International Journal of Chemical Studies

P-ISSN: 2349–8528
E-ISSN: 2321–4902
IJCS 2018; 6(2): 2257-2263

Received: 19-01-2018
Accepted: 21-02-2018

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A comparative study on tillage practices and their impact on soil properties and root attributes of plants

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Abstract
Local soil characteristics are important in determining the type of tillage practice to be adopted in a particular cropping system. Tillage has a profound impact on the soil physicochemical properties and the microbial activity therein. Thus, the growth and yield of the crop are to a large extent determined by the type of tillage practice adopted. There are ample reports of a positive correlation between crop yield, productivity and nutritional quality with judiciously appointed tillage practice. However, indiscriminate use of heavy machinery in higher frequencies, over the field for tillage purposes, are also linked with environmental problems such as soil erosion, loss of organic carbon and nutrients from the topsoil and formation of hardpan in the subsoil. Thus, over time, conventional tillage practices are being increasingly replaced by conservational tillage practices that aim to improve the soil physicochemical and biological properties and prepare the land in a short span of time for the immediate sowing of the successive crop in an intensive cropping system. These tillage modifications are also being criticised for their lower return and negative environmental impact over the long run. This review presents a comparative study of the conservational tillage and other tillage practices such as conventional tillage and deep tillage for their respective impact on soil physicochemical properties.

Keywords: conservational tillage, conventional tillage, deep tillage, yield, soil physiochemical properties, root attributes

Introduction

Tillage is one of the most ancient soil manipulation practice, employed since time immemorial and is an essential technique employed in most modern day crop production systems with subtle modifications. Tillage influences wide range of physicochemical and biological properties of the soil, such as bulk density, penetration resistance, and aggregate stability. Numerous reports suggest that tillage influences both biotic and abiotic processes, modify structural properties of soil such as cracks, aggregates, and pore continuity, as well as affect the aeration, temperature, and heat dissipation and moisture content of soil [1, 2]. Much emphasis has been given to the studies linking modulations in the tillage equipment and their subsequent effect on the growth and yield of the crop [3]. Tillage is done for seedbed preparation and its influence is reflected in the germination percentage, seedling establishment and yield of the crop. Different tillage methods are developed and adopted for different cropping systems. However, a hardpan at deeper soil depths is usually formed over the long run of heavy tillage machinery over the farmland. Soil compaction is caused by repeated wheel traffic at the soil surface and formation of a hardpan in subsurface layers [4]. Thus, with time, increasing fraction of farmland is resorting to conservational tillage that deviates from the conventional tillage in ideology, type, and degree of mechanization and frequency of tilling operations themselves. Conservation tillage is defined as any tillage practice that minimizes the loss of soil and water [5]. With this definition, conservation tillage can include shallow surface tillage (reduced tillage, RT), no-tillage (NT), crop residue mulching, and subsoil mulching each having differential impact over the chemical, biological, and physical properties of soil [6]. Conservational tillage has emerged as one of the main tools for moisture conservation in dryland farming and is an effective means of improving soil moisture regimes [7]. Conservation tillage practices allow the residual organic matter to be on the soil surface thus improving water absorption capacity and have shown to improve yield over 6-8 years of practice [8].Reduced tillage practices are increasing worldwide due to their benefits of soil and water conservation as well as their reduced requirement for fuel, equipment, and labour [9-11].

However, adoption of these practices has been much slower, partly due to production subsidies and smaller-scale farming structure [12]. Changes in soil physical properties due to the use of no-tillage depend on several factors including differences in soil properties, weather conditions, history of management, intensity, and type of tillage and thus the ends obtained are contrasting [13, 14]. The effectiveness of conservation tillage also depends upon the crop requirements, rainfall probability, and soil water-storage capacity [15].

Yield reduction has also been observed in some fields if conservation tillage is practiced in short span of two to three years. Cost of cultivation may not be economical on the sustainable basis in the long run for affecting organic matter status of the soil [16]. Intensive crop production, traditional management practices and increased frequency of heavy machinery over farmland also leads to devastating effects over soil physicochemical and biological properties. Over the last three decades, there has been considerable research on the effects of conservation tillage on crop yield in many areas including its economic and environmental effects [17]. However, the evidence from different studies often seems contradictory and is therefore difficult to interpret [18]. This is to be expected since both the agro-environmental conditions as well as the type of conservation tillage applied vary greatly between individual studies. Considerable research has been done on the performance of crops under different tillage systems. Due to gradual constriction of resources, there has been much work done and is still in progress to evaluate various existing tillage systems and their impact on crop performance and to develop new tillage systems [19, 20]

Impact of tillage on Physicochemical and biological properties of soil

Cultivation on the same farmland over the long run can result in compacted soil layers with increased bulk density due to the formation of a hardpan below plow layers. Such layers inhibit root penetration and water movement through the soil profile. Several authors have reported greater soil bulk density under conservation tillage than conventional tillage while others did not find differences or obtained lower values of bulk density under soils with a residue layer on the surface [21, -26]. No-Tillage has been shown to lower the bulk density of soil near the surface, while no significant changes in bulk density were observed in the top 30 cm [27, 28]. Others have reported that the bulk density may vary differently between trilling practices at different depths. No significant change in bulk density was reported between conservational tillage and no-tillage at 0–5 cm and 10–20 cm soil depths, whereas at 5–10 cm soil depth no tillage had higher bulk density than conventional tillage [29-31]. Similarly, Huang *et al.* 2012, found no significant difference in bulk density between conservational tillage and no-tillage at 0–7 cm and 14–21 cm soil depths, but significantly higher bulk density at 7–14 cm soil depth under no-tillage than conservational tillage [32- 34].

Residual organic carbon in conservational tillage has been reported to influence the soil organic nitrogen mineralization; however the reverse has also been reported [35, 36]. Conventional tillage has been shown to record significantly higher values of soil phosphorus and potassium than zero tillage. The organic matter content is expected to increase with conservation tillage, but remain constant or even decrease further, with conventional tillage on a soil that is initially low in soil organic matter [22]. A decrease in soil organic matter was also observed to a depth of 10 cm after 3 years in a oxisol and to a depth of 20 cm after 11 years of zero tillage as compared to tilled soil, while others have found no significant change in soil organic matter content down to 30 cm depth in a clayey Typic Hapludox oxisol after 13 years of zero tillage. Reports also suggest that long-term effects of no-tillage include desirable changes in the soil physical properties, soil fertility, and moisture but lead to greater soil bulk density and soil strength [37, 38].

Rotational tillage treatments significantly reduce soil bulk density, when compared with conventional tillage, since no tillage coupled with sub-soiling can loosen the soil, and eliminate soil compaction caused by random wheel traffic. Related studies have shown that long-term no-tillage positively affects the total porosity of the soil and sub-soiling can break compacted layers underneath the layer and increase the porosity of the A horizon of the soil. The rotational tillage treatments have resulted in significantly greater total porosity compared with conventional tillage at a 0–40 cm depth due to the interval with no-tillage and sub-soiling thus avoiding frequent soil disturbances, which decreases soil bulk density [40]. Insufficient soil moisture during seed germination can create water stress resulting in delayed germination. Transmission and storage pores are generally high with zero tillage. Some studies have shown that tillage disrupts pore continuity and decreases water infiltration, whereas others report either no change or decreased rates. Soil water contents were shown to be consistently higher under no-tillage than conventional tillage or decreased rates. [41, 42].

According to the results of various studies, soils under no-tillage had the highest moisture contents [43]. Reduced tillage also increased soil water content [44]. Soil water content was increased due to reduced tillage that improved water infiltration, reduced surface runoff, and decreased evaporation.

An important aspect of tillage with respect to soil property is its effect on soil fauna activity. Studies comparing effects of deep-plowing versus reduced tillage showed enhanced soil biological activities as a consequence of not turning the soil [45]. Microbial activity causes profound changes in soil quality [46]. Microbial-based indicators of soil quality, such as microbial biomass, are believed to be more dynamic than those based on physical and chemical properties of soil. Therefore, early signals of soil degradation or soil improvement can be more accurately traced by microbial-based indicators. Doran reported that total aerobic counts and facultative anaerobic counts for no-till soil were 1.35 and 1.57 times (35 and 57%) higher, respectively than those for conventionally tilled soil. Among the aerobic organism, the fungi and aerobic bacteria increased most with no-till as compared with conventional tillage. The population of denitrifying bacteria was 2.7 times higher in no-till relative to plowed soils [47]. On the other hand, Stately and Fairchild found no effect of tillage on denitrifier population size in samples from the surface 30 cm [48].

Impact of tillage on nutrient content of plants

Tillage system affects the organic matter, nitrate-N concentration, aeration and available. Frequently, N2O emissions from soil are higher under no-tillage than conventional-till. The adoption of no-tillage enhanced soil carbon storage and aggregation. Phosphorus, Potassium, Calcium, Magnesium, Iron and Zinc content under plow tillage have been found to be significantly higher than those under no-tillage at different growing stages. Potassium concentration and uptake generally decrease with increasing soil compaction. Lipiec and others have reported that N_2O

flux from direct-drilled soil (no-till but mulch removed by burning) was three to five times greater than the flux from plowed plots [49, 50]. Plow-tillage practice has been shown to have no effect on the potassium concentration in the grain but was found to increase the potassium concentration in the straw. Zero tillage practices have been shown to reduce the concentration of nutrients in winter wheat and oats [52]. Conventional tillage practices were found to yield significantly higher leaf N, P, K content and tuber yield of sweet potato compared with zero tillage [53]. These results suggest that tillage decreases soil compaction and soil bulk density thus improve root growth which led to higher nutrient delivery rate. On the contrary, Waddell, and Weil, 2006 reported that tillage and fertilizer placement do not significantly affect nitrogen uptake [54]. Similarly, Potassium content in the shoot was shown to be unaffected by tillage treatments [55]. After ten years of grain sorghum production, the extractable phosphorus was found to be significantly greater in no-till compared with chisel till in the 0.05 m layer [56]. Most studies have shown that soils under zero-till management exhibit a strong stratification of phosphorus and other immobile nutrients, with higher concentrations in the surface 5 cm, followed by sharp concentration decreases below this depth [57]. Zero tillage management in an Oxisol for five years has reported a significant increase in the concentration of labile forms phosphorus in the surface 4 cm of the soil. The stratification of phosphorus found in soil under zero-till management has been attributed to the accumulation of residual fertilizer phosphorus reaction products and to increased accumulation of organic residues at the soil surface [58, 59]. This has raised concerns with regards to plant use of the near-surface nutrient under zero-till management [60].

A set of complex interactions between nitrogen and water availability, yield, and temperature affect the protein content of the grain. Some studies have analyzed wheat grain protein content as a function of tillage system, reporting no significant differences as protein content was found to be similar between tillage systems [61]. In contrast, Lo´ pez-Bellido *et al*. have reported that crops grown on conventional tilled land produce more crude protein than crops grown with no-tillage practice [62].

Impact of tillage on root growth

Tillage not only affects soil properties but also crop growth and nutrient uptake under various agro-ecological conditions. The cultivation practices affect the root architecture of crops and have a direct impact on the water and nutrient uptake by roots [29, 50]. The root system has important physiological functions, such as nutrient and water uptake, anchorage of shoot and synthesis and recirculation of hormones [63-66]. Roots are the fundamental component of terrestrial ecosystems, and the above-ground growth and biomass yield are greatly dependent on the root system [29, 64]. Root development and, distribution in the soil profile determines the capacity for nutrient uptake and water extraction by crop plants [63]. Thus, the root system serves as a bridge between the impacts of agricultural practices on soil and changes in shoot function and harvested yield. Most important impact of tillage on crop development is achieved by affecting root development and distribution in the soil profile. However, the continuous use of conventional tillage machinery can create hardpans in the subsoil, which can be detrimental to root proliferation [67]. It is generally accepted that roots are more likely to concentrate in the topsoil due to the greater availability of water and nutrient. As with impact of tillage on root distribution, a no-tillage practice can gradually increase mechanical impedance of the surface soil, limiting the distribution of roots in the upper soil profile and root growth in deeper layers of the soil [69]. The roots are thicker with less absorbing surfaces in reduced tilled soil than plow-tilled soil, and finer and longer under tilled soil compared with no-tilled soil, at all depths [70]. Others have also reported that no-tillage promotes greater and deeper water accumulation in the soil profile and greater root growth [69]. Merrill *et al*. observed that spring wheat roots penetrate to greater soil depths under no-tillage than conventional tillage, with larger root length density due to the cooler soil and superior soil water conservation in the near-surface zone [70]. Root length density is known to be an important parameter for the evaluation of tillage system and their impact on crop growth and yield [71]. Other growth parameters such as root length, root numbers, root volume, root dry weight and root density are also influenced by tillage. Better penetration of root into deeper soil layer is expected on tilled raised furrow due to the more pulverized and loose soil, which encourages the roots to grow deeper. Similarly, compact soil under zero-till offers greater penetration resistance to roots thus hampering their growth, consequently, more numbers of fibrous and thin roots develop on top layers of the soil [75]. Root growth decreases as penetration resistance increases showing a linear exponential or inverse relationship [76, 77]. Several reports have indicated that roots elongate more slowly at first under no-tillage than with conventional ploughing, whereas lateral branching generally starts earlier, resulting in a dense but shallow root system in undisturbed soil. Allmaras and Nelson observed that straw mulch on untilled soil enhanced root growth in the upper 15 cm of soil and increased the lateral spread of roots during the early staged of crop development [70].

High soil compaction has been proved to be responsible for reduced root growth. The roots in the no-tillage system are reported to get accumulated to a greater extent in 0-5 cm soil depth as compared to the roots in the conventional tillage system [70]. Higher bulk density can impede root growth, stimulate root branching and hinder the growth of the main axes [72]. Sidiras *et al*. reported thicker barley roots under conventional tillage than under no tillage [78]. Root length density profiles sometimes showed greater values for no-tillage than for the other tillage systems, revealing good soil condition for root growth under no tillage. Therefore, an increase in soil strength is observed under no-tillage in the first year after its introduction and doesn't greatly affect root growth in well-structured soils [6]. Qin *et al*. reported slightly lower root length density and a slightly larger mean root diameter under no-tillage when compared with conventional tillage [75].

Root length density is an important parameter for the characterization of the root system, in particular, the behaviour of fine roots, and for the prediction of its response to changes in the environment [83]. Root length density and root surface area density are pertinent parameters for characterizing root systems [66, 74]. Root length density showed variable differences among tillage practices at different soil depths and also differing with the crop growth stage, being insignificant at the uppermost soil profile (0–10 cm) at early crop growth stage but significantly greater for plow tillage and reduced tillage than no-tillage at maturity. Similar findings were reported for tillage systems on maize by Mosaddeghi *et al*. [72] Qin *et al*. reported that root length density is significantly higher under no tillage than under conventional tillage at a depth of 5 cm, whereas it is higher under conventional tillage than under no-tillage in 10–50 cm soil profile [75]. Root surface area density a component proportional to root length and diameter, is the most important morphological characteristic influencing plant water and nutrient uptake [66]. Root surface area density under different tillage practices showed similar varied trends to RLD in the 0–100 cm soil profile. In other words, Root surface area density under PT was significantly higher than under no-tillage in the 0–50 cm soil profile, whereas there was no difference in Root surface area density below 50 cm. Root surface area density is significantly higher under MP (mould board plow) than no-tillage. Gregory found that no-tillage was associated with higher root length density in the topmost layer [68]. However, other studies in temperate climates found no difference in root growth for winter wheat under no-tillage and conventional tillage [75, 76]. The impact of tillage on root growth may depend on the length of time since the implementation of no-tillage. Rasmussen has observed that the influence of tillage on root length density is evident in the layer affected by ploughing; noting that root accumulation is greater in the 0–5 cm layer under no tillage than under conventional tillage [75]. Similar findings were reported for temperate climates and loamy silt and sandy loam soils by Qin *et al*. [79, 80]. By contrast, root length density is found to be lower at greater depths under no-tillage [75, 76]. Merrill *et al*. found that root development in winter wheat was better under no tillage than under conventional tillage, with an increase in root length density values of up to 40%. These conflicting results may be due to variation in soil type [64]. Probert *et al*. working in clayey vertisols suggested that the influence of tillage system on root growth and proliferation is due to their smaller pore size [77].

According to Chassot *et al*., under zero tillage, compaction may occur in the surface soil, presenting greater soil strength than under conventional tillage and may hinder root growth [81, 82]. If there is enough topsoil for root growth, roots will concentrate at surface and increases in density of the subsoil may not result in significant decreases in yield. Rosolem and Takahashi studied the effects of soil subsurface compaction on root growth and nutrient uptake by soybean grown on sandy loam and reported that sub-surface compaction led to an increase in root growth in the superficial soil layer [83]. Wilhelm and Wortmann found that root length density of winter wheat increased only in the upper soil layers of a zero tillage system when compared to a conventional tillage system. Soil physical changes that occur under zero tillage can negatively affect the growth of the main root axes, particularly, at the initial stages of plant development [84].

Root diameter is one of the most important parameters for rhizosphere modeling [38]. At the plant level, large-diameter roots account for most of the root system biomass, whereas small-diameter roots account for most of the root system surface area and are the site of the soil-plant exchanges of water and nutrient [69]. Sidiras *et al*. reported thicker barley roots under conventional tillage, in contrast to Braim *et al.* while Qin *et al.* found no effect of tillage on the diameter of wheat roots [19, 78, 79].

Carter found that shallow tillage removed some of the constraints associated with direct drilling and provided an alternative to conventional tillage [85]. Ellis and Barnes found highest root counts in conservation tillage compared to wheat seeded in plowed soil [74].

Effect on yield parameters

The replacement of conventional tillage with conservation tillage improves crop yields and reduces operational costs, among other economic benefits. However, Taa *et al*. observed that wheat yields from minimum and no-tillage sometimes were lower than those from conventional tillage [86]. Lampurlanés *et al*. found no difference among tillage systems in crop yield and overall water-use efficiency [6]. Cereal grain response to conservation tillage practices is variable and higher yield is often obtained under arid and semi-arid regions that is caused due to increased water conservation or utilization by the crop, whereas any lower yield is attributed to greater disease and weed infestations and nutrient immobilization [59, 87]. It has been reported that in cases where soil moisture limits plant growth, grain yield was always equal or greater in conservation tillage than in mould board plowing, and positively correlated with earlier/greater seedling emergence and autumn growth. Some authors found the conservation tillage to occasionally diminish yield through decreased N availability [87]. Unger noted that among chisel (winged type), disk and no-tillage methods, maximum yield was obtained by the chisel method and lowest yields by the no-tillage method [45].

Zero tillage results in lower yields than conventional tillage in barley. Conversely, Brandt observed that zero-tillage obtained higher yields than conventional tillage [88]. Similarly, several studies have shown that crops grown under zero tillage have yielded similar or better than those grown under conventional tillage [89]. Buhler reported that corn yields were not affected by tillage [50]. However, Vencill and Banks observed that sorghum grain yields were higher with the no-tillage system when it was combined with a high degree of weed management than in conventional tillage system [90]. Both corn and soybean yields were greater in mould board plowing than in no-tillage [36].

Kandasamy and Krishnakumar reported that tractor and power tiller puddling increased the grain yield in rice [91]. Higher grain yield of maize was recorded by disc plowing followed by cultivator tillage. Zero tillage was found to be particularly effective in enhancing crop yield during years of relatively low precipitation. Reports over highest grain yield of rice have been recorded in the plot puddled by rotavator and lowest in the direct sown unpuddled soil. Whereas, Sathyamoorthi *et al*. working in black clay and red sandy loam soils recorded higher grain and stover yields of maize with disc plowing followed by cultivator tillage. Crop yield in reduced tillage was comparable with conventional tillage if weeds were controlled [92]. Wilhelm and Wortmann reported that tillage treatment has a significant effect on corn yield and concluded that no-tillage treatment yielded less than with plow [84].

In cases where soil moisture limits plant growth, no-tillage (drilling directly into the untilled soil) has been reported to produce crop yields similar to or higher than conventional tillage [85]. Aase and Pikul has shown that no-tillage in a spring wheat production system was the most efficient soil management practice in terms of grain yield, water use efficiency, soil organic carbon sequestration and reducing soil bulk density [93]. Grain yield ranking from the highest to the lowest was found to be greater under the conventional tillage when averaged across years, indicating that grain production increased as tillage decreased [18].

Lo´pez and Arru´e reported that conservation tillage produced an alternative to conventional tillage to maintain crop productivity in the dry land cereal growing area; however, crop yields under no-tillage management were lower than conventional ones in wet soil conditions [17]. The opposite was true in dry years, where the effect of tillage was insignificant or less favourable with conventional tillage [59].

Conclusion

Tillage has profound impact over the physiochemical properties of the soil as well as on the growth and yield of crops. The variation in agro climatic zones demands modification of conventional or prevailing tillage system in any particular region. This review brings together the findings of various research works carried out in different climatic conditions to get a comparative picture of the improvements that can be brought by modifying tillage operations. While conservational tillage can bring desirable changes in soil physicochemical properties and biological activity in soil, its long term use has been detrimental in obtaining higher yield of various crops. Reduced tillage can be used in rotation with zero tillage and deep tillage to get a sustainable improvement in all aspects of farming.

Conflict of interest

Authors declare there is no conflict of interest for this study.

Acknowledgement

The authors acknowledge Dr. T.C. Thakur for his suggestions and critical feedback.

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