International Journal of Chemical Studies

P-ISSN: 2349–8528
E-ISSN: 2321–4902
IJCS 2019; 7(1): 1731-1736

Received: 17-11-2018
Accepted: 22-12-2018

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Soil health: Looking for the effect of tillage on soil physical health

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Abstract
Soil health refers to the ecological equilibrium and the functionality of a soil and its capacity to maintain a well balanced ecosystem with high biodiversity above and below surface, and productivity. However, feeding seven billion people with environmental sustainability is a challenge for the next generations. Good soil physical health is essential for optimum sustained crop production. Soil tillage has a direct influence on the soil physical health. Tillage exerts impact on the soil purposely to produce crop and consequently affects the environment. An appropriate tillage system needs to be practiced so as to take care of the soil health, plant growth and the environment simultaneously. Therefore, to achieve sustainable food production with minimal impact on the soil and the atmosphere, conservation tillage practices become more important now than ever ensuring sustainable food production and maintaining environmental integrity. This paper aims to review the work done on maintaining and restoring soil health, an overview of the soil health indicators and above all the impact of tillage and its different types in different agro-ecological regions so as to understand its influence from the perspectives of the soil, the crop and the environment.

Keywords: Soil health, soil physical parameters, tillage

Introduction

The concerns on the sustainability of agricultural systems have increased recently because the agricultural edges have already expanded near to the maximum all over the world (Cardoso *et al*., 2013) [15]. Feeding seven billion people with environmental sustainability is a challenge for the next generations. Sustainable agriculture aims at meeting the needs of the present without compromising the productive potential for the next generations. Rational soil use practices must allow economically and environmentally sustainable yields, which will only be reached with the maintenance or recovery of the soil health. The interest in soil health can be traced back to the ancient Roman civilization. This concept of soil science dates back to the 1970s. The Soil Science Society of America (SSSA), after much discussion about the subject, came with a broad definition:

"The ability of a specific type of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or improve air quality and water to support human health and livable" (Karlen *et al*., 1997) [37].

Soil function describes what the soil does. Soil functions are: (1) Sustaining biological activity, diversity, and productivity; (2) Regulating and partitioning water and solute flow; (3) Filtering and buffering, degrading, immobilizing, and detoxifying organic and inorganic materials, including industrial and municipal by-products and atmospheric deposition;(4) Storing and cycling nutrients and other elements within the earth's biosphere; and (5) providing support of socioeconomic structures and protection for archeological treasures associated with human habitation (Seybold *et al.,* 1998) [69].

Subsequently the soil health and soil quality terms are used interchangeably. Although it is important to distinguish that, soil quality is related to soil function (Letey *et al.,* 2003) [45], whereas soil health presents the soil as a finite non-renewable and dynamic living resource. The concept of soil quality emerged in the literature in the early 1990s, and the first official application of the term was approved by the Soil Science Society of America Ad Hoc Committee on Soil Quality (S- 581) and discussed by Karlen *et al.* (1997) [37]. However, the term soil health is most preferred by some researchers because it describes the soil as a living entity with a dynamic system. Because of the numerous alternative uses of soil as a living resource, the meaning of the terms soil health and soil quality depend on the defined purpose such as for agricultural use (Andrews and Carroll, 2001) [6]. In agriculture, we mainly pay attention to plant and animal productivity as these would be of greatest importance in cultivated soils as opposed to urban soils (Idowu *et al.,* 2007) [53]. Soil health in a broader concept, identifies the functionality of a soil to promote environmental quality, preserve plant and animal health and sustain biological productivity, while the term soil quality is associated with the fitness of the soil for a specific purpose (Doran and Zeiss, 2000) [25].

Effect of tillage on soil physical indicators

The physical indicators are related to the organization of the particles and pores, reflecting effects on root growth, speed of plant emergence, compaction and water infiltration. Since soil physical properties influence rooting depth and volume, they also affect nutrient availability and plant growth. Physical properties provide information related to the soil's ability to withstand physical forces associated with splashing raindrops or rapid water entry into soil that contribute to aggregate breakdown, soil dispersion, and erosion. Near-surface soil physical properties can be altered by human manipulation; however, many physical properties are determined by genetic soil properties. Research has indicated that physical properties are sensitive to tillage and other disturbances (Busscher *et al*., 2006). Tillage has both advantageous and unfavorable effects on soil physico-chemical properties and on climate change (Alam *et al*., 2016) [3]. Extensive tillage practices may lead to breakdown of soil organic matter (SOM) (Alam *et al*., 2014) [2] and undesirable change in soil physical properties (Busscher *et al*., 2004) [14]. Soil physical properties such as texture, bulk density, soil depth, hydraulic conductivity, aggregate size distribution, water infiltration rate and water holding capacity can serve as indicators of healthy soils. The roles of several physical indicators are influenced by other parameters or inherent properties of the soil. Physical indicators commonly used to assess soil function and quality includes:

Bulk density

A soil's bulk density is defined as "the mass of dry soil per unit bulk volume" (Soil Science Society of America, 2001). The bulk density (ρ_b) can change relatively rapidly; therefore bulk density can be viewed as 'red flag' indicator of overall soil health (Brady and Weil, 2002) [13]. Bulk density is routinely assessed in agricultural systems to characterize the state of soil compactness in response to land use and management. It is considered as a useful indicator for the assessment of soil health with respect to soil functions such as aeration and infiltration (e.g. Pattison *et al*., 2008; Reynolds *et al*., 2009) [58, 63].

The effect of tillage and residue management on soil bulk density is mainly confined to the topsoil (plough layer). In deeper soil layers, soil bulk density is generally similar in zero and conventional tillage (Haynes *et al*., 2008) [30]. A plough pan may be formed by tillage immediately underneath the tilled soil, causing higher bulk density in this horizon in tilled situations (Dolan *et al*., 2006) [24]. Abu-Hamdeh (2004) studied the effect of tillage treatments (moldboard ploughing MB; chisel ploughing CS; and disk ploughing DP) for comparison of axle load on a clay loam soil. He reported that the dry bulk density from 0 to 20 cm was affected by the tillage treatments and from 20 to 40 cm by axle load. The MB treatment caused the maximum percentage increase of dry bulk density at all depths. Al-Kaisi *et al*., (2005) [4] used wide range of tillage systems in the Corn-Belt in the United States soil and found that bulk density values of no-tillage (NT) and chisel plow (CP) treatments were not significantly different after 7 years. Osunbitan *et al*. (2005) [57] observed greater bulk density in no-till system in the 5 to 10 cm soil depth. In contrast, other studies reported greater to similar BD in conventional tillage compared to no tillage (Logsdon and Cambardella, 2000; Unger, 1996) [48, 77].

Blanco-Canqui and Lal, (2006) [11] measured bulk density in zero tillage plots that had been uncropped and receiving three levels of wheat straw mulch (0, 8, and 16 Mg ha^{-1} yr^{-1}) for 10 consecutive years on a silt loam in central Ohio. Straw management had a large impact on bulk density in the 0-10 cm depth. Differences in bulk density among the treatments were not significant in the 10-20 cm depth. The bulk density under the high-mulch treatment was 58% lower and that under the low-mulch treatment was 19% lower than the bulk density under the unmulched treatment for the 0-3 cm depth. In the 3-10 cm depth, bulk density under the high-mulch treatment was only 36% lower and that under the low-mulch treatment was 9% lower than under the control. These results are similar to those reported by Lal (2000) [42], who observed that annual application of 16 Mg ha^{-1} of rice (*Oryza sativa* L.) straw for 3 years decreased bulk density from 1.20 to 0.98 Mg m-3 in the 0-5 cm layer on a sandy loam. Treatments of conventional tillage, chisel tillage and zero tillage, all with either residue returned or harvested, were imposed on a silt loam soil with a maize-soyabean rotation in Minnesota (Dolan *et al*., 2006) [24].

Soil aggregate

It is considered a useful soil health indicator since it is involved in maintaining important ecosystem functions in soil including organic carbon (C) accumulation, infiltration capacity, movement and storage of water, and root and microbial community activity; it can also be used to measure soil resistance to erosion and management changes (Moebius *et al*., 2007; Rimal and Lal, 2009) [53, 66]. Because of its association with the storage of soil organic carbon (SOC) and water, its measurement can be useful to guide for quantifying effect of tillage on soil health, especially in areas that are likely to experience high and intense rainfall and consequently increased erosion events.

Soil tillage conventional system based on annual ploughing had the effect of reducing hydro stability of structural aggregates, increasing vulnerability to degradation by soil compaction, erosion etc. (Cerbari, 2011) [17]. Salinas-Garcia *et al*. (1997) [68] reported that, in fallow and conservation tillage, residues accumulate at the surface where the litter decomposition rate is slowed. This is due to drier conditions and reduced contact between soil microorganisms and litter. Stable aggregates can better withstand factors such as erosion and compaction and facilitate water movement. Pinheiro *et al*. (2004) [61] reported the reduction of large aggregates in the tilled soils than untilled and attributed it to the physical disturbance of soil. The more systematic soil aggregate classes observed in conventional tillage were an indication to loss of soil structure. This was attributed to mechanical disruption and exposure of soil organic matter previously preserved to oxidation (Tisdall and Oades, 1982) [75]. It also pulverised soil aggregates into microaggregates hence a reduction in amount of macroaggregates (Tisdall and Oades,

1982) [75]. Elliot (1986) reported that, the primary source of organic matter lost during cultivation is the organic matter binding microaggregates into macroaggregates.
Jacobs *et al*. (2009) [34] found that minimum tillage (MT), compared with CT, did not only improve aggregate stability but also increased the concentrations of SOC and N within the aggregates in the upper 5–8 cm soil depth after 37–40 years of tillage treatments. Ashagrie *et al*. (2007) [8] found that 26 years of continuous cultivation reduced water stable aggregates relative to natural forest. Most of the differences were attributed to tillage, type of organic matter, and mycorrhizal hyphae. The same study found that most differences in management were found in macro-aggregates rather than micro-aggregates. Microaggregates are more stable and less affected by soil use and management. In addition, they are responsible for long-term stabilization of soil organic carbon (Six *et al*., 2004) [73]. On the other hand, macroaggregates are more susceptible to the soil use and management, and are especially related to the dynamics of the soil organic matter (Six *et al*., 2004) [73]. The dispersion of soil aggregates under intensive management is usually less severe than in soils with more inputs of organic matter, which results in greater microbial activity (Qin *et al*., 2010) [62]. On the other hand, the decrease of soil organic matter followed by dispersion of aggregates reduces the macro porosity and the soil oxygenation, and impairs the performance of decomposing microbiota and their access to the organic material (Chodak and Niklinska, 2010) [21]. Soil aggregates affect aeration, permeability, nutrient cycling, and serve as refuge for microorganisms and soil fauna in microsites. By turn, the soil biota (microorganisms, fauna, and plants) affects the soil aggregates.

Water holding capacity

The water holding capacity of a soil is the volume of water that can be stored in a form accessible or available for plants use. The major management practices that influence water-holding capacity are tillage and crop residue management. Soils that are highly tilled tend to lose water-holding capacity. Water use efficiency has also been reported to be greater in soils under reduced tillage (McVay *et al*., 2006) [51] and NT (Li *et al*., 2005) [46] systems as compared with CT. Su *et al*. (2007) found that the soil water storage quantity using ZT was 25% higher than CT during a six year study while WUE was significantly higher in ZT than CT and RT. Kargas *et al*. (2012) [36] observed that untilled plots retain more water than tilled plots. In comparison with conventional ploughing, Pagliai *et al*. (2004) [61] reported that minimum tillage improved the soil pore system by increasing the storage pores (0.5–50 mm) and the amount of the elongated transmission pores (50–500 mm). They related the higher microporosity in minimum tillage soils to an increase of water content in soil and consequently, to an increase of available water for plants. Higher water holding capacity or moisture content has been found in the topsoil (0–10 cm) under NT than after ploughing (McVay *et al*., 2006) [51]. Therefore, to improve soil water storage and increase water use efficiency (WUE) most researchers have proposed replacement of traditional tillage with conservation tillage (Silburn *et al*., 2007) [72].

Soil porosity

Soil porosity plays a critical role in the biological productivity and hydrology of agricultural soils. Pores are of different size, shape and continuity and these characteristics influence the infiltration, storage and drainage of water, the movement and distribution of gases and the ease of penetration of soil by growing roots (Kay and Vanden Bygaart, 2002.) [39]. Tillage operation in general increases the total soil porosity by increasing the pore size distribution and pores. Allmaras (1977) [5] reported that the increase in total porosity by tillage is more due to increase in macropores than in microspores. Soils need large pores and channels for adequate aeration and good drainage. Large pores that can be seen by the human eye are known as macropores. Mesopores and micropores are too small to be seen by the human eye and are respectively responsible for storing plant available water and holding the water that is unavailable to plant roots. The movement of air through micropores is very slow. For good plant growth, the soil needs a balance of macro-, meso-and micro-pores. Soil porosity characteristics are closely related to soil physical behavior, root penetration and water movement (Sasal *et al*. 2006) and differ among tillage systems. Tillage increases the total soil porosity by increasing the pore size distribution and pores (Linden, 1982).

Hydraulic conductivity:

The hydraulic conductivity, Ks is an indicator of the soil's ability to transmit the water needed for plants to the root zone, as well as drain excess water out of the root zone (Topp *et al*., 1997) [76]. Reports on tillage effects on hydraulic conductivity are controversial. Some researchers have reported no or negative impact of tillage on soil water characteristics (Obi & Nnabude 1988; Heard *et al.* 1988) [56, 31], while others found beneficial effects of zero-tillage on soil water retention (Blevins *et al.* 1983; Datiri& Lowery 1991) [12, 23]. Significant positive effect of zero-tillage on hydraulic conductivity was reported due to the either greater continuity of pores (Benjamin 1993) [9] or water flow through a very few large pores (Sharratt *et al.* 2006).
Reynolds *et al*. (2009) [63] reported higher Ks for woodland than agricultural fields and fallow the trend woodland > no-tillage > annual tillage. Such a trend is not surprising because of the higher macroporosity of the soils of the natural woodland than soils under no-tillage or conventional tillage system. The second possible reason could be the arrangement of macropores, three dimensional infiltration and restrictions to flow by the membrane. However, average Ks values did not follow the conventional wisdom and were higher for fields under conventional tillage than no-tillage in the other study in Ohio. This could be due to a number of factors including the larger sample size used for determining the Ks from no-tillage fields than from fields under annual tillage, measurement errors in the field and laboratory while collecting and preparing the core samples, timing of tillage operations and errors during sample analyses.
Bhattacharyya *et al.* (2006) [10] compared the effects of no-tillage and conventional tillage practices in a four-year study, and reported that the hydraulic conductivity values were higher in no-tillage than tilled soils. Several researchers have found higher hydraulic conductivity under shallow tillage than under mouldboard ploughing and attribute it to stable macropores (Allmaras *et al*., 1977; Rizvi *et al*. 1987; Coote and MalcolmMcGovern, 1989) [5, 67, 22]. In shallow tillage biopores and cracks in the lower topsoil are not destroyed by tillage action. Several researchers also found higher Ks in shallow tillage than mouldboard ploughing where they explained presence of earthworm channels, and root channels as the responsible factors (Allmaras *et al*., 1977; Rizvi *et al*., 1987; Coote and Malcolm-McGovern, 1989) [5, 67, 22]. In addition, in shallow tillage crop residues are left close to the

surface or mixed within only 10-12 cm which could be another reason for higher Ks (Lampurlanes and Cantero-Martínez, 2006) [43]. Furthermore, inversive tillage (ploughing) makes the aggregates unstable during wetting (Vakali *et al*., 2011; Riley *et al*., 2008) that could cause lower Ks. However, Ks is extremely variable even between samples taken adjacent to each other (Russo and Bresler, 1981; Lauren *et al*., 1988; Mohanty *et al*., 1994). Thus, although there was a tendency for greater Ks in ST than in MP, the values were not always statistically different from each other. This is due to the variation in size and number of macropores.

Lampurlanes and Cantero−Martinez (2006) [43] compared three tillage systems (subsoil tillage, minimum tillage and no-tillage) under three field situations (continuous crop, fallow and crop after fallow) on two soils and found soil under no-tillage had lower hydraulic conductivity than under subsoil tillage or minimum tillage during 1 of 2 years in continuous crop due to a reduction of soil porosity. However, Mahboubi *et al*. (1993) [49] found that no-tillage resulted in higher saturated hydraulic conductivity compared with conventional tillage after 28 years of tillage on a silt loam soil in Ohio. Kahlon *et al*. (2013) [35] in a long term experiment found higher Ks were measured in NT than PT treatments with increase in mulch rate from 0 to 16 Mg ha^{-1}. Heard *et al*., (1988) [31] reported that saturated hydraulic conductivity of silt clay loam soil was higher when subjected to 10 years of tillage than no-tillage in Indiana. They attributed the higher hydraulic conductivity of tilled soil to the greater number of voids and abundant soil macropores caused by the tillage implementation. Iqbal *et al*., (2005) [32] reported that deep tillage increase the Ksat compared to the no tillage.

Conclusion

The conclusions arising from this paper are derived from the premise that soil is the site of a vital range of ecosystem functions which provide humans with a range of essential services. An integrative approach is essential for assessment of soil health. Furthermore, soil health is related to functional capacity rather than actual service outputs. As argued above, an effective approach appears to be using a set of diagnostic tests for soil system performance, chosen to be indicative of habitat condition, i.e. physical and chemical, of energetic reservoirs and key organisms and community structure. Moreover a long-term favorable state of the physical quality of the soil arable layer can be created by a permanent flow of organic matter in degraded soils and creating a system of minimal tillage.

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