

A Review: Impact of Long Term Zero Tillage on Hydrological Properties of Soils

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ABSTRACT

Zero tillage has the ability to enhance the soil's hydrological properties in the long run. It is the most critical aspect of agriculture for conservation. The need for an hour is conservation farming. It is a win-win operation for farmers as well as for the environment. Although green revolution technologies introduced in the country during 1966-67 led to food security, intensive cultivation, inadequate and imbalanced use of fertilisers, high yielding crop varieties, the use of heavy machinery, excess tillage, etc., for more than five decades resulted in deterioration of soil health and quality and altered the physical matrix and thus hydrological properties. There is a great lack of a systematic approach to linking tillage practises to soil hydrological properties. Soil hydrological characteristics are highly affected by management practises. Tillage aimed to create a soil environment favourable to plant growth on a short-term basis, but noted negative effects on soil properties, structure and ultimately hydrological properties of soils on a long-term basis. Keeping all of these under consideration, this analysis is compiled to create a perfect tillage scheme, i.e. zero tillage, which eliminates the adverse effects of tillage and retains soil resources and eventually contributes to sustainable agriculture. The influence on soil hydrological characteristics, however, depends on the site-specific biophysical environment, such as soil texture, prevailing climate variations, site characteristics, adoption period, and seasonal rainfall variability.

Keywords: Conventional tillage, Zero tillage, Sustainable agriculture, Soil moisture.

INTRODUCTION

Via regulating plant water status and indirectly through its impact on nutrient transport, uptake, transformation, aeration and temperature, soil water directly affects plant growth. Soil water status and its movement in soil is critical for optimum plant growth and has practical implications in agricultural,

environmental and hydrological situations (Ali & Turrall, 2001; & Ali, 2010a). There is a need to measure sufficient and reliable information on soil hydraulic properties that play an important role in implementing effective water management practises that are capable of improving the efficiency of input usage and alleviating soil output constraints.

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Both water retention and water transfer characteristics of soils include hydraulic properties. The soil's water retention and transmission properties are influenced by the texture, structure, quality of organic matter, soil compaction, soil solution concentration and composition (Hillel, 1982). The soil's water retention characteristics describe the capacity of the soil to store and release water and are described as the relationship between the content of soil water and soil suction or matric potential. Water retention involve field capacity, saturation capacity, plant available water, permanent wilting point, etc., while water transmission properties include infiltration, hydraulic conductivity, percolation, etc. The hydraulic properties also provide useful information regarding land-use assessment, estimate of drainage, chemical leaching and effect of pollution on the subsurface ecosystem (Klute & Dirksen, 1986). Soil hydraulic characteristics are therefore very critical for determining the movement of soil water and the status of developing sustainable soil development strategies. Zero tillage has significant and beneficial implications for the soil hydrological properties due to addition of more organic matter in form of crop residues. Zero tillage therefore tends to be a feasible management choice for all soil hydrological resources to be preferred. The physical matrix and thus the hydraulic properties of soils can be altered by tillage and crop residue management. The hydraulic conductivity of soils under zero tillage has been found to be higher (Mahboubi et al., 1993, & Mielke et al., 1984) compared to soils under conventional tillage. In contrast to traditional tillage, infiltration rate and saturated hydraulic conductivity were found to be greater in soils subject to zero tillage (Dao, 1993, & Mielke et al., 1984). The addition of residues to the soil (Barzegar et al., 2002) under zero tillage can also improve infiltration, as well as water retention of the soil. There are but a few studies which have examined the effect on soil hydraulic properties of long-term tillage and crop residue management. Mahboubi et al.

(1993) found that, twenty-eight years after developing tillage treatments on a silt loam in Ohio, zero tillage resulted in higher saturated hydraulic conductivity and greater retention of water compared to traditional tillage. Twenty years after developing tillage treatments in Alberta, Chang and Lindwall (1989) did not observe any improvement in saturated hydraulic conductivity and water retention of a clay loam, but they noticed that infiltration was greater for zero tillage versus traditional tillage. After around 12 years of zero tillage versus traditional tillage in northern British Columbia, Arshad et al. (1999) found infiltration and water retention of a silt loam to be greater. In comparison to the above studies, Heard et al. (1988) found that when subjected to 10 years of tillage, the saturated hydraulic conductivity of a silty clay loam was greater than that of zero tillage in Indiana. They related the higher conductivity of tilled soil to larger or a greater number of voids and cracks created by the tillage implement. Studies which document the impact on soil hydraulic properties of long-term tillage and crop residue management are even rarer. In one such analysis, Sharratt (1996) discovered that a silt loam retained more water and had higher saturated conductivity compared to traditional tillage after being subjected to seven years of zero tillage. We are unaware of other long-term studies that have explored the effect of tillage and residue management on soil hydrological properties, so characterising soil hydraulic properties under zero tillage is the aim of this study.

As they save energy and provide optimal soil conditions for sustainable crop production and reduced cultivation costs, conservation tillage practises like zero tillage or limited soil disturbance and residue retention on the soil surface are becoming economically and ecologically viable options. Conservation tillage is now considered a promising alternative to conventional tillage practise (Teklu, 2011). Conservation tillage is a promising alternative to traditional tillage practise. Long-term zero tillage improves the status of soil organic carbon and modifies soil

pore geometry that ultimately affects soil hydraulic conductivity, infiltration rate, water retention capacity, etc. The effects of zero tillage, however, are highly variable across climate, soil type and depth, cropping system, and vary widely with the system's adoption period. Tillage can be defined as the physical manipulation of soil through a range of cultivation operations aimed at creating a soil environment favourable to plant growth, either manually or by complete machinery (Lal, 1979; Klute 1982; & Ahn & Hintze, 1990). Conventional tillage is the conventional cultivation method where, with tractor-driven ploughs (primary tillage implements), a few inches of the upper soil is completely inverted, followed by subsequent smoothing of the soil surface by secondary tillage implements. The traditional tillage method is associated with two elements, the inversion of soil and the burial or removal or burning in situ of crop residue. Conservation tillage, on the other hand, does not invert the soil, and produces 'nil' or 'minimum' soil disturbance. Conservation tillage is defined as any tillage and planting system, according to the Conservation Technology Information Center (CTIC), that leaves at least 30 percent of the soil surface covered by residue after planting. Conservation agriculture encompasses three concepts, namely (1) direct planting of crops with minimal soil disturbance (no-till or minimal till), (2) permanent soil covering or covering crops with crop residues (at least 30% of the soil surface) and (3) crop rotation (rotational crops, pulse / legume inclusion) (FAO, 2011; & Hobbs et al., 2008). As one would expect, the impact on soil hydrological characteristics of conventional and zero tillage could differ greatly. Mondal et al. (2018b) stated that the transition, however, varies widely with climate, land, agro-management and tillage system adoption period.

Impact of zero tillage on hydrological properties of soils

Soil Porosity

In order to understand water and air movement in the soil, knowledge of soil pore geometry and distribution is necessary. The hydraulic

characteristics of the soil depend entirely on the distribution of pore sizes. Factors that determine the rate of water absorption and transmission at the time of measurement are the soil moisture condition and pore stability as altered by tillage systems. Wahl et al. (2004) recorded higher amounts of macro-pore (>1 mm) in CT in the 0-30 cm soil layer, but in conservation tillage, the vertical continuity of macro-pore was greater. From air and water permeability, a soil's ability to achieve ecological functions in an agroecosystem can be predicted. Air permeability is more adaptive and can be an indication of shift in pore system due to various management practises (Schjønning et al., 2013). Continuous macro-pores are favoured by both air and water permeability (Iversen et al., 2003) and potential predictors (Blanco-Canqui et al., 2007), while soil compaction can severely limit the flow of air-water (Reichert et al., 2009; & Schjønning et al., 2013) and adversely affect root growth (Krebstein et al., 2014). The infiltration is affected by soil pores of different size, shape and continuity, maintaining the air-water ratio balance and determining the ease of soil for root growth (Kay & Vanden Bygaart, 2002; Pagliai & Vignozzi, 2002; & Sasal et al., 2006). To remember, the notion of structural hierarchy includes water flowing through linked pores (Dexter, 1988; & Dexter et al., 2008). Tillage has a major effect on the porosity of the soil again (Shipitalo et al., 2000; & Lipiec et al., 2006). It is understood that aggregates are broken down by tillage, leading to pore continuity obliteration, and soil pores are gradually created by rearrangement after rain or irrigation of soil particles. On the other hand, biological activity is the primary cause of pore formation in no-tilled soil. No tillage favours the development of decayed root canals, bio-pores, earthworm and other macro-fauna burrows, and macro-pore networks, cracks and other structural voids from which much of the water flows deeper into the profile of the soil (Gerke, 2006; & Jarvis, 2007). The geometry of pores has a prominent role in soil compressibility. Immediately after the tillage,

the macro-pores formed by tillage are unstable in nature and mostly efficient (Dexter, 2004b). In comparison, pore network in zero tillage is less prone to destruction and promotes water drainage and aeration despite compaction (Wahl et al., 2004; & Schäffer et al., 2008b). Especially in the plough layer, the CT system generally brings lower bulk density and greater porosity, while zero tillage increases the density of the surface soil and decreases total porosity. Changes in total porosity depending on the type of soil are related to the change in pore geometry. The water potential of the soil was increased by increased capillary porosity in limited or no-tillage (Wang et al., 2004; & Glab & Kulig, 2008). Also reported was increased capillary porosity in conventional tillage (Tangyuan et al., 2009). In New Zealand silt loam soil, total porosity under zero tillage decreased after 10 years (Horne et al., 1992), whereas for both silt loam and sandy loam of the north-western Canadian prairies the amount of micro-pores was slightly lower than traditional tillage (Azooz et al., 1996). Better aggregate stability resulted in higher total porosity in zero tillage system than conventional tillage (Busari et al., 2015). Thus, the undesirable effects of higher bulk density are compensated by greater numbers of macro-pores and pore continuity in reduced or zero tillage. Soil compaction and not the total pores were adversely affected only by larger pores (> 6 mm) (Capowicz et al., 2009). In the 30 cm deep plane, substantially fewer pores were reported than in the above and below layers. Zero tillage resulted in lower macro-pore (> 30 µm) volume on sandy and silty loam soils under similar conditions, but greater volume on sandy loam soil (Schjønning & Rasmussen, 2000).

Hydraulic conductivity and infiltration rate

One of the most relevant parameters for water flow and chemical transport phenomena in soils is known to be saturated hydraulic conductivity (Reynolds et al., 2002). The physical properties of soil bulk density and effective porosity that affect hydraulic conductivity are commonly calculated (Strudley et al., 2008; & Jabro et al., 2009).

Highly variable soil properties in both space and time (Coutadeur et al., 2002) are saturated and unsaturated hydraulic conductivity. Unsaturated conductivity is a function of the content of soil water and, with little change in the content of soil water, can change considerably (Strudley et al., 2008). Tillage can change the distribution of surface roughness, aggregation, porosity and crop residue. All these changes influence the hydraulic features of the soil. While bulk density and porosity are the two widely measured physical properties of the soil that affect soil hydraulic processes, a clear understanding of pore geometry and continuity can provide an essential inside to identify the effects of tillage on these properties (Kutilek, 2004). With the amount of total porosity, the infiltration rate may increase or decrease, but it may not always be true if the cohesion of larger pores is disrupted. The results of tillage are not consistent with the form, length and depth of tillage and are widely varied. Tillage usually makes the soil more available to water and air. Immediately after tillage, soil hydraulic conductivity improves and gradually decreases over the season (Schwartz et al., 2003; Bormann & Klaassen, 2008; & Petersen et al., 2008) and this decrease could be attributed to increased bulk density (Mellis et al., 1996) in conjunction with a concomitant decrease in conductive meso-pores (Messing & Jarvis, 1993). Strudley et al. (2008) emphasised the need for irrigation or rainfall impact studies on hydraulic properties of recently tilled soil. At the end of the first year, Busari and Salako (2012) had higher infiltration rate and unsaturated hydraulic parameters under conventional tillage than zero tillage, but less during the second year. This initial greater infiltration was due to the presence of rapidly draining macro-pores, which subsequently decreased due to soil particle settlement (Martínez et al., 2008; Pikul & Aase, 2003; & Shukla et al., 2003a). In the cropping systems that have implemented zero tillage for many years, soil infiltration has increased (Azooz & Arshad, 1996). One of the contributing factors may be the rise in

earthworm populations. The rate of infiltration and earthworm population in the zero tillage system was considerably higher (West, 2001). Under the zero tillage, the channels created by earthworms and decayed roots remain largely unchanged and thus, even under high bulk densities, higher hydraulic conductivity is achieved (Osunbitan et al., 2005). Zero tillage on the soil surface with crop residue retention will increase water penetration (Shaver et al., 2002), decrease erosion and improve the quality of water usage (Johnston & Bailey, 2002) compared to traditional tillage. Due to drier soil surface in conventional tillage as compared to zero tillage, a higher infiltration rate was reported in conservation tillage except for initial growth stage (Das et al., 2018). Over time, however, the slaked soil particles have blocked the pores that cause surface sealing in conventional tillage (Kahlon et al., 2013). Residues under zero tillage minimise rain drops or irrigation water's kinetic energy and reduce the risk of slaking and surface sealing (Kahlon et al., 2013). Residues under zero tillage further decompose and increase the SOC material, which leads to soil aggregate formation and stabilisation. Nyamadzawo et al. (2007) reported a higher rate of infiltration under fallow compared to continuous maize, likely due to the revival of soil physical properties by fallowing. Better pore connectivity, decayed root channel presence and vertical cracks (Alvarez & Steinbach, 2009; Mupangwa et al., 2013; & Huang et al., 2015a) and earthworm holes can radically change soil hydraulic characteristics (Busari et al., 2015; & Castellanos-Navarrete et al., 2012). Even though overall porosity was lower, greater pore consistency, mainly the macro- and meso-pores, significantly increased soil infiltration (Nielsen et al., 2005). Guerif et al., (2001) and Beven and Germann, (2013) have documented the role of macro-pores in rapid infiltration under ponded conditions (preferential flow) in studies. Lin et al. (1996) estimated that approximately 89 percent of the overall water flux in the soil belonged to 10 percent of macro-pores (> 0.5 mm) and meso-pores (0.06–0.5 mm). In order

to improve hydraulic conductivity and infiltration rate, the adoption of reduced tillage has also been reported (Horn & Smucker, 2005; Bhattacharyya et al., 2006a; Alvarez & Steinbach, 2009; & Parvin et al., 2014) due to increased biological activity and numerous macro-pores connected to the surface. Compared with traditional tillage in the alluvial soil of the semi-arid subtropics, McGarry et al. (2000) observed an improvement in hydraulic conductivity and infiltration rate under zero tillage. In some tests, the infiltration rates of ZT plots were either comparable (Ankeny et al., 1990) or even lower (Gómez et al., 1999; & Rasmussen, 1999) compared to tilled soil. No improvement in soil infiltration rate was observed by Sasal et al. (2005) in ZT, while aggregate stability increased by 30 percent compared to CT. In traditional terms, Kumar et al. (2000) observed greater specific water intake compared to zero tillage in Haryana's clay loam soil. Bodner et al. (2008) investigated the impact on hydraulic properties of various cover crop canopy and residue coverage and found substantial increases in hydraulic conductivity over the bare soil while continuous cultivation decreased hydraulic conductivity even for the root region. Bhattacharyya et al. (2006 a) found a substantial increase in hydraulic conductivity in zero tillage as compared to traditional tillage practise after rice crop under rice-wheat method and attributed to better porosity and pore size distribution resulting from the increased root biomass and crop residues under zero tillage as well as maintenance of pore continuity due to better aggregates stability and pore geometry. In the increase of pore continuity, activity and population of soil organisms also played an important role.

Maximum water holding capacity

Appropriate land management practises such as zero tillage have the ability to increase the optimum capacity for water holding. When it is fully saturated and is a measure of total porosity, the overall water holding capacity of the soil is the volume of water retained by the soil. Soil properties, such as soil compaction,

soil composition, distribution of pore size and biological activities, influence the soil's water retention and release ability. In zero tillage, the addition of organic matter to the soil due to crop residues typically increases the soil's water holding capacity. Water holding capacity in the soil increased by 3.7 percent for every 1 percent rise in soil organic matter (Hudson, 1994). Increased organic matter due to crop residues and no soil disturbance increases soil particle aggregation, resulting in large amounts of soil micropores and macropores (Reicosky, 2005). Stepniewski et al. (1994), by increasing saturated hydraulic conductivity and water holding capacity under better soil structure due to higher macro and micro porosity of soils, pragmatic improvement in soil hydraulic properties.

Soil Profile Moisture

Under zero tillage and mulched conditions, Bhatt and Khera, (2006) recorded greater moisture content. Based on the results of five years of experimentation on zero wheat tillage in the Haryana rice-wheat cropping system, zero tillage was found to result in higher upper soil surface moisture content compared to traditional tillage systems. Similarly, there was no tilled soil in the topsoil with a higher moisture content than the ploughed soil (McVay et al., 2006).

Soil Moisture Retention

Intensive tillage affected the properties of the soil and resulted in lower water and nutrient availability (Kumar et al., 2013), resulting in reduced yield (Hou et al., 2012; & Chan & Heenan, 2005). During the tillage process, crop residue removal from the soil surface before tillage or residue incorporation leaves no residue mulch on the soil surface and aggravates the evaporation of soil water. Conservation tillage preserves at least 30 percent of surface coverage with crop residue or cover crops, and has become popular as the best soil and water conservation management method (Corsi et al., 2012). Zero tillage can maintain agricultural productivity in water-deficit arid and semi-arid regions due to its in-situ moisture conservation (Ngigi et al., 2006). For successful crop production, minimum root

impedance and adequate soil moisture are necessary. Radiation is intercepted by crop residue on the soil surface and soil evaporation is minimised (Jalota et al., 2006; Salado-Navarro & Sinclair, 2009; Regina & Alakukku 2010; & Van Wie et al., 2013) and soil moisture is conserved (Alletto et al., 2011; & Mondal et al., 2018b). In comparison, Su et al. (2007) reported higher evapotranspiration in zero tillage due to more vegetation. The number of storage pores was increased by zero tillage and minimal tillage (Pagliai et al., 2004; Bhattacharya et al., 2006a; & Mondal et al., 2013) and thus retained higher plant water than traditional practise (McVay et al., 2006; Kargas et al., 2012; & Alvarez & Steinbach, 2009). Zero tillage is marketed as a safer alternative to the conventional system because of an increase in the soil hydro-thermal climate (Fabrizzi et al., 2005). The increase in SOC content favoured the preservation and conservation of soil water (Murphy, 2015; & Mosaddeghi et al., 2009) and thus increased the capacity to retain water (Lampurlanés et al., 2016). Rawls et al. (2003) concluded that changes in the concentration of SOC may or may not affect the retention of water depending on the composition of clay and initial SOC composition. As slaking of soil aggregates and sealing of the soil surface is prevented due to absorption of rain drop effect energy by crop residue mulch, zero tillage decreases surface runoff. In order to improve soil moisture storage, studies have shown zero tillage as an efficient method (Moret & Arrue, 2007; & Castellini & Ventrella, 2012). Hangen et al. (2002) indicated that, by minimising runoff, zero tillage on silty soils caused an improved water retention capacity. In zero tilled plots (5.07 and 4.86 cm after rice and wheat crops, respectively), Bhattacharyya et al. (2006a) recorded significantly higher plant water potential than conventionally tilled plots (4.23 and 4.21 cm after rice and wheat crops, respectively) in 30 cm of soil layer. Studies conducted by Vanapalli et al. (1999) and Zhou and Yu (2005) have shown that the characteristic curve of soil water is dependent on many variables, such as soil structure,

texture and compaction. Soil moisture was maintained for the preservation of surface residues and minimal soil disturbances under zero tillage (Moreno et al., 2001; Boydaş & Turgut, 2007; & Zhang et al., 2007). In contrast to traditional tillage, zero tillage resulted in a 28 percent rise in soil water available to plants during sowing (Mc Garry et al., 2000). Under zero tillage, the storage of soil water was 25 percent higher than traditional, and plant water available was also significantly higher in the rice-wheat cropping system with zero than conventional tillage (Bhattacharyya et al., 2006b; Su et al., 2007; & Bhattacharyya et al., 2008). In comparison to traditional tillage in maize-wheat rotation, Sharma et al. (2015) recorded an increase in soil moisture content of 12.4 percent in maize and 16.6 percent in wheat under zero tillage.

CONCLUSION

Finally, we can conclude that long-term zero tillage practises enhance the hydrological characteristics of the soil and conserve soil and water for sustainable agriculture. The 1960s Green Revolution improved food production, but due to intensive cultivation, heavy farm machinery, excessive irrigation usage, and indiscriminate use of fertilisers and pesticides, there were strong confrontational effects on the climate, including depletion of SOC stock, increased risks of soil degradation by erosion and salinization, and deterioration of hydrological properties of soil. Because of the unparalleled rise in world population and rapid economic development, the number of food-insecure individuals can increase. In addition, due to growth in popularity, soil depletion, urbanisation, and other competing uses, the per capita cropland region is also declining. The stratagem is therefore to balance food production demand with the need for soil regeneration and reduction of the environmental footprint of agro ecosystems. By following sustainable practises such as zero tillage, this can be done. The strategy is to improve soil quality by restoring SOC stock, improving the productivity of inputs for usage, narrowing the yield gap and implementing

sustainable agro ecosystem intensification systems. The goal is to generate more from less soil, less water usage, less fertiliser and pesticide production, and less energy consumption. In order to transform scientific information into effect, the much needed paradigm change will also entail defining and enforcing effective policies. Zero tillage is one of the best choices, properly applied, with the ability to enhance all soil hydrological properties, preserve soil and water, and sustain productivity. By designing site-specific packages and informing the agricultural community and the general public about the merits of zero tillage and stewardship of soil resources, its implementation can be strengthened.

REFERENCES

- Ahn, P. M., & Hintz, B. (1990). No tillage, minimum tillage, and their influence on soil physical properties. In IBSRAM Proceedings (Thailand). IBSRAM.
- Ali, M. H. (2010a). Soil – a media of plant growth (Chapter-4). *In: Fundamentals of Irrigation & On-farm Water Management, Springer, 1*, pp. 107-218.
- Ali, M. H., & Turrall, H. N. (s2001). Behavior study of cracking clay soil *I. Hydraulic and swelling properties. Journal of the Institution of Engineers, 27*, 9–18.
- Alletto, L., Coquet, Y., & Justes, E. (2011). Effects of tillage and fallow period management on soil physical behaviour and maize development. *Agricultural Water Management, 102*, 74-85.
- Alvarez, R., & Steinbach, H. S. (2009). A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. *Soil & Tillage Research, 104*, 1-15.
- Arshad, M. A., Franzluebbers, A. J., & Azooz, R. H. (1999). Components of surface soil structure under conventional and

- no-tillage in northwestern Canada. *Soil Tillage Res.* 53, 41–47.
- Azooz, H., & Arshad, M. A. (1996). Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems. *Canadian Journal of Soil Science*, 76, 143-52.
- Azooz, R. H., Arshad, M. A., & Franzluebbers, A. J. (1996). Pore size distribution and hydraulic conductivity affected by tillage in northwestern Canada. *Soil Science Society of America Journal*, 60, 1197-1201.
- Barzegar, A. R., Yousefi, A., & Daryashenas, A. (2002). The effect of addition of different amounts and types of organic materials on soil physical properties and yield of wheat. *Plant Soil* 247, 295–301.
- Beven, K., & Germann, P. (2013). Macropores and water flow in soils revisited. *Water Resources Research*, 49, 3071-3092.
- Bhatt, R., & Khera, K. L. (2006). Effect of tillage and mode of straw mulch application on soil erosion in the submontaneous tract of Punjab, India.
- Bhattacharyya, R., Kundu, S., Pandey, S., Singh, K. P., & Gupta, H. S. (2008). Tillage and irrigation effects on crop yields and soil properties under rice–wheat system of the Indian Himalayas. *Agricultural Water Management*. 95, 993–1002.
- Bhattacharyya, R., Prakash, V., Kundu, S., & Gupta, H. S. (2006a). Effect of tillage and crop rotations on pore size distribution and soil hydraulic conductivity in sandy clay loam soil of the Indian Himalayas. *Soil & Tillage Research*, 82, 129–140.
- Blanco-Canqui, H., & Lal, R. (2007). Soil structure and organic carbon relationships following 10 years of wheat straw management in no-till. *Soil & Tillage Research* 95, 240-254.
- Bodner, G., Loiskandl, W., Buchan, G., & Kaul, H. P. (2008). Natural and management-induced dynamics of hydraulic conductivity along a cover-cropped field slope. *Geoderma*, 146, 317–325.
- Bormann, H., & Klaassen, K. (2008). Seasonal and land use dependent variability of soil hydraulic and soil hydrological properties of two Northern German soils. *Geoderma*, 145, 295-302.
- Boydacş, M. G., & Turgut, N. (2007). Effect of tillage implements and operating speeds on soil physical properties and wheat emergence. *Turkish Journal of Agriculture and Forestry*, 31, 399-412.
- Busari, M. A., & Salako, F. K. (2012). Effect of tillage and poultry manure application on soil infiltration rate and maize root growth in a sandy Alfisol. *Agro-Science*, 11, 24-31.
- Busari, M. A., Kukal, S. S., Kaur, A., Bhatt, R., & Dulazi, A. A. (2015). Conservation tillage impacts on soil, crop and the environment. *International Soil and Water Conservation Research*, 3, 119-129.
- Capowiez, Y., Cadoux, S., Bouchant, P., Ruy, S., Roger-Estrade, J., Richard, G., & Boizard, H. (2009). The effect of tillage type and cropping system on earthworm communities, macroporosity and water infiltration. *Soil & Tillage Research*, 105, 209-216.
- Castellanos-Navarrete, A., Rodriguez-Aragones, C., De Goede, R. G. M., Kooistra, M. J., Sayre, K. D., Brussaard, L., & Pulleman, M. M. (2012). Earthworm activity and soil structural changes under conservation agriculture in central Mexico. *Soil & Tillage Research*, 123, 61-70.
- Castellini, M., & Ventrella, D. (2012). Impact of conventional and minimum tillage on soil hydraulic conductivity in typical cropping system in Southern Italy. *Soil and Tillage Research*, 124, 47–57.
- Chan, K. Y., & Heenan, D. P. (2005). The effects of stubble burning and tillage

- on soil carbon sequestration and crop productivity in southeastern Australia. *Soil Use and Management*, 21, 427-431.
- Chang, C., & Lindwall, C. W. (1989). Effect of long term minimum tillage practices on some physical properties of a Chernozemic clay loam. *Can. J. Soil Sci.* 69, 443–449.
- Corsi, S., Friedrich, T., Kassam, A., Pisante, M., & Sà, J. D. M. (2012). Soil organic carbon accumulation and greenhouse gas emission reductions from conservation agriculture: a literature review. Food and Agriculture Organization of the United Nations (FAO).
- Coutadeur, C., Coquet, Y., & Roger Estrade, J. (2002). Variation of hydraulic conductivity in a tilled soil. *European Journal of Soil Science*, 53, 619-628.
- Dao, T. H. (1993). Tillage and winter wheat residue management effects on water infiltration and storage. *Soil Sci. Soc. Am. J.* 57, 1586– 1595.
- Das, A., Lyngdoh, D., Ghosh, P. K., Lal, R., Layek, J., & Idapuganti, R. G. (2018). Tillage and cropping sequence effect on physico-chemical and biological properties of soil in Eastern Himalayas, India. *Soil & Tillage Research*, 180, 182-193.
- Dexter, A. R. (2004b). Soil physical quality: Part II. Friability, tillage, tilth and hard-setting. *Geoderma*, 120, 215-225.
- Dexter, A. R., Czyż, E. A., Richard, G., & Reszkowska, A. (2008). A user-friendly water retention function that takes account of the textural and structural pore spaces in soil. *Geoderma*, 143, 243-253.
- Fabrizzi, K. P., Garcia, F. O., Costa, J. L., & Picone, L. I. (2005). Soil water dynamics, physical properties and corn and wheat responses to minimum and no-tillage systems in the southern Pampas of Argentina. *Soil & Tillage Research*, 81, 57-69.
- FAO (2011). The state of the world's land and water resources for food and agriculture (SOLAW)-Managing systems at risk. Food and Agriculture Organization of the United Nations, Rome and Earthscan, London.
- Gerke, H. H. (2006). Preferential flow descriptions for structured soils. *Journal of Plant Nutrition and Soil Science*, 169, 382-400.
- Głąb, T., & Kulig, B. (2008). Effect of mulch and tillage system on soil porosity under wheat (*Triticum aestivum*). *Soil & Tillage Research*, 99, 169-178.
- Gómez, J. A., Giráldez, J. V., Pastor, M., & Fereres, E. (1999). Effects of tillage method on soil physical properties, infiltration and yield in an olive orchard. *Soil & Tillage Research*, 52, 167-175.
- Hangen, E., Buezko, U., Bens, O., Brunotte, J., & Huttel, R. F. (2002). Infiltration patterns into two soils under conventional and conservation tillage. Influence of the spatial distribution of plant root structures and soil animal activity. *Soil and Tillage Research*, 62, 181-186.
- Heard, J. R., Kladvko, E. J., Mannering, J. V. (1988). Soil macroporosity, hydraulic conductivity and air permeability of silty soils under long-term conservation tillage in Indiana. *Soil Tillage Res.* 11, 1–18.
- Hillel (1982). Field testing of Soil moisture model simulating water table fluctuations. *Soil Science Society of America Journal*, 46, 396-404.
- Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. Philosophical Transactions of the Royal Society of London B: *Biological Sciences*, 363, 543-555.
- Horn, R., & Smucker, A. (2005). Structure formation and its consequences for gas and water transport in unsaturated arable and forest soils. *Soil & Tillage Research*, 82, 5-14.

- Horne, D. J., Ross, C. W., & Hughes, K. A. (1992). Ten years of a maize/oats rotation under three tillage systems on a silt loam in New Zealand. 1. A comparison of some soil properties. *Soil & Tillage Research*, 22, 131-143.
- Hou, X., Jia, Z., Han, Q., Sun, H., Wang, W., Nie, J., & Yang, B. (2012). Effects of different rotational tillage patterns on soil structure, infiltration and water storage characteristics in dryland. *Transactions of the Chinese Society of Agricultural Engineering*, 28, 85-94.
- Huang, M., Liang, T., Wang, L., & Zhou, C. (2015a). Effects of no-tillage systems on soil physical properties and carbon sequestration under long-term wheat–maize double cropping system. *Catena*, 128, 195-202.
- Hudson, B. D. (1994). Soil organic matter and available water capacity. *Journal of Soil and Water Conservation*, 49, 189-194.
- Iversen, B. V., Moldrup, P., Schjønning, P., & Jacobsen, O. H. (2003). Field application of a portable air permeameter to characterize spatial variability in air and water permeability. *Vadose Zone Journal*, 2, 618-626.
- Jabro, J. D., Sainju, U. M., Stevens, W. B., Lenssen, A. W., & Evans, R. G. (2009). Long-term tillage influences on soil physical properties under dryland conditions in northeastern Montana. *Archives of Agronomy and Soil Science*, 55, 633-640.
- Jalota, S. K., Sood, A., Chahal, G. B. S., & Choudhury, B. U. (2006). Crop water productivity of cotton (*Gossypium hirsutum* L.) – wheat (*Triticum aestivum* L.) system as influenced by deficit irrigation, soil texture and precipitation. *Agricultural Water Management*, 84, 137-146.
- Jarvis, N. J. (2007). A review of non-equilibrium water flow and solute transport in soil macropores: Principles, controlling factors and consequences for water quality. *European Journal of Soil Science*, 58, 523-546.
- Johnston, C. E., & Bailey, A. C. (2002). Soil compaction. In: Upadhyaya, S. K., Chancellor, W. J., Perumpral, J. V., Schafer, R. L., Gill, W. R., & VandenBerg, G. E. (Eds.), *Advances in Soil Dynamics*, 2, *American Society of Agricultural Engineers, St. Joseph, MI*, pp. 155-178.
- Kahlon, M. S., Lal, R., & Ann-Varughese, M. (2013). Twenty two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. *Soil & Tillage Research*, 126, 151-158.
- Kargas, G., Kerkides, P., & Poulouvasilis, A. (2012). Infiltration of rain water in semiarid areas under three land surface treatments. *Soil & Tillage Research*, 120, 1524.
- Kay, B. D., & VandenBygaart, A. J. (2002). Conservation tillage and depth stratification of porosity and soil organic matter. *Soil & Tillage Research*, 66, 107-118.
- Klute, A., & Dirksen, C. (1986). Hydraulic conductivity and diffusivity. Laboratory methods. p. 687-734. In A. Klute (ed.) *Methods of soil analysis. Part 1: Physical and mineralogical properties*. 2nd ed. ASA, Madison, WI.
- Klute, A. (1982). Tillage effects on the Hydraulic Properties of Soil: A Review. *Predicting tillage effects on soil physical properties and processes, (predictingtilla)*, 1, 29-43.
- Krebsteyn, K., Von Janowsky, K., Kuht, J., & Reintam, E. (2014). The effect of tractor wheeling on the soil properties and root growth of smooth brome. *Plant, Soil and Environment*, 60, 74-79.
- Kumar, B., & Sharma, R. P. R. (2000). Effect of preceding crops and nitrogen rates on growth, yield and yield attributes of wheat. *Indian Journal of Agricultural Research*, 34, 34-38.

- Kumar, V., Saharawat, Y. S., Gathala, M. K., Jat, A. S., Singh, S. K., Chaudhary, N., & Jat, M. L. (2013). Effect of different tillage and seeding methods on energy use efficiency and productivity of wheat in the Indo-Gangetic Plains. *Field Crops Research*, 142, 1-8.
- Kutilek, M. (2004). Soil hydraulic properties as related to soil structure. *Soil & Tillage Research*, 79, 175-184.
- Lal, R. (1979). Importance of tillage systems in soil and water management in tropics. In *Soil Tillage and Crop Production*, 2, 25-32.
- Lampurlanés, J., Plaza-Bonilla, D., Álvaro-Fuentes, J., & Cantero-Martínez, C. (2016). Long-term analysis of soil water conservation and crop yield under different tillage systems in Mediterranean rainfed conditions. *Field Crops Research*, 189, 59-67.
- Lin, H. S., McInnes, K. J., Wilding, L. P., & Hallmark, C. T. (1996). Effective porosity and flow rate with infiltration at low tensions into a well-structured subsoil. *Transactions of the American Society of Agricultural Engineers*, 39, 131-135.
- Lipiec, J., Kuś, J., Słowińska- Jurkiewicz, A., & Nosalewicz, A. (2006). Soil porosity and water infiltration as influenced by tillage methods. *Soil & Tillage Research*, 89, 210-220.
- Mahboubi, A. A., Lal, R., & Faussey, N. R. (1993). Twenty-eight years of tillage effects on two soils in Ohio. *Soil Sci. Soc. Am. J.* 57, 506– 512.
- Martínez, E., Fuentes, J. P., Silva, P., Valle, S., & Acevedo, E. (2008). Soil physical properties and wheat root growth as affected by no-tillage and conventional tillage systems in a Mediterranean environment of Chile. *Soil & Tillage Research*, 99, 232-244.
- Mc Garry, D., Bridge, B. J., & Radford, B. J. (2000). Contrasting soil physical properties after zero and traditional tillage of an alluvial soil in the semi-arid subtropics. *Soil & Tillage Research*, 53, 105-115.
- McVay, K. A., Budde, J. A., Fabrizzi, K., Mikha, M. M., Rice, C. W., & Schlegel, A. J. (2006). Management effects on soil physical properties in long-term tillage studies in Kansas. *Soil Science Society of America Journal*, 70, 434-438.
- Mellis, D. A., Bruneau, P. M. C., Twomlow, S. J., & Morgan, R. P. C. (1996). Field assessment of crusting on a tilled sandy clay loam. *Soil Use & Management*, 12, 72-75.
- Messing, I., & Jarvis, N. J. (1993). Temporal variation in the hydraulic conductivity of a tilled clay soil as measured by tension infiltrometers. *Journal of Soil Science*, 44, 11-24.
- Mielke, L. N., Wilhelm, W. W., Richards, K. A., & Fenster, C. R. (1984). Soil physical characteristics of reduced tillage in a wheat-fallow system. *ASAE* 27, 1724–1728.
- Mondal, S., Chakraborty, D., Tomar, R., Singh, R., Garg, R., Aggarwal, P., Sindhu, G., & Behra, U. (2013). Tillage and residue management effect on soil hydrophysical environment under pigeonpea (cajanuscajan)-wheat (triticumaestivum) rotation. *Indian Journal of Agricultural Sciences*, 83, 502-507.
- Mondal, S., Das, A., Pradhan, S., Tomar, R., Behera, U., Sharma, A., Paul, A., & Chakraborty, D. (2018b). Impact of tillage and residue management on water and thermal regimes of a sandy loam soil under pigeonpea-wheat cropping system. *Journal of the Indian Society of Soil Science*, 66, 40-52.
- Moreno, F., Murillo, J. M., Pelegrin, F., & Fernandez, J. E. (2001). Conservation and traditional tillage in years with lower and higher precipitation than the average (south-west Spain). In: *Conservation Agriculture, a Worldwide Challenge* (García-Torres L., Benites J., & Martínez- Vilela A.,

- ed.) *European Conservation of Agricultural Federation, Food & Agriculture Organisation*, Cordoba, Spain, pp. 591-595.
- Moret, D., & Arrue, J. L. (2007). Characterizing soil water-conducting macro- and mesoporosity as influenced by tillage using tension infiltrometry. *Soil Science Society of America Journal*, 71, 500–506.
- Mosaddeghi, M. R., Mahboubi, A. A., & Safadoust, A. (2009). Short-term effects of tillage and manure on some soil physical properties and maize root growth in a sandy loam soil in western Iran. *Soil & Tillage Research*, 104, 173-179.
- Mupangwa, W., Twomlow, S., & Walker, S. (2013). Cumulative effects of reduced tillage and mulching on soil properties under semi-arid conditions. *Journal of Arid Environments*, 91, 45-52.
- Murphy, B. (2015). Key soil functional properties affected by soil organic matter evidence from published literature. In IOP conference series: *Earth and Environmental Science* 25(1), 1-2.
- Ngigi, S. N., Rockström, J., & Savenije, H. H. (2006). Assessment of rainwater retention in agricultural land and crop yield increase due to conservation tillage in EwasoNg'iro river basin, Kenya. *Physics and Chemistry of the Earth*, 31, 910-918.
- Nielsen, D. C., Unger, P. W., & Miller, P. R. (2005). Efficient water use in dryland cropping systems in the Great Plains. *Agronomy Journal*, 97, 364-372.
- Nyamadzawo, G., Chikowo, R., & Giller, K. E. (2007). Improved legume tree fallows and tillage effects on structural stability and infiltration rates of a kaolinitic sandy soil from central Zimbabwe. *Soil & Tillage Research*, 96, 182-194.
- Osunbitana, J. A., Oyedeleb, D. J., & Adekalua, K. O. (2005). Tillage effects on bulk density, hydraulic conductivity and strength of a loamy sand soil in southwestern Nigeria. *Soil & Tillage Research*, 82, 57-64.
- Pagliai, M., & Vignozzi, N. (2002). The soil pore system as an indicator of soil quality. *Advances in Geocology*, 35, 69-80.
- Pagliai, M., Vignozzi, N., & Pellegrini, S. (2004). Soil structure and the effect of management practices. *Soil & Tillage Research*, 79, 131-143.
- Parvin, N., Parvage, M. M., & Etana, A. (2014). Effect of mouldboard ploughing and shallow tillage on sub-soil physical properties and crop performance. *Soil Science and Plant Nutrition*, 60, 38-44.
- Petersen, C. T., Trautner, A., & Hansen, S. (2008). Spatio-temporal variation of anisotropy of saturated hydraulic conductivity in a tilled sandy loam soil. *Soil & Tillage Research*, 100, 108-113.
- Pikul, J. L., & Aase, J. K. (2003). Water infiltration and storage affected by subsoiling and subsequent tillage. *Soil Science Society of America Journal*, 67, 859-866.
- Rasmussen, K. J. (1999). Impact of ploughless soil tillage on yield and soil quality: a Scandinavian review. *Soil & Tillage Research*, 53, 3-14.
- Rawls, W. J., Pachepsky, Y. A., Ritchie, J. C., Sobecki, T. M., & Bloodworth, H. (2003). Effect of soil organic carbon on soil water retention. *Geoderma*, 116, 61-76.
- Regina, K., & Alakukku, L. (2010). Greenhouse gas fluxes in varying soils types under conventional and no-tillage practices. *Soil & Tillage Research*, 109, 144-152.
- Reichert, J. M., Suzuki, L. E. A. S., Reinert, D. J., Horn, R., & Håkansson, I. (2009). Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. *Soil & Tillage Research*, 102, 242-254.

- Reicosky, D.C. (2005). Conservation agriculture: Zero tillage impact on soil organic matter. p. 39-47. Proc. 27th Annual Zero Tillage and Winter Wheat Workshop, Brandon, Canada. 1-2 Feb., 2005. Manitoba-North Dakota Zero Tillage Farmers Association.
- Reynolds, W. D., Elrick, D. E., & Youngs, E. G. (2002). Single-ring and double or concentric-ring infiltrometers. In: Dane, J. H., & Topp, G. C. (eds.) Methods of Soil Analysis. *Soil Science Society of America journal*, 8, 21-26.
- Salado-Navarro, L. R., & Sinclair, T. R. (2009). Crop rotations in Argentina: analysis of water balance and yield using crop models. *Agricultural Systems*, 102, 11-16.
- Sasal, M. C., Andriulo, A. E., & Taboada, M. A. (2006). Soil porosity characteristics and water movement under zero tillage in silty soils in Argentinian Pampas. *Soil & Tillage Research*, 87, 9-18.
- Sasal, M. C., Andriulo, A. E., & Taboada, M. A. (2005). Instituto Nacional de Tecnología Agropecuaria, Estacion Experimental Pergamino, Gruposuelos, CC 31, 2700 Pergamino, Buenos Aires, Argentina.
- Schäffer, B., Stauber, M., Mueller, T. L., Müller, R., & Schulin, R. (2008b). Soil and macro-pores under uniaxial compression. I. Mechanical stability of repacked soil and deformation of different types of macro-pores. *Geoderma*, 146, 183-191.
- Schjønning, P., & Rasmussen, K. (2000). Soil strength and soil pore characteristics for direct drilled and ploughed soils. *Soil & Till. Res.* 57, 69-82.
- Schjønning, P., Lamandé, M., Berisso, F. E., Simojoki, A., Alakukku, L., & Andreasen, R. R. (2013). Gas diffusion, non-Darcy air permeability, and computed tomography images of a clay subsoil affected by compaction. *Soil Science Society of America Journal*, 77, 1977-1990.
- Schwartz, R. C., Evett, S. R., & Unger, P. W. (2003). Soil hydraulic properties of cropland compared with reestablished and native grassland. *Geoderma*, 116, 47-60.
- Sharma, V. K., Pandey, R. N., & Sharma, B. M. (2015). Studies on long term impact of STCR based integrated fertilizer use on pearl millet (*Pennisetum glaucum*)-wheat (*Triticum aestivum*) cropping system in semi-arid condition of India. *Journal of Environmental Biology*, 36(1), 241.
- Sharratt, B. S. (1996). Tillage and straw management for modifying physical properties of a subarctic soil. *Soil Tillage Res.* 38, 239–250.
- Shaver, T. M., Peterson, G. A., Ahuja, L. R., Westfall, D. G., Sherrod, L. A., & Dunn, G. (2002). Surface soil properties after twelve years of dryland no-till management. *Soil Science Society of America Journal*, 66, 1292–1303.
- Shipitalo, M. J., Dick, W. A., & Edwards, W. M. (2000). Conservation tillage and macropore factors that affect water movement and the fate of chemicals. *Soil & Tillage Research*, 53, 167-183.
- Shukla, M. K., Lal, R., & Ebinger, M. (2003a). Tillage effects on physical and hydrological properties of a typical Argiaquoll in central Ohio. *Soil Science*, 168, 802-811.
- Stepniewski, W., Glinski, J., & Ball, B. C. (1994). Effects of compaction on soil aeration properties. *Elsevier Science*, pp: 167–189.
- Strudley, M. W., Green, T. R., & Ascough II, J. C. (2008). Tillage effects on soil hydraulic properties in space and time: State of the science. *Soil & Tillage Research*, 99, 44-48.
- Su, Z., Zhang, J., Wu, W., Cai, D., Lv, J., & Jiang, G. (2007). Effects of conservation tillage practices on

- winter wheat water-use efficiency and crop yield on the Loess Plateau, China. *Agricultural Water Management*, 87: 307-314.
- Tangyuan, N., Bin, H., Nianyuan, J., Shenzhong, T., & Zengjia, L. (2009). Effects of conservation tillage on soil porosity in maize-wheat cropping system. *Plant, Soil and Environment*, 55, 327-333.
- TekluEr, K. (2011). Tillage effects on physical qualities of vertisol in the central highlands of Ethiopia. *African Journal of Environmental Science and Technology*, 5, 1008-1016.
- Van Wie, J. B., Adam, J. C., & Ullman, J. L. (2013). Conservation tillage in dryland agriculture impacts watershed hydrology. *Journal of Hydrology*, 483, 26-38.
- Vanapalli, S., Fredlund, D., & Pufahl, D. (1999). The Influence of soil structure and stress history on the soil-water characteristics of a compacted till. *Géotechnique*, 49, 143-159.
- Wahl, N. A., Bens, O., Buczko, U., Hangen, E., & Hüttl, R. F. (2004). Effects of conventional and conservation tillage on soil hydraulic properties of a silty-loamy soil. *Physics and Chemistry of the Earth, Parts A/B/C*, 29, 821-829.
- Wuest, S. B. (2001). Earthworm, infiltration, and tillage relationships in a dryland pea-wheat rotation. *Applied Soil Ecology*, 18, 187-192.
- Zhang, J., Song, C., & Yang, W. (2007). Tillage effects on soil carbon fractions in the Sanjiang Plain, Northeast China. *Soil & Tillage Research*, 93, 102-108.
- Zhou, J., & Yu, J. L. (2005). Influences Affecting the Soil-Water Characteristic Curve. *Journal of Zhejiang University Science*, 6, 797-804.