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Conservation tillage impacts on soil, crop and the environment

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Abstract

There is an urgent need to match food production with increasing world population through identification of sustainable land management strategies. However, the struggle to achieve food security should be carried out keeping in mind the soil where the crops are grown and the environment in which the living things survive. Conservation agriculture (CA), practising agriculture in such a way so as to cause minimum damage to the environment, is being advocated at a large scale world-wide. Conservation tillage, the most important aspect of CA, is thought to take care of the soil health, plant growth and the environment. This paper aims to review the work done on conservation tillage in different agro-ecological regions so as to understand its impact from the perspectives of the soil, the crop and the environment. Research reports have identified several benefits of conservation tillage over conventional tillage (CT) with respect to soil physical, chemical and biological properties as well as crop yields. Not less than 25% of the greenhouse gas effluxes to the atmosphere are attributed to agriculture. Processes of climate change mitigation and adaptation found zero tillage (ZT) to be the most environmental friendly among different tillage techniques. Therefore, conservation tillage involving ZT and minimum tillage which has potential to break the surface compact zone in soil with reduced soil disturbance offers to lead to a better soil environment and crop yield with minimal impact on the environment.
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Keywords: Atmosphere; Greenhouse gases; Conservation tillage; Sustainable crop yield

Contents

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1. Introduction

The growing concern for food security through improved soil management techniques demands identification of an environmental friendly and crop yield sustainable system of tillage.

Tillage is defined as the mechanical manipulation of the soil for the purpose of crop production affecting significantly the soil characteristics such as soil water conservation, soil temperature, infiltration and evapotranspiration processes. This suggests that tillage exerts impact on the soil purposely to produce crop and consequently affects the environment. As world population is increasing so the demand for food is increasing and as such the need to open more lands for crop production arises. The yearning for yield increases to meet growing demand must be done in a way that soil degradation is minimal and the soil is prepared to serve as a sink rather than a source of atmospheric pollutants. Thus, conservation tillage, along with some complimentary practices such as soil cover and crop diversity (Corsi, Friedrich, Kassam, Pisante, & de Moraes Sà, 2012) has emerged as a viable option to ensure sustainable food production and maintain environmental integrity. This implies that conservation tillage is a component of conservation agriculture (CA).

Corsi et al. (2012) define CA as a method of managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. They added that minimum mechanical soil disturbance, permanent organic soil cover and crop diversification are the three basic principles of CA. According to CTIC (2004), conservation tillage is any tillage system that leaves at least 30% of the soil surface covered with crop residue after planting to reduce soil erosion by water. Lal (1990) described conservation tillage as the method of seedbed preparation that includes the presence of residue mulch and an increase in surface roughness as the key criteria. Conservation tillage is an ecological approach to soil surface management and seedbed preparation. Conversion from conventional to conservation tillage, when this is done in line with the principle of CA, may improve soil structure, increase soil organic carbon, minimize soil erosion risks, conserve soil water, decrease fluctuations in soil temperature and enhance soil quality and its environmental regulatory capacity. Crop residue is an important and a renewable resource. Developing techniques for effective utilization of this vast resource is a major challenge. Improper uses of crop residues (e.g. removal, burning or ploughing under) can aid accelerated erosion, soil fertility depletion and environmental pollution through burning.

The principle of conservation tillage involves maintenance of surface soil cover through retention of crop residues achievable by practicing zero tillage and minimal mechanical soil disturbance. Retention of crop residue protects the soil from direct impact of raindrops and sunlight while the minimal soil disturbance enhances soil biological activities as well as soil air and water movement. The aim of this review, therefore, was to examine the effects of conservation tillage on soil, crop and the net effect on the environment. This may provide farmers and other land users the information on the desirability of a conservation tillage system for sustainable crop yield increases with minimal negative impact on the soil and the environment.

2. Types of conservation tillage

Conservation tillage practices range from zero tillage (No-till), reduced (minimum) tillage, mulch tillage, ridge tillage to contour tillage. No tillage (NT) involves land cultivation with little or no soil surface disturbance, the only disturbance being during planting while minimum tillage means reduced level of soil manipulation involving ploughing using primary tillage implements. In mulch tillage, the soil is prepared or tilled in such a way that the plant residues or other materials are left to cover the surface to a maximum extent. Ridge tillage involves planting crops in rows either along both sides or on top of the ridges which are prepared at the commencement of the cropping season. When tillage is at right angles to the direction of the slope it is referred to as contour tillage.

3. Conservation tillage and soil properties

Tillage impact is noticeable on soil physical, chemical and biological properties though in different magnitudes. Tillage impact also includes the effect on the soil environment in the form of runoff and soil erosion (Bhatt & Khera, 2006).

3.1. Soil physical properties

Effects of conservation tillage on soil properties vary, and these variations depend on the particular system chosen. No-till (NT) systems, which maintain high surface soil coverage, have resulted in significant change in soil properties, especially in the upper few centimeters (Anikwe & Ubochi, 2007). According to Lal (1997a), soil physical properties are generally more favourable with no-till than tillage-based systems. Many researchers have found that NT significantly improved saturated and unsaturated hydraulic conductivity owing to either continuity of pores (Benjamin, 1993) or flow of water through very few large pores (Allmaras, Rickman, Ekin, & Kimball, 1977). It has been reported that well-drained soils, light to medium in texture with low humus content, respond best to conservation tillage (Butorac, 1994) especially to no-tillage. According to Lal, Reicosky, and Hanson (2007) NT technologies are very effective in reducing soil and crop residue disturbance, moderating soil evaporation and minimizing erosion losses. More stable aggregates in the upper surface of soil have been associated with no-till soils than tilled soils and this correspondingly results in high total porosity under NT plots. In Gottingen, Germany, Jacobs, Rauber, and Ludwig (2009) 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. In terms of water conservation, NT has been found to be more effective in humid and sub-humid tropics. Kargas, Kerkides, and Poulovassilis (2012) observed that untilled plots retain more water than tilled plots. In comparison with conventional ploughing, Pagliai, Vignozzi, and Pellegrini (2004) 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). Therefore, to improve soil water storage and increase water use efficiency (WUE) most researchers have proposed replacement of traditional tillage with conservation tillage (Fabrizzi, Garcia, Costab, & Picone, 2005; Silburn, Freebairn, & Rattray, 2007). Water use efficiency has also been reported to be greater in soils under reduced tillage (McVay et al., 2006) and NT (Li, Huang, & Zhang, 2005) 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. On a sandy Alfisol in southwestern Nigeria, Busari and Salako (2012) observed higher unsaturated water flow parameters and infiltration rate under CT and MT than ZT at the end of the

Table 1
Effect of tillage on field unsaturated water flow at the end of each of the two years of the study.
Source: Busari and Salako (2012).

Year	2008					2009				
Tillage	CI (cm)	Sorptivity (cm $h^{-1/2}$)	SSF (cm h^{-1})	K_o (cm h^{-1})	*IR* (cm h^{-1})	CI (cm)	Sorptivity (cm $h^{-1/2}$)	SSF (cm h^{-1})	K_o (cm h^{-1})	*IR* (cm h^{-1})
CT	3.32	3.55	9.17	8.50	9.53	2.15	2.41	6.40	6.09	7.12
MT	3.93	3.79	10.98	10.25	11.34	2.30	2.46	7.02	6.69	7.79
ZT	2.87	3.13	8.11	7.59	8.50	2.15	2.45	6.79	6.46	7.35
LSD ($P \leq 0.05$)	0.36	0.22	1.23	1.18	1.23	ns	ns	ns	ns	ns

CI – cumulative infiltration; SSF – steady state flow; K_o – unsaturated hydraulic conductivity; *IR* – infiltration rate; ns – not significant.

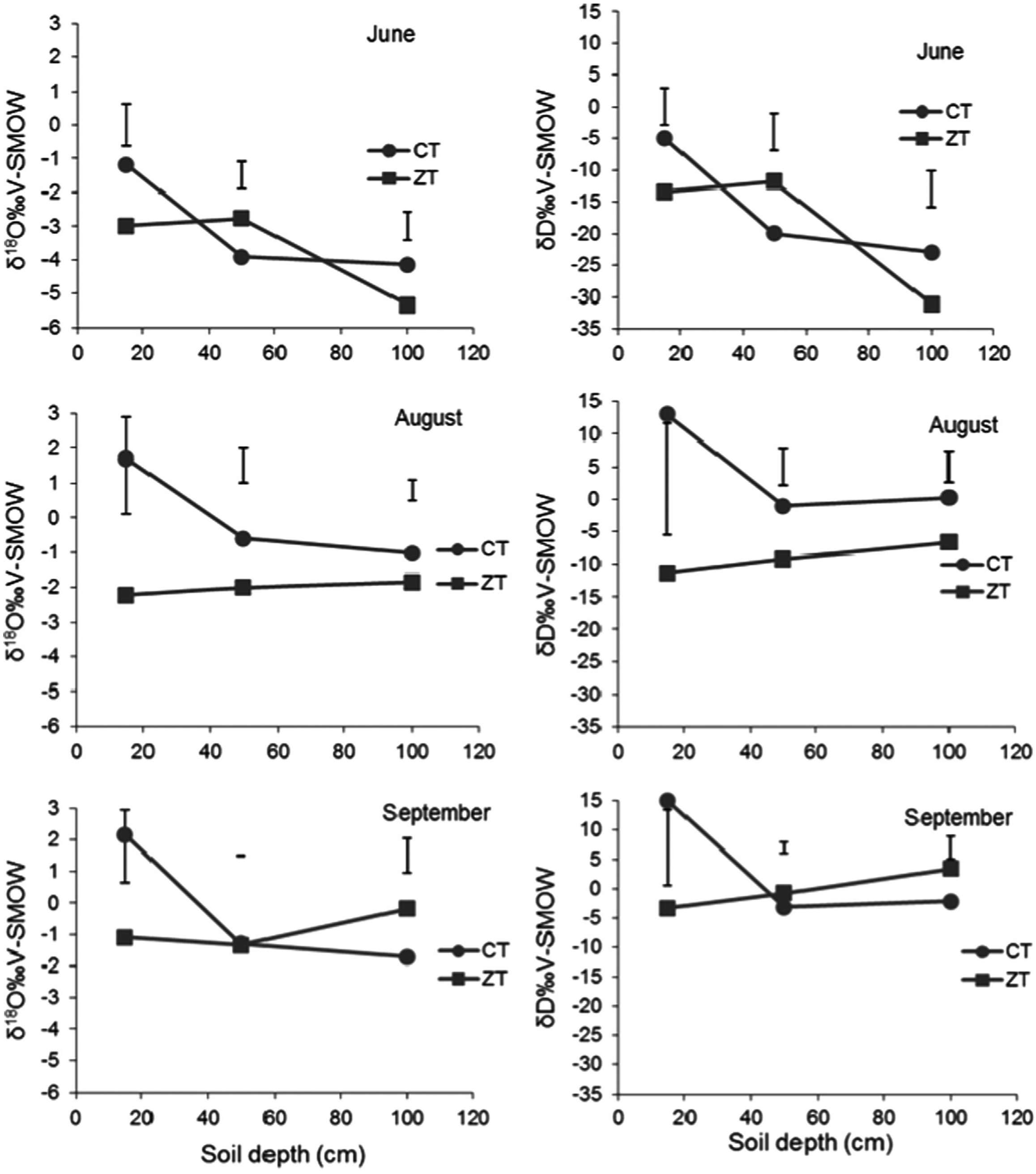

Fig. 1. Comparative effect of conventional tillage (CT) and zero tillage (ZT) on fractionation of: (a) $\delta^{18}O$, and (b) δD of soil water. Vertical lines on data points are standard deviation bars. V-SMOW = Vienna Standard Mean Ocean Water.
Source: Busari et al. (2013).

first year of the study (Table 1) but at end of the second year, ZT had higher infiltration parameters compared with CT. This is beacuse the fast draining macro-pores (FDP) created by CT could facilitate infiltration momentarily after tillage, but these FDP reduced with time as a result of repackaging of soil aggregates (Martınez, Fuentes, Silva, Valle, & Acevedo, 2008), leading to a lower infiltration rate under CT than ZT over time. Other studies (Pikul & Aase, 1995; Shukla, Lal, Owens, & Unkefer, 2003) have found higher infiltration rates under NT than CT because of the protection of the soil surface and effect of SOC. Kemper, Trout, Segeren, and Bullock (1987) found that less intense tillage not only kept the crop residue at the soil surface but it also increased the activity of surface-feeding earthworms, leaving the root channels undisturbed, which in turn leads to the presence of numerous surface-connected macro-pores and inter-pedal voids resulting in higher infiltration.

The rate and quantity of evaporation from the soil surface is a complicated process affected by many soil characteristics, tillage and environmental interactions (Lal & Shukla, 2004). Under conservation tillage, higher water content in the topsoil and more plant residues on the soil surface, resulting in declined evaporation, have been linked with the lower soil temperature (Rasmussen, 1999). A higher evapotranspiration (ET) in NT plots than in CT and RT plots has also been reported and was attributed to greater and deeper soil water storage (Su et al., 2007) as extensive tillage usually expose soil surface to water loss and evaporation. Using the stable isotope technique, Busari et al. (2013) reported that soil water stable isotopes ($\delta^{18}O$ and δD) were more enriched near the soil surface under CT compared with ZT (Fig. 1) indicating more evaporation under conventionally tilled soils.

3.2. Soil chemical properties

Soil chemical properties that are usually affected by tillage systems are pH, CEC, exchangeable cations and soil total nitrogen. According to Lal (1997b) soil chemical properties of the surface layer are generally more favourable under the no-till method than under the tilled soil. Annual no-tillage, implying yearly practice of no-till system over a long period of time, is beneficial to maintenance and enhancement of the structure and chemical properties of the soil, most especially the SOC content. Rasmussen (1999) and During, Thorsten, and Stefan (2002) observed that with annual no-tillage, plant residues left on the soil surface increase the organic matter in the topsoil. Similarly, Ismail, Blevins, and Frye (1994) and Lal (1997b) reported a significantly higher SOC in soil with NT compared to un-tilled soil. A reduced total N loss was also observed under NT compared to CT by Dalal (1992). Higher mineralization and/or leaching rate could be implicated for reduction in organic C and total N under tilled plot due to soil structure deterioration following tillage.

Tillage technique is often shown to have no effect on soil pH (Rasmussen, 1999), though soil pH has been reported to be lower in no-till systems compared to CT (Rahman Okubo, Sugiyama, & Mayland, 2008). The lower pH in ZT was attributed to accumulation of organic matter in the upper few centimeters under ZT soil (Rhoton, 2000) causing increases in the concentration of electrolytes and reduction in pH (Rahman et al., 2008). Conversely, Cookson, Murphy, and Roper (2008) found that surface soil pH decreased with increasing tillage disturbance and Lal (1997b) reported a significantly higher soil pH in NT plots compared to those in tilled plots. Therefore, tillage may not directly affect soil pH but its effects on pH will depend on the prevailing climatic condition, soil type and management factors.

Ismail et al. (1994) and Rahman et al. (2008) reported that exchangeable Ca, Mg, and K, were significantly higher in the surface soil under NT compared to the ploughed soil. According to Ali, Ayuba, and Ojeniyi (2006), the lowest values of soil OM, N, P, K, Ca and Mg were recorded in conventional till plots and it could be due to the inversion of top soil during ploughing which shifts less fertile subsoil to the surface in addition to possible leaching. In southwestern Nigeria, Busari and

Table 2
Effect of tillage on soil chemical properties after maize harvest.
Source: Busari and Salako (2013).

Year	2008					2009				
Tillage	pH (H_2O)	OC ($g\ kg^{-1}$)	TN ($g\ kg^{-1}$)	Avail. P ($mg\ kg^{-1}$)	ECEC ($cmol\ kg^{-1}$)	pH (H_2O)	OC ($g\ kg^{-1}$)	TN ($g\ kg^{-1}$)	Avail. P ($mg\ kg^{-1}$)	ECEC ($cmol\ kg^{-1}$)
CT	6.0	16.50	1.38	26.64	6.31	6.69	2.79	0.32	65.59	8.05
MT	6.2	19.80	1.52	24.33	6.24	6.79	4.59	0.55	40.47	8.51
ZT	6.1	21.20	1.58	33.28	7.36	6.64	5.00	0.53	61.13	9.39
LSD ($P \leq 0.05$)	0.05	2.20	ns	7.13	0.49	0.04	0.44	0.08	13.25	0.79

OC = organic carbon; TN = total nitrogen; Avail. P = available phosphorus, ECEC = effective cation exchange capacity; ZT = zero tillage; MT = minimum tillage; CT = conventional tillage; LSD=least significant difference; ns = not significant.

Salako (2013) observed that ZT soil had a significantly higher pH at the end of the first year after tillage but the pH became significantly lower compared with the CT soil at the end of the second year after tillage. However, the soil organic C (SOC) and the effective cation exchange capacity (ECEC) were significantly higher at the end of the two years of study under ZT than under CT (Table 2). The study however, revealed that minimum tillage (MT) resulted in significantly higher pH and SOC than CT at the end of each of the two years of the study suggesting that less soil disturbance is beneficial to soil chemical quality improvement.

3.3. Soil biological properties

The soil biological property most affected by tillage is SOC content (Doran, 1980). The soil organic matter content influences to a large extent the activities of soil organism which in turn influence the SOC dynamics. Earthworms which are a major component of the soil macrofauna are important in soil fertility dynamics as their burrowing activities aid in improvement of soil aeration and water infiltration. The fact that the population of earthworms are affected by tillage practices has been documented in a ploughless tillage review by Rasmussen (1999). A six year study by Andersen (1987) revealed a significantly higher earthworm population under no-till soil than under ploughed soil. Kemper et al. (1987) reported that less intense tillage increased the activities of surface-feeding earthworms. Due to disruption of fungi mycelia by tillage technique, Cookson et al. (2008) observed a decreased fungal biomass and increased bacterial biomass with increasing tillage disturbance. They also reported alteration in the composition and substrate utilization of the microbial community with distinct substrate utilization in no-till soil.

4. Conservation tillage and crop performance

Tillage impact on crop yield is related to its effects on root growth (Boone & Veen, 1994), water and nutrient use efficiencies (Davis, 1994) and ultimately the agronomic yield (Lal, 1993). An increase in root length density has been found only in the upper soil layers of NT (Martınez et al., 2008) and reduced tillage (Lal, 1989) systems compared to the CT system because soil compaction of deeper soil layers under NT may impede proper development of roots. However, Malhi and Lemke (2007) reported a 22% increase in root mass under NT compared with CT. This could be attributed to the cracks, worm channels and higher number of biopores (Francis & Knight, 1993), which may facilitate root growth under NT. Busari and Salako (2012) found that during the first year of a tillage experiment, there was no significant difference in maize root mass among the tillage systems though root mass under MT was consistently higher than other tillage treatments in all the sampling periods (Fig. 2). In the second year, they observed that at 12 weeks after planting, the root masses under MT and CT were significantly higher than under ZT (Fig. 2). The significantly lower root mass obtained under ZT compared with tilled plots suggested that soil compaction under ZT impeded root development and the growth of the main root axes (Martınez et al., 2008) while conventional tillage increased root penetration (Shirani, Hajabbasi, Afyuni, & Hemmat, 2002). The consistently higher maize root mass observed under MT than under CT and ZT occurred probably because minimum tillage broke the compact soil surface that is often associated with ZT and prevented intense soil perturbation that occurred under CT which could later minimize root growth (Busari & Salako, 2015). This also emphasized the more resilient nature of soil maintained under a minimum tillage system (Lal, 1993) compared with other tillage systems.

Weather conditions in the growing season have been reported to play a part in the success of no-till systems (Wang, Dian-Xiong, Hoogmoed, Oenema, & Perdok, 2006). According to an FAO (2012) report, climate adaptation benefits of no-tillage can be significant. The report stated that during Kazakhstan's 2012 drought and high temperatures, wheat grown under no-till practices were more resilient, leading to yield increases over conventionally cultivated crops. A review by Riley, Berresen, Ekeberg, and Rydberg (1994) indicated that in Norway, better results were often observed under conservation tillage in dry years than in wet years. This could be attributed to greater water storage under conservation tillage. According to Busari and Salako (2013), maize yield under a minimum tillage system is likely to be more sustainable compared with conventional tillage. They added that best crop yield under MT than other tillage methods could be linked with poor root development that is usually associated with low yield under ZT and rapid structural deterioration caused by slaking and dispersion under CT (Guzha, 2004) which were possibly not the case under MT.

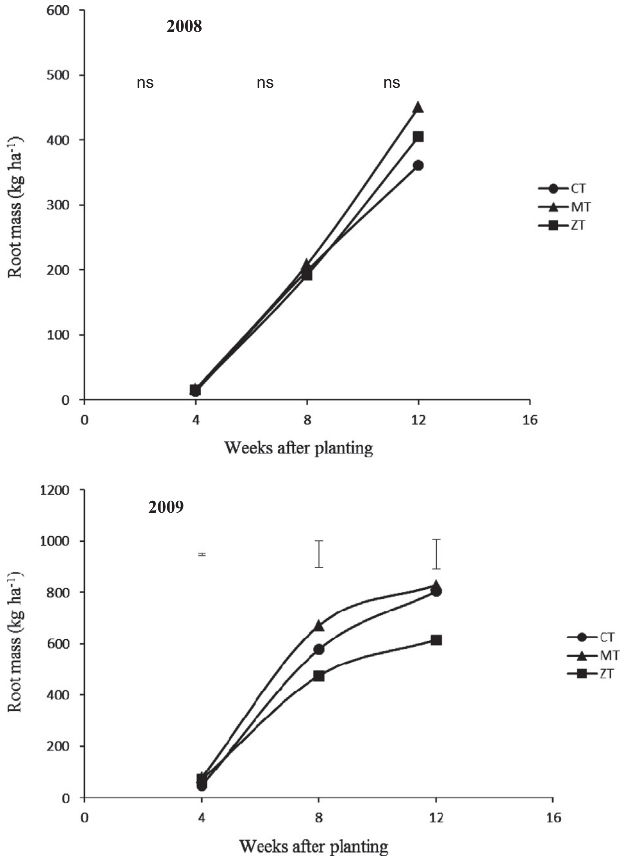

Fig. 2. Effect of tillage on (maize) root mass during the 2008 and 2009 cropping ns = not significant. Vertical lines on data points are LSD ($P \leq 0.05$) bars.
Source: Busari and Salako (2012).

5. Conservation tillage and the environment

5.1. Soil environment

One of the major benefits of conservation tillage is reduction in runoff which normally carries along with it the residual agrochemicals and soil sediments (Kukal, Sur, & Gill, 1991). For instance, the reduction in runoff that is usually associated with zero till plots offers great opportunity to reduce surface and even ground water pollution. Duiker and Myers (2005) reported that the threat of surface water contamination is very small under ZT because of dramatic reduction in erosion (runoff), and because the herbicides are very quickly broken down by soil organisms (which are usually numerous under ZT) into harmless compounds. When such agrochemicals are used in intensively ploughed soil they move more freely beyond the vadose zone compared to how it would be in ploughless soil.

In the USA, it has been reported that no-till practices resulted in reduction of cropland erosion by more than one-third (from 3.1 billion tonnes of soil to 1.9 billion tonnes) between 1982 and 1997 (Claassen, 2012). In the submontaneous tract of Punjab, India, Bhatt and Khera (2006) reported that runoff and soil loss were 5% and 40% higher under CT compared with MT. While Lal et al. (2007) indicated that intensive tillage loosens the soil, it buries the crop residues and exposes the soil to high-intensity rainfall and high wind speeds that lead to severe erosion. Therefore, conservation tillage practices, such as NT and MT were developed to protect the soil from wind and water erosion (Miura et al., 2008).

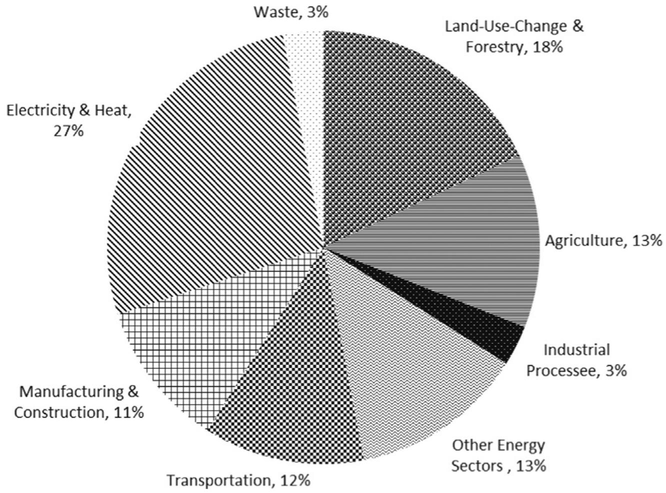

Fig. 3. Sources of global greenhouse gas emissions Adapted from: EarthTrends, 2008; using data from the Climate Analysis Indicators Tool (CAIT).

5.2. Atmosphere

Tillage impact on the atmosphere occurs mainly through emissions of radioactive gases from soil to the atmosphere (Lal et al., 2007). It was reported that about one-third of the global greenhouse gas emission (Fig. 3) is attributed to changes in agriculture and land use, including deforestation in tropical areas, out of which 74% emanated from developing countries (Gattinger, Jawtusch, Muller, & Mäder, 2014). Tubiello et al. (2013) also estimated that in 2010, direct emissions from agriculture contributed 10–12% of global greenhouse gas emissions. It was in the light of this that UNEP (2013) emission gap report identified agriculture as the first of the four sectors that are contributing to national goals and have proven to be efficient in reducing greenhouse gas emissions. The report emphasized the promotion of no-tillage practice if agriculture should play the right role in reducing greenhouse gas emissions.

High carbon sequestration has been given as one of the credits of no-tillage (Lal et al., 2007). Conversion from conventional tillage to no-till has been reported to yield a carbon sequestration rate of 367–3667 kg CO_2 ha^{-1} $year^{-1}$ (Tebrügge & Epperlein, 2011). Gambolati et al. (2005) observed that conservation tillage practices decreased the exposure of unmineralized organic substances to the microbial processes, thus reducing SOM decomposition and CO_2 emission. Apart from C, other greenhouse gases (GHGs) notably, nitrous oxide (N_2O) and methane (NH_4), have been reported to be influenced by tillage regimes (Parkin & Kasper, 2006; Steinbach & Alvarez, 2006). About 38% of the emissions to the atmosphere can be ascribed to nitrous oxide from soils (Bellarby, Foereid, Hastings, & Smith, 2008) while methane is considered as the most potential greenhouse gas after carbon dioxide (IPCC, 2001). Significantly higher N_2O emissions from ploughed than no-tilled sites has been reported by Kessavalou et al. (1998). The higher aeration in tilled soil increases oxygen availability, possibly resulting in increased aerobic turnover in the soil and thus an increased potential for gaseous emissions (Skiba, van Dijk, & Ball, 2002).

6. Conclusion

Soil perturbation by conventional tillage makes the soil serve as a source rather than a sink of atmospheric pollutants and thus is not sustainable and environmentally friendly. However, the international development organizations seem to be in favour of promoting conservation agriculture in general rather than no-tillage exclusively. In fine-textured and poorly drained soils, the use of MT is encouraged while in well-drained soils with light to medium texture and low humus content, the NT seems to be advantageous. Zero or MT is beneficial to soil physical improvement as process of soil physical degradation normally sets in immediately after CT. Research reports indicate that conservation tillage, particularly MT, is better than CT in terms of soil chemical improvement. All available reports are in agreement that soils under conservation tillage are more favoured than CT in terms of soil fauna activities and biological properties improvement. There is emphasis on the importance of transition to NT system on reduction of runoff and maintenance of environmental quality. Also, crop grown with NT has more climate adaptation (e.g. drought and high temperatures) benefits and thereby high yield than those on tilled plots while crops grown on minimum tillage have the benefit of better yield than CT and NT due to breaking of compact layer and moderate soil perturbation.

The potential benefits of conservation tillage along with other practices such as soil cover in reducing carbon and nitrous-oxide emissions to the atmosphere cannot be over emphasized. Therefore, to achieve sustainable food production with minimal impact on the soil and the atmosphere, conservation tillage practices become more important now than ever.

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