumn when compared to conventional tillage. These conditions during spring can imply cooler soils, which are detrimental to crop development, whereas slightly drier soils in autumn would reduce optimal conditions for seed germination. Therefore, the authors conclude that conventional tillage present slightly better conditions in the given location and climatic conditions.

Saturated hydraulic conductivity presented inconsistent results among studies, having better (Vogeler et al. 2009), worse (Tebrügge and Düring 1999) or inconsistent but generally better (Rücknagel et al. 2017) performance in reduced tillage. Pöhlitz et al. (2018) compared strip tillage, no tillage and reduced tillage and found that strip tillage combined benefits from no tillage and reduced tillage, presenting greater soil moisture in the rows between seeding as no tillage does, and lower bulk density in the rows within seeding where minimum tillage is performed.

Wiermann et al. (2000) concluded that conventional tillage, compared to reduced tillage, leads to permanent destruction of the aggregates resulting in a weak structure against dynamic pressure, showing impacts after a single compression by a 2.5 Mg load, whereas the reduced tillage system developed a structure that resisted this load. Similarly, also in Germany, Tebrügge and Düring (1999) and Rücknagel et al. (2017) found conventional tillage plots were more vulnerable to structural settlement after compression; however, the resulting bulk densities between treatments were similar. Further studies on structural stability in Poland show greater amounts of readily dispersible clay in conventionally tillaged fields, which represents weaker soil structures (Czyz and Dexter 2008, 2009). Moreover, in Germany, reduced tillage had higher yields of macroaggregate water-stable aggregates than conventional tillage, although the dynamics of the macroaggregates in tilled land was unclear, as there were no differences in results from before and after a single ploughing event (Andruschkewitsch et al. 2014).

19.2.3 Boreal Region

In the boreal biogeographical region, agriculture is concentrated in the southern part where soils are more suitable and the growing season is longer, although the short window for biomass production is still the main limitation for agriculture in the region, varying from 100 to 200 days. Acidic soils and peat soils are common in the area, although agriculture usually is established on nutrient-rich mineral soils.

In several studies on different soil types around the boreal region, no and minimum tillage increased bulk density (Comia et al. 1994; Rasmussen 1999; Tamm et al. 2016) compared to conventional tillage, despite increasing aggregate stability at surface layers (Rasmussen 1999; Sheehy et al. 2015). Similarly, as in the other biogeographical regions, studies show that by increasing bulk density, conservation tillage practices generally decrease macroporosity, although it increases mesopore abundance and has no effect on microporosity. When looking at the origin of the pores, conservation tillage practices increased biopores on a clay Vertic Cambisol in Finland (Aura 1999). Equally, as in the previously presented cases in other regions, these increases in mesopores translate into a higher soil moisture content (Aura 1999; Rasmussen 1999; Kankanen et al. 2001). However, moister soils during spring are a limitation for crop growth as it reduces soil temperature, delaying crop development in a region that already has constrained growing seasons.

When it comes to water and airflow, pore connectivity is especially important. Rasmussen (1999) found a higher hydraulic conductivity and air diffusivity in conventionally ploughed fields, compared to no-tillage fields. Conversely, Comia et al. (1994) found better pore connectivity, and therefore greater hydraulic conductivity and air diffusivity in minimum-tillage fields of clay and clay loam soils in Sweden. Indeed, more recent studies in Lithuania showed that the effects of conservation tillage on soil physical properties are soil-specific (Feiza et al. 2015; Feiziene et al. 2018). Feiziene et al. (2018) found that crop residues behaved as aggregation agents on fine-textured soils, whereas on coarse-textured soils, residues obstructed the pore system increasing waterlogging. Additionally, Feiza et al. (2015) found overall porosity was higher on a silt loam Planosol but pore obstruction by crop residues occurred, whereas the sandy loam Cambisol was more suitable due to greater macroporosity. Therefore, as Rasmussen (1999) stated in his review, suitability of conservation tillage is climate-, soil- and crop-specific.

19.3 Conclusions

Healthy soils are well structured, with high aggregate stability and continuous porous systems, enabling air and water flows and benefiting crop growth. Therefore, maintaining these soil properties has to be considered an aim for any farming practice.

Conservation tillage effects on soils' physical and hydrological properties vary geographically because the intrinsic and environmental factors that influence aggregate stability, soil structure and consequently the porous system vary geographically.

Organic matter plays an important role as an aggregation agent and in stabilising soil structure, but in some locations, other agents have this major role. Conservation tillage practices have shown to increase aggregate stability in the Mediterranean, Atlantic and West Continental and Boreal regions, increasing soil structural stability and soils' bearing capacity for heavy machinery.

Overall, conservation tillage increases bulk density; however, it rarely has a limited effect on root growth. The increase in bulk density is linked to a reorganisation process of soils' structure, resulting in a decrease of macropores and an increase of meso- and micropores, increasing soils' water holding capacity, which can be considered a benefit depending on the geographical region and crops' needs during their growing cycle.

Better surface structural stability under conservation tillage might increase infiltration rates, and maintenance of vertical biopores might improve drainage. However, the evidence is inconsistent with other cases under different conditions reporting pore clogging due to crop residues.

The complexity of the interactions among all the factors influencing soil physical and hydrological processes highlights that site-/farm-specific variations in climate, soil and cropping system, and overall land suitability should be carefully considered by farmers before using conservation practices. Flexibility within the choice of tillage is also important for successful adoption of conservation tillage.

Further research with new technologies focusing on soil topology and involving farming communities, who are leading the spread of conservation agriculture, will increase and improve our current knowledge about conservation tillage effects on soils' physical and hydrological processes.

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