Conservation agriculture – a panacea to improve soil physical health

A. K. Indoria*, Ch. Srinivasa Rao, K. L. Sharma and K. Sammi Reddy

ICAR-Central Research Institute for Dryland Agriculture, Hyderabad 500 059, India

Maintenance of soil physical health at its optimum level is essential for sustainable crop production and rational use of natural resources without jeopardizing their quality. The ongoing conventional tillage practices for crop production using intensive ploughing and removal of crop residue from the field have resulted in an increase in surface crusting, soil compaction, soil erosion, decrease in water infiltration and ultimately aggravation of the overall soil physical health deterioration. In recent years, many agricultural scientists across the world have recommended conservation agriculture as a solution to overcome the adverse effects of conventional tillage practices on soil physical health. Conservation agriculture is mainly an integration of three crop management practices, viz. minimum or no-tillage, permanent retention of crop residue and crop rotation. The present data indicates that conservation agriculture can improve soil physical properties and associated processes especially, soil water infiltration and storage, soil aeration, soil structure and soil porosity. It reduces soil erosion, soil compaction and crusting, and optimizes the soil temperatures for successful crop production. This article reviews the role of conservation agriculture in improving soil physical health and its associated processes.

Keywords: Conservation agriculture, conservation tillage, crop residues, crop rotation, soil physical health.

FARMERS are generally well acquainted to practise conventional tillage, which disturbs the soil by repeated ploughing, harrowing, discing and other inter-cultural operations. Although conventional tillage practices help in good seed bed preparation, controlling the weed, and hastening the process of decomposition of soil organic matter and nutrient mineralization, these practices increase soil compaction, soil erosion, salinization and decrease soil organic matter and nutrient content[1]. As a result, the crop production costs rise due to faulty management practices and high-input demand from fertilizers to meet crop requirement in conventional tillage practices.

Conservation agriculture (CA) mainly comprises three crop management principles, viz. minimum or no tillage (minimum soil disturbance), surface residue retention and crop rotation. The effect of CA on crop yield component[2] and its application in various farming perspective[3], is under debate across the world. The existing crop production systems involving repeated tillage and straw removal practices result in surface crusting and soil compaction, which reduce water infiltration and enhance soil erosion, ultimately causing an overall deterioration in soil physical health. However, it is inevitable to maintain soil physical health at its optimum level for sustainable crop production, efficient use of natural resources and improved response to added inputs. This article reviews the role of CA in improving soil physical health and associated processes for successful crop production.

Conservation agriculture and its components

FAO[4] of the United Nations defines CA as a 'concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment'. CA has three principle components, namely: (i) no or minimum soil disturbance through no or minimum tillage; (ii) permanent soil-surface cover through organic residues, and (iii) suitable crop rotations through diversification in the annual crops, by using the shallow and deep-rooted crops or including pulse in crop rotation, and suitable plant species in perennial cropping system. In this review article, we have considered zero tillage or no tillage and reduced tillage or minimum tillage terminologies for conservation tillage as a part of CA. According to FAO[4], conservation tillage 'is a set of practices that leave crop residues on the surface which increases water infiltration and reduces erosion. It is a practice used in CA to reduce the effects of tillage on soil erosion. However, it still depends on tillage as the structure forming element in the soil. Nevertheless, conservation tillage practices such as zero tillage practices can be transition steps towards conservation agriculture'.

Tillage and conservation agriculture

From the farmers' perspective, the main objective of tillage operation is to create a desirable soil surface condition for seedbed preparation and make it suitable for

*For correspondence. (e-mail: akumar.indoria@crida.in)

sowing, planting, inter-culture operation, irrigation, drainage, weed control, harvesting operations, etc. The overall effect of tillage results in loosening of soil depending on the type of soil, soil moisture content at the time of tillage, type of tillage implements and the number of tillage operations[5]. The major harmful impact of excessive long-term tillage is loss of soil structure, possibly due to reduction in soil organic matter and humus content. Therefore, excessive tillage is one of the major factors responsible for decline of soil organic matter and consequently it adversely changes the physical health of the soil[6]. Due to loosening of soil, many soil physical properties such as bulk density, soil penetration resistance, infiltration rate, moisture retention capacity, soil moisture content, air circulation and soil heat distribution may be affected within the soil profile[7,8]. Conventional tillage is reported to increase soil erosion and promote soil degradation, which further causes considerable loss of soil organic matter, and consequently aggravates various soil physical health deterioration[9]. Therefore, it is essential to find an appropriate location-specific and climatic-specific tillage practices to improve soil physical health and crop productivity. In this regard, conservation tillage practices have proved quite effective in controlling soil erosion, increasing soil moisture retention, profile water recharging by increasing water infiltration and conductivity, improving soil organic matter and soil biological properties, thus, ultimately enhancing the overall soil physical health for desirable crop growth conditions[10].

Land cover and conservation agriculture

Conventional practices include either removal of crop residues or its burning in the field. Presently, *in situ* and *ex situ* burning of crop residues has attracted attention in several foras in India. Removal or burning of crop residues adversely affects surface soil properties. The bare soils in conventional tillage are susceptible to particle detachment, transport and resettlement by the action of direct beating of raindrops. It causes surface sealing, and after the rain ceases and surface dries, crusting takes place which increases surface soil compaction. In CA presence of crop residue on the soil surface improves soil physical health and its associated processes, as it (i) decreases the striking impact of raindrops on soil particles; (ii) acts as an insulator for soil and thus minimizes evaporation loss; (iii) decreases the impact of wind erosion; (iv) enhances water productivity; (v) minimizes soil loss and water run-off, and (vi) regulates hydrothermal regime by freeze-thaw and wet-dry cycles. Thus, land cover by crop residue in CA improves long-term productivity[11]. Moreover, during decomposition crop residue releases various chemical compounds and substances, viz. organic mucilages, polysaccharides, humic and aromatic substances, which act as binding agents for different soil particles converting them into stable soil aggregates. Crop residues also enhance the activity of various soil macro and micro-organisms, which further helps to form stable soil aggregates. It is reported that crop residues minimize surface compactness, surface sealing and crusting, and decreases dispersion and breakdown of soil aggregates[12]. A positive impact of crop residue cover in a region depends on bio-physical factors such as soil type, topography, intensity and amount of rainfall, wind speed, temperature, amount and magnitude of soil surface cover by crop residues[13] and prevailing cropping pattern. But is clear that more the land surface cover, greater is the protection of soil physical properties against natural and man-made disturbances[14]. Though land cover by crop residues improves soil physical health and reduces adverse effects of conventional tillage, it is difficult to combine it with other components of conservation agriculture and to afford and manage[15]. According to FAO[4], the area of land surface cover by crop residues should be at least 30% of the total cultivated area measured just after sowing/planting of the subsequent crop. Depending on the magnitude of land surface cover, there are three categories[4], viz. (i) between 30% and 60%, (ii) 61% and 90% and (iii) 91% + surface land cover.

Crop rotation and conservation agriculture

Besides tillage and land cover components of CA, the third important component is crop rotation. The nature and type of crops in crop rotation determines the extent and magnitude to which soil physical health could be modified. In CA, crop rotation (inclusion of shallow and deep rooted crops alternatively and leguminous crops) helps in improving soil structure, organic matter content, water infiltration and its retention in soil and other associated soil properties. Appropriate crop rotation creates various micro and macro-pores or channels that facilitate movement of water, nutrients, and air into the soil, and help in developing of successive crop root growth. Thus, integration of tillage-crop residues with crop rotation in CA may have beneficial impacts on soil physical health. However, the beneficial impacts of crop rotations in terms of improvement in soil physical health depend on factors such as type of legume in cropping system[16], cropping intensification[17], reduced incidence of fallow and the type of tillage[18]. According to FAO[4], any crop rotation should involve at least three different crops alternatively, having shallow and deep rooted systems.

Impact of conservation agriculture on soil physical properties

As already discussed, CA brings desirable changes in many soil physical properties, viz. reduction in water runoff and soil loss, increase in soil water infiltration, and decrease in evaporation loss, just after its inception, while other desirable changes such as improvement in soil structure, porosity, macro-micro fauna activity and organic matter content, occur on a over long-term basis. CA is reported to decrease the impact of many constraints related to soil physical health degradation such as soil compactness, soil structure degradation, soil crusting and declining soil organic matter[19]. Some of the important soil physical health parameters as influenced by CA are described below.

Soil structure

Soil structure can be defined as the manner in which the individual soil particles of sand, silt and clay are bound together in a definite pattern by suitable binding agents. Individual soil particles which bind together and convert into larger particles are called soil aggregates. Aggregate stability against different stresses (water, tillage, etc.) is quite important for assessing the structural stability. After 15 years of practising, zero till and residue retention improved the dry aggregate size distribution compared to conventional tillage[20]. Wet aggregate size and stability also increased in conservation tillage under different types of soil and agro-ecological conditions compared to the conventional tillage[20–22]. The increased aggregate size and its stability in conservation tillage might be due to the presence of organic matter (root fragments) and mycorrhizal hyphae, which act as a binding agent for soil particles[23].

Although in conventional tillage, a good soil structural distribution is present, the aggregate stability is too weak to withstand against irrigation, rainwater and tillage compared to zero tillage with crop residue retention. Because in conventional tillage, soil is tilled several times and the aggregate formation process is disturbed each time resulting in destruction of aggregates[24]. During multiple tillage operations, soil organic matter is redistributed within the soil profile and minor changes in it may affect the formation and stability of soil-aggregates. A high linear correlation was reported between soil organic carbon content and aggregate size[25], and thus proved effective in minimizing the intensity of slaking and disintegration of aggregates when exposed to water[26]. Higher aggregate stability under conservation agriculture is the result of (i) retention of organic residue on soil surface, which reduces detachment and disintegration of the soil aggregates; (ii) decomposing organic matter increases the aggregation process; (iii) no soil disturbance increases the fungal hyphae and soil microbes; and (iv) increase in soil density makes aggregates more resistant to changes. Apart from these, it has also been reported that not only soil microbes but macro-fauna populations also decreased in conventional tillage, compared to conservation agriculture, ultimately decreasing the beneficial effect of macrofauna on soil aggregate formation process[27].

Bulk density

Bulk density of soil reflects the mass or weight of a certain volume of soil. In conventional tillage, soil bulk density decreases depending on the magnitude and intensity of soil manipulation during different tillage operations. It has been reported that soil dry bulk density increased with increase in the number of traffic passes during tillage operations[28]. Besides this, in conventional tillage, irrigation and rainwater also cause an increase in bulk density depending on the amount and frequency of irrigation and rain. Thus, in conventional tillage system, after tilling, soil bulk density decreased for the time being but it again increased due to irrigation and rain[29]. Results obtained in earlier studies depended on soil type, climatic conditions and the period and amount of residue retention in conservation tillage. He *et al.*[30] found that bulk density of soil was higher in conservation tillage during initial few years (up to 5), but after that, lower bulk density was recorded in conservation tillage compared to conventional tillage, suggesting that the effect of conservation tillage on bulk density was not immediate, it takes some years to record the decrease in bulk density compared to conventional tillage. Some researchers have reported a higher soil bulk density in conservation tillage compared to the conventional tillage[31,32] while others have not found significant differences[33,34] or reported lower soil bulk density in conservation tillage with organic residues retention in comparison to conventional tillage[35,36]. No doubt, addition of crop residues in conservation tillage plays a pivotal role in decreasing bulk density, because residue is lighter than mineral matter and its decomposition products promote more aggregation[37,38]. In CA, crop rotation also helped in maintaining lower bulk density compared to conventional farming[39].

Surface seal and soil crust

When raindrops hit the bare soil surface, it causes dispersion, detachment, movement and orientation of fine soil particles that clog soil surface pores forming a thin layer sealing it. After cessation of rain it gets converted to crust restricting entry of water into the soil. The impact of rain on formation of surface seal and crust is high in convention tillage, due to insignificant amount of residues on soil surface. Due to surface sealing and crusting, the movement (or passage) of air in and out of the soil is altered, and the infiltration capacity and conductivity are decreased, resulting in stagnation of water on the soil surface for longer periods enhancing the water runoff and soil loss. Studies revealed that crusted soils reduced water infiltration rate ten-fold as compared to un-crusted soils under stimulated rainfall condition, and after drying, surface seals convert to strong soil crusts[40]. Blanco-Canqui *et al.*[41] observed that soils without surface mulching of crop residue developed a 3 ± 0.7 cm thickness crust and 0.6 ± 0.5 cm width cracks during dry spell. Crust increases the surface bulk density due to consolidation of soil particles, and reduces hydraulic conductivity, which reduces air and water movement, adversely affects heat fluxes, promotes soil erosion and hampers seedling emergence[42]. Permanent soil surface cover by crop residues plays an important role in reducing soil surface seals formation[13]. Cassel *et al.*[43] observed that crop residues on soil surface in no-tillage eliminates the negative impact of surface sealing formation and crusting, even in soils with low organic matter content and high silt percentage[44].

Soil compaction and soil strength

Soil compaction is the process of physical consolidation of soil particles against an applied force, often resulting in destruction of soil structure, reduced porosity, restricted water and air movement hampering root penetration and consequently decreasing crop performance. In agriculture, wheel of heavy farm machineries is the major cause of soil compaction, and the magnitude of compactness increases when tillage operation is carried out at inappropriate soil moisture conditions and a larger number of tillage operations are performed. In conventional tillage, farmers adopt the same equipment and crop sequence every year which consequently develops a plough pan (compact layer) in the sub soil. Cone penetrometer is generally used to assess the compactness in field and the numerical value given by it is called cone index (CI). It directly measures the applied force, required to press the penetrometer into a soil at a desired depth or indirectly it is an index of shear resistance of the soil. Earlier studies reflect that a higher CI value was observed in no-tillage systems compared to conventional tillage systems in upper soil layers (0–20 cm)[45–47] due to various tillage operations. Although higher CI value was recorded below the tilled layer in conventional tillage system, it might have been due to formation of plough pan layers by using the same agricultural implements over the years[48]. Moreover, the CI value in no-tillage system was closely correlated to the soil moisture content, depth of soil and percentage of sand particles, whereas in conventional tillage system, it was closely correlated to the percentage of clay and depth of tillage operations[49]. As crop rotation and addition of crop residues are also important features of the conservation agriculture, data showed that inclusion of pea crop in the cropping system decreased the CI values, whereas inclusion of flax caused increased soil CI values, thus suggesting the role of cropping systems in influencing soil compactness[39]. Other studies highlighted the role of various crop residue additions in no-till system and recorded that addition of *Pisum sativum* crop residues decreased the CI value compared to the addition of *Brassica napus* or *Triticum aestivum* crop residues[48]. It is proved that inclusion of long and strong tap root crops in crop rotation can overcome the soil compaction constraint[50].

Soil profile moisture

Conservation tillage plays a significant role in improving soil moisture availability, especially under low rainfall conditions[51], probably due to mulching effect of stubble and crop residues left on the soil surface. It protects soil surface from direct contact with solar radiations, and acts as barrier to air flow across the soil surface, consequently reducing evaporation loss in un-tilled soils compared to tilled soils[52]. It also improves water infiltration by reducing water runoff[53]. Earlier studies have reported higher water availability in conservation tillage compared to conventional tillage, especially in arid and semi-arid climatic conditions across the world[54–58]. Shaxson and Barber[59] concluded that in conservation tillage, due to higher soil porosity and physical aggregation, there was increase in water infiltration and decrease in surface runoff, which resulted in higher plant-available moisture in the soil. But others have concluded that no-tillage was not very effective for improving soil water content for plants, especially near the soil surface even in low rainfall[60]. Another study in Argentina[61] (based on 35 trials) found that the impact of no-till on soil water content was greater (18 mm water) in semi-arid coarse textured soil, while it was less (9 mm water) in humid fine textured soil, compared plow and reduced tillage, suggesting the role of no-till under limited water condition. They further concluded that on average, about 13–14% higher soil water content was recorded in no-till compared to other tillage practices. Various other reports reflect that higher soil water content in no-tillage might be due to improvement in soil structure, organic matter, infiltration rate, pore characteristics, and decrease in evaporation loss, as a result of reduction in tillage operations[62,63].

Soil hydraulic conductivity

Soil hydraulic conductivity is defined as transmission of water within soil profile against hydraulic gradient. Many factors such as topography, climate and inherent parent materials influence this property, but tillage plays a major role in altering this by instantly altering soil bulk density and porosity. Various studies showed contrasting results on the impact of tillage on soil hydraulic conductivity. Some studies revealed that different tillage practices did not change the hydraulic conductivity, while in some cases there was negative impact[64,65]. Some also concluded that zero tillage practice increased soil hydraulic conductivity compared to the conventional tillage[66,67]. There are also reports of similar values of hydraulic conductivity in no-tillage and conventional tillage[68,69], however, in some cases, no-tillage showed decrease in hydraulic conductivity compared to the conventional tillage[70,71]. One of the reasons reported for improvement in hydraulic conductivity in no-tillage could be the improved pore characteristics of soil such as pore contiunity[72], pore diameter[73] and increase in the number of macropores[66]. In some studies, the role of higher fungal activity and accumulated organic matter by the addition of crop residues, has been highlighted in increasing the hydraulic conductivity[74]. These contradictory and inconsistent results might be due to the extent of soil disturbance, type of soil structure, soil water content, period of different ongoing tillage practices, amount of residue, climate, etc.

Soil infiltration and water retention

Soil infiltration is the downward entry of water from soil surface. It is governed by inherent soil properties, presence of crop residues or vegetation on soil surface, topography, soil moisture content during sampling, etc. However, this property is important for deciding the impact of different tillage practices, conservation practices, irrigation, drainage and suitable land-use of a particular region[75]. Soil water retention capacity is defined as the capacity of soils to hold the water against gravity. CA is generally characterized by higher soil organic matter and improved aggregation and pore size distribution[67], that will help in enhancing soil infiltration and water retention capacity. Many studies concluded that water retention and infiltration capacity increases in zero tillage due to higher amounts of organic matter accumulated by the addition of crop residue and more number of pores, compared to tilled plots across different regions of the world[67,76–79]. Contrary to the above findings, others reported that the infiltration rate decreased in no-tillage systems compared to tilled soil, because of high bulk density and less scope to break the crust in no-tillage[80]. Yet another study indicated that if conservation practices such as minimum tillage, crop rotations, and crop residue retention are systematically followed as a combined system, these can reduce soil crusting and sealing impact, consequently enhancing infiltration and water retention capacity of the soil[81].

Soil porosity

Soil porosity is the ratio of non-solid volume to total volume of soil. In crop production, soil porosity is important to conduct water, air and nutrients into soil. It is a dimensionless quantity and can be written either as a percentage or as a decimal fraction. Total porosity is indirectly measured by using the formula, total porosity (%) = 1 – (bulk density/particle density, i.e. density of soil solid) × 100. Water retained in the soil against the given suction in a specially designed instrument, gives macroporosity of soil, which is generally equal to the volumetric water content when subjected to 33 kPa of suction (field capacity). After assessing macroporosity, it is subtracted from the total porosity for microporosity values. The water held in macropores is easily available for plant roots but that held by micropores is not easily available. Based on the diameter of pores, usually, soil pore diameters larger than about 0.06 mm are called macropores and those smaller than this are termed as micropores. Tillage is the most common factor that influences pore characteristics such as shape, size, volume, continuity, air permeability and total porosity[28]. In general, tillage operations increase the total porosity including macroporosity by reducing the bulk density in the surface layer (0.00–0.05 m), but this effect decreases over time due to further increase in the bulk density by rain or irrigation activities. It has been reported that in conventional tillage system, soil disturbance caused by different tillage implements increased the macroporosity each time but decreased microporosity as compared to the no-tillages systems, it also enhanced the process of formation of different smaller size diameter pores classes[82]. As already mentioned, the effect of tillage decreases over time, and on a long term basis, conventional tillage system results in decrease in both macroporosity and microporosity and increase in bulk density, resulting in less water and nutrient availability[83]. In no-tillage, the higher amount of crop residues received by the soil year after year, enhances the process of formation of stable soil aggregates and increases soil organic matter which might increase both soil resistance and resilience to deformation of pores. Besides, higher biological activity in conservation agriculture practices also improved the soil organic matter status through various micro-organism activities such as fungal-hyphae development, exudates released during bacterial growth, and macro-organism activities such as earthworm or termites, ultimately leading to a more stable soil pore system with improved aggregate size, and facilitates the crop root to explore the soil profile[24,82].

Soil temperature

The available energy for soil heating is calculated by the balance between incoming and outgoing radiation. Higher soil temperatures in hot tropic eco-regions and low soil temperature in temperate eco-regions, are a major constraint to crop production. In many hot tropical eco-regions, it was noticed that after tillage, the soil maximum temperatures exceeded 40°C at 5 cm depth and 50°C at 1 cm during the crop growth period[4]. Obviously, high soil temperatures adversely affect seed germination, crop growth as well as soil micro-organism growth and their mechanism. In conservation agriculture, growing cover crops and retaining crop residues as mulch, helps in moderating and stabilizing the fluctuations in soil temperature during the crop growth period as compared to un-mulched soil. Moreover, different tillage operations in conventional tillage disturb the soil surface each time, increase soil drying and heating, and also increase air pockets, resulting in more moisture loss due to evaporation[84]. One report reveals that zero tillage with residue retention recorded 2–8°C less soil temperature during day time in summer season compared to the conventional tillage[85]. It was also reported that residue retention in zero tillage acts as an insulator against the sharp decline in the soil temperature during night which results in less fluctuation in day and night temperature. Dahiya *et al.*[86] reported that wheat straw mulching decreased the average soil temperature by a magnitude of 0.74°C, 0.66°C, 0.58°C at 5, 15 and 30 cm soil depths respectively, as compared to the un-mulched conditions. Gupta *et al.*[87] reported that zero tillage with residue cover had a lower soil temperature as compared to the zero tillage without residue and mould board ploughing. In hot tropical regions, soil, mulch cover minimizes the peak period of high soil temperatures to a desirable condition, which enhances the various soil biological activities, boosts initial crop growth, root development and overall crop performance[54]. In temperate regions lower soil temperatures create an unfavourable crop growth condition by cooling down the soil, particularly when late frost occurs[88]. A residue free strip was suggested[88,89] in the centre of the alternatively maize row in zero tillage practice, and that the soil surface heat flux and soil temperature were not much different from a conventional tillage system, but were significantly higher than in zero tillage without residue-free strip, suggesting the applicability of zero till in temperate regions.

Water runoff and soil erosion

In agriculture, apart from topography and slope, water runoff and soil erosion occur due to surface and subsurface compactness, crusting and sealing, hardpans, and decreased macropores that hinder water infiltration. Although conventional tillage practices may reduce water runoff and soil erosion for the time being, after some time, this effect is decreased due to formation of soil crust[90] due to irrigation and rain. It has been reported that about 10–25% of rainwater may be lost from ploughed and un-covered soil and about 30–35% lost as evaporation from un-covered soil surface[62,91]. High crop residue addition and growing of cover crops in conservation tillage, decreased the energy impact of water droplets on soil surface and slowed down the processes of detachment, displacement, movement and deposition of soil particles that seal the surface and convert into crust after drying. Both, crop residue and cover crops slow down the velocity of runoff water across the soil surface, provide more opportunity and time for infiltration, and act as surface storage of rain or irrigation water. Simon and Klocke[92] highlighted the role of water infiltration in no-till wheat stubble residues and reported less runoff (0.2 inches) in no-till with wheat stuble soil as compared to ploughed soil (1.7 inches runfoff), when 3 inches of water was applied through rainfall simulator. Lindstrom[93] showed that addition of crop residue in maize crop @ 927, 1853 and 3706 kg ha^{-1}, reduces the runoff by 35.6, 25.4 and 22.9 mm respectively, compared to no-crop residue addition. Data revealed that conventional farming system caused up to 150 t ha^{-1} $year^{-1}$ soil losses in different parts of the world[94].

It is reported that direct crop seeding reduces about 80% of soil erosion, compared to conventional mouldboard ploughing[95]. Similarly, studies in Zimbabwe showed a mean annual soil erosion of 5.1 t ha^{-1} $year^{-1}$ in conventional tillage system, compared to 1.0 t ha^{-1} $year^{-1}$ with mulch ripping system (similar to no-till with residue retention)[96]. Ailincai *et al.*[97] also reported that successive addition of crop residues at the rate of 2471, 4942 and 9884 kg ha^{-1}, decreased soil erosion at the rate of 64%, 85% and 98%, respectively, compared to no-crop residues addition. The results of long-term experiments (1994–2007) from Austria revealed that cover crop in conservation tillage reduced mean soil losses from 6.1 t ha^{-1} $year^{-1}$ to 1.8 t ha^{-1} $year^{-1}$ and it came down to 1.0 t ha^{-1} $year^{-1}$ in direct seed drilling[98]. Ghosh *et al.*[51] reported that mean runoff coefficients and soil loss with conservation agriculture were 45% and 54% less than conventional agriculture plots. Crop rotation in conservation agriculture also significantly reduced soil erosion[97]. Carroll *et al.*[99] reported that soil erosion in mono-crop sunflowers was reduced by adopting the wheat–sunflower crop rotation in zero tilled condition. Further, they reported that zero tillage wheat recorded the lowest average annual water runoff and soil loss compared to the conventional sunflower, suggesting the importance of crop rotation.

CA as an effective measure of mitigation and adaptation to climate change

There are predictions that as a consequence of the climate change, there is high probability of increase in temperature, heavy rainfall, frequent drought, floods, higher rates of green house gas (GHG) emissions, etc. In this context, CA has a vital role to play as mitigation and adaptation for extreme events occurring due to climate change. CA will help in mitigating atmospheric GHGs, by reducing fuel emissions as a result of reduced tillage operation and more sequestering of organic C in soil. According to

Baker *et al.*[100], adoption of conservation tillage in all the crop land could potentially sequester 25 Gt C over the next 50 years, which is equivalent to 1833 Mt CO_2-eq year^{-1}. Thus, adoption of conservation tillage practices can provide a vital path for stabilization of GHG emissions globally.

CA also acts as a strong adaptation strategy to manage extreme climatic events such as wind and water erosion, because in this system soil is protected by crop residues, and not frequently loosened by tillage. Moreover, improved soil aggregation makes it more resistant towards wind and water erosion. Improved soil moisture status and decreased evaporation loss might mitigate drought situations. These practices also help in regulating the extreme temperature flow (heat/frost) in soil by covering the soil surface. Another important beneficial aspect of conservation agriculture is that it can help in improving water infiltration into soil and enhances groundwater recharge with rain water, consequently reducing flood and erosion problems during heavy rainfall. Thus CA practices can contribute significantly to make crop systems more resilient to climate change.

Conclusion

In any crop production system, optimum soil physical health is very important for efficient utilization of nutrients. Water present in soil profile is needed by plant roots and also provides physical support to plants. In conventional tillage system, continuous use of farm machineries over the year develops a sub-surface hardpan, which hampers water movement and root-penetration, resulting in decline in crop performance. Moreover, continuous use of machineries also pulverizes the upper surface making the soil more prone to erosion. In conservation agriculture, successive addition of crop residues over the years increases soil organic matter. In the beginning, the increase in organic matter is confined to the upper soil layer, but over time, it extends to deeper soil layers also. It plays an important role in improving various soil–water characteristics, and stabilizing the soil temperature. In many soils across the world which are low in crop productivity, maintaining permanent soil cover through crop residues and cover crops can help in restorating soil organic matter and consequently improving in soil physical properties. Suitable crop rotation is an important feature of conservation agriculture, which also helps in improving many soil physical properties and reducing soil erosion. The total impact of CA system on soil physical health varies location-to-location and is dependent on soil inherent properties, site limitations, period of time under CA system, per cent soil disturbance, nature of the crop, intensity of the crop rotation, type of cover crops, per cent of total surface area covered by crop residues, soil moisture regime, soil temperature, and other prevailing climatic factors of a particular region. Hence, CA is a site-specific technology and all three components of CA, viz. minimum or no-tillage, crop residue and crop rotation significantly impact soil physical health. Thus, systematic conservation agriculture is a panacea to cure the soil of its many physical health disorders on a long term basis.

1. FAO, *Conservation agriculture-Case studies in Latin America and Africa*, FAO Soil Bulletin 78, Rome, 2001.
2. Brouder, S. M. and Gomez-Macpherson, H., The impact of conservation agriculture on smallholder agricultural yields: a scoping review of the evidence. *Agric. Ecosyst. Environ*., 2014, **187**, 11–32.
3. Stevenson, J. R., Serraj, R. and Cassman, K. G., Evaluating conservation agriculture for small-scale farmers in Sub-Saharan Africa and South Asia. *Agric. Ecosyst. Environ*., 2014, **187**, 1–10.
4. FAO, Agriculture and Consumer Protection Department, Rome, 2007; http://www.fao.org/ag/ca/
5. Tripathi, R. P., Sharma, P. and Singh, S., Soil physical response to multi-year rice wheat production in India. *Int. J. Soil Sci.*, 2006, **12**, 91–107.
6. Rasmussen, P. E. and Collins, H. P., Long-term impacts of tillage, fertilizer and crop residue on soil organic matter in temperate semi arid regions. *Adv. Agron.*, 1991, **45**, 93–134.
7. Acharya, C. L. and Kapur, O. C., Amelioration of soil physical constraints for crop production in hilly areas. *J. Agric. Phys.*, 2001, **1**, 86–92.
8. Mohanty, M., Painuli, D. K., Misra, A. K. and Ghosh, P. K., Soil quality effects of tillage and residue under rice-wheat cropping on a Vertisol in India. *Soil Till. Res.*, 2007, **92**, 243–250.
9. Plante, A. F. and McGill, W. B., Soil aggregated dynamics and retention of organic matter in laboratory-incubated soil with differing simulated tillage frequencies. *Soil Till. Res.*, 2002, **66**, 79–92.
10. Andrews, S. S. *et al.*, On farm assessment of soil quality in California's Central Valley. *Agron. J.*, 2002, **94**, 12–23.
11. Hobbs, P. R., Sayre, K. and Gupta, R., *The Role of Conservation Agriculture in Sustainable Agriculture*, 2008; doi: 10.1098/rstb.2007.2169.
12. Acharya, C. and Sharma, P. D., Tillage and mulch effects on soil physical environment root growth, nutrient uptake and yield of maize and wheat on an Alfisol in north-west India. *Soil Till. Res.*, 1994, **32**, 291–302.
13. Ruan, H. X., Ahuja, L. R., Green, T. R. and Benjamın, J. G., Residue cover and surface-sealing effects on infiltration: Numerical simulations for field applications. *Soil Sci. Soc. Am. J.*, 2001, **65**, 853–861.
14. Blanco-Canqui, H., Lal, R., Post, W. M., Izaurralde, R. C. and Owens, L. B., Soil structural parameters and organic carbon in no-till corn with variable stover retention rates. *Soil Sci.*, 2006, **171**, 468–482.
15. Liang, Y. and Wang, Z., The benefit and prospect of no-till and cropland mulch on water conservation of Loess Plateau in China. In Proceedings of the 12th Conference of International Soil Conservation Organization (ISCO), Beijing, China, 25–31 May 2002.
16. Whitebread, A. M., Blair, G. J. and Lefroy, R. D. B., Managing legume ley residues and fertilizers to enhance the sustainability of wheat cropping systems in Australia. 2. Soil physical fertility and carbon. *Soil Till. Res.*, 2000, **54**, 77–89.
17. Benjamin, J. G., Mikha, M., Nielsen, D. C., Vigil, M. F., Calderon, F. and Henry, W. B., Cropping intensity effects on physical properties of a no-till silt loam. *Soil Sci. Soc. Am. J.*, 2007, **71**, 1160–1165.

18. Halvorson, A. D., Peterson, G. A. and Reule, C. A., Tillage system and crop rotation effects on dry land crop yields and soil carbon in the Central Great Plains. *Agron. J.*, 2002, **94**, 1429–1430.
19. Dalal, R. C. and Bridge, B. J., Aggregation and organic matter storage in Subhumid and Semi-arid soils. In *Advances in Soil Science* (eds Carter, M. R. and Stewart, B. A.), CRC Lewis Publishers, Boca Raton, FL, 1996, pp. 263–307.
20. Govaerts, B. *et al.*, Conservation agriculture as a sustainable option for the central Mexican highlands. *Soil Till. Res.*, 2009, **103**, 222–230.
21. Li, H. W., Gao, H. W., Wu, H. D., Li, W. Y., Wang, X. Y. and He, J., Effects of 15 years of conservation tillage on soil structure and productivity of wheat cultivation in northern China. *Aust. J. Soil Res*., 2007, **45**, 344–350.
22. Lichter, K., Govaerts, B., Six, J., Sayre, K. D., Deckers, J. and Dendooven, L., Aggregation and C and N contents of soil organic matter fractions in a permanent raised-bed planting system in the highlands of Central Mexico. *Plant Soil*, 2008, **305**, 237–252.
23. Bronick, C. J. and Lal, R., Soil structure and management: a review. *Geoderma*, 2005, **124**, 3–22.
24. Six, J., Feller, C., Denef, K., Ogle, S. M., Moraes, J. C. S. A. and Albrecht, A., Soil organic matter, biota and aggregation in temperate and tropical soils – effects of no-tillage. *Agronomie*, 2002, **22**, 755–775.
25. Carter, M. R., Influence of reduced tillage systems on organic-matter, microbial biomass, macro-aggregate distribution and structural stability of the surface soil in a Humid climate. *Soil Till. Res*., 1992, **23**, 361–372.
26. Blevins, R. L., Lal, R., Doran, J. W., Langdale, G. W. and Frye, W. W., Conservation tillage for erosion control and soil quality. In *Advances in Soil and Water Conservation* (eds Pierce, F. J. and Frye, W. W.), Ann Arbor Press, MI, USA, 1998, pp. 51–68.
27. Six, J., Bossuyt, H., Degryze, S. and Denef, K., A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil Till. Res*., 2004, **79**, 7–31.
28. Mamman, E. and Ohu, J. O., The effect of tractor traffic on air permeability and millet production in a sandy loam soil in Nigeria. *Ife J. Technol*., 1998, **8**, 1–7.
29. Osunbitan, J. A., Oyedele, D. J. and Adekalu. K. O., Tillage effects on bulk density, hydraulic conductivity and strength of a loamy sand soil in southwestern Nigeria. *Soil Till. Res*., 2005, **82**, 57–64.
30. He, J., Kuhn, N. J., Zhang, X. M., Zhang, X. R. and Li, H. W., Effects of 10 years of conservation tillage on soil properties and productivity in the farming–pastoral ecotone of Inner Mongolia, China. *Soil Use Manage*., 2009, **25**, 201–209.
31. Ferreras, L. A., Costa, J. L., Garcia, F. O. and Pecorari, C., Effect of no-tillage on some soil physical properties of a structural degraded Petrocalcic Paleudoll of the southern ‘Pampas’ of Argentina. *Soil Till. Res.*, 2000, **54**, 31–39.
32. Moraru, P. I. and Rusu, T., Effect of different tillage systems on soil properties and production on wheat, maize and soybean crop. *Int. J. Bio. Food Vet. Agr. Eng*., 2013, **7**, 689–692.
33. Rusu, T. *et al.*, Implications of minimum tillage systems on sustainability of agricultural production and soil conservation. *J. Food Agric. Environ*., 2009, **7**, 335–338.
34. Calegari, A. *et al.*, Effect of soil management and crop rotation on physical properties in a long term experiment in Southern Brazil. In Proceedings of the 19th World Congress of Soil Science (eds Gilkes, R. and Prakongkep, N.), Australian Society of Soil Science Incorporated, Victoria, Australia, 2010, 6142–6145.
35. Veenstra, J. J., Horwath, W. R., Mitchell, J. P. and Munk, D. S., Conservation tillage and cover cropping influence soil properties in San Joaquin Valley cotton-tomato crop. *Calif Agric.*, 2006, **60**, 146–153.
36. Abid, M. and Lal, R., Tillage and drainage impact on soil quality. I. Aggregate stability, carbon and nitrogen pools. *Soil Till. Res.*, 2008, **100**, 89–98.
37. Acharya, C. L., Hati, K. M. and Bandyopadhyay, K. K., Mulches. In *Encyclopaedia of Soils in the Environment* (eds Hillel, *et al.*), Elsevier, Amsterdam, 2005, 521–532.
38. Shaver, T., Crop residue and soil physical properties. Proceedings of the 22nd Annual central plains irrigation conference, Kearney, NE, Available from CPIA, 760 N. Thompson, Colby, Kansas, 24–25 February 2010.
39. Grant, C. A. and Lafond, G. P., The effect of tillage systems and crop sequences on bulk density and penetration resistance on a clay soil in southern Saskatchewan. *Can. J. Soil Sci.*, 1993, **73**, 223–232.
40. Benyamini, Y. and Unger, P. W., Crust development under stimulated rainfall on four Soils. In *Agronomy Abstracts*, American Society of Agronomy (ASA), Madison, WI, 1984, p. 243.
41. Blanco-Canqui, H., Lal, R., Post, W. M., Izaurralde, R. C. and Owens, L. B., Corn stover impacts on near-surface soil properties of no-till corn in Ohio. *Soil Sci. Soc. Am. J.*, 2006, **70**, 266–278.
42. Baumhardt, R. L., Unger, P. W. and Dao, T. H., Seedbed surface geometry effects on soil crusting and seedling emergence. *Agron. J.*, 2004, **96**, 1112–1117.
43. Cassel, D. K., Raczkowski, C. W. and Denton, H. P., Tillage effects on corn production and soil physical conditions. *Soil Sci. Soc. Am. J.*, 1995, **59**, 1436–1443.
44. Kladivko, E. J., Residue effects on soil physical properties. In *Managing Agricultural Residues* (ed. Unger, P. W.), CRC Press, Boca Raton, FL, 1994, pp. 123–141.
45. Chen, Y., Cavers, C., Tessier, S. and Lobb, D., Short-term tillage effects on soil cone index and plant development in a poorly drained heavy clay soil. *Soil Till. Res*., 2005, **82**, 161–171.
46. Bueno, J., Amiama, C., Hernanz, J. L. and Pereira, J. M., Penetration resistance, soil water content, and workability of grassland soils under two tillage systems. *Trans. ASAE*, 2006, **49**, 875–882.
47. Singh, B. and Malhi, S. S., Response of soil physical properties to tillage and residue management on two soils in a cool temperate environment. *Soil Till. Res.*, 2006, **85**, 143–153.
48. Doan, V., Chen, Y. and Irvine, B., Effect of residue type on the performance of no-till seeder openers. *Can. Biosyst. Eng.*, 2005, **47**, 2.29–2.35.
49. Kumar, A., Chen, Y., Sadek, A. and Rahman, S., Soil cone index in relation to soil texture, moisture content, and bulk density for no-tillage and conventional tillage. *Agric. Eng. Int: CIGR J.*, 2012, **14**, 26–37.
50. Hamza, M. A. and Anderson, W. K., Soil compaction in cropping systems: a review of the nature, causes and possible solutions. *Soil Till. Res.*, 2005, **82**, 121–145.
51. Ghosh, B. N., Dogra, P., Sharma, N. K., Bhattacharyya, R. and Mishra, P. K., Conservation agriculture impact for soil conservation in maize–wheat cropping system in the Indian Sub-Himalayas. *Int. Soil Water Conserv. Res.*, 2015; doi: 10.1016/j.iswcr.2015.05.001
52. Dardanelli, J. L., Ritchie, J. T., Calmon, M., Andriani, J. M. and Collino, D. J., An empirical model for root water uptake. *Field Crop Res.*, 2004, **87**, 59–71.
53. Kroulík, M., Hula, J., Sindelar, R. and Illek, F., Water infiltration into soil related to the soil tillage intensity. *Soil Water Res.*, 2007, **2**, 15–24.
54. Acharya, C. L., Kapur, O. C. and Dixit, S. P., Moisture conservation for rainfed wheat production with alternative mulches and conservation tillage in the hills of north-west India. *Soil Till. Res*., 1998, **46**, 153–163.
55. Lopez-Fando, C., Dorado, J. and Pardo, M. T., Effects of zone-tillage in rotation with no-tillage on soil properties and crop

yields in a semi-arid soil from central Spain. *Soil Till. Res.,* 2007, **95**, 266–276.
56. Mkoga, Z. J., Tumbo, S. D., Kihupi, N. and Semoka, J., Extrapolating effects of conservation tillage on yield, soil moisture and dry spell mitigation using simulation modelling. *Phys. Chem. Earth*, 2010, **35**, 686–698.
57. Jamshidi, A. R., Tayari, E., Jasem Nejad, M. and Neisy, A., Effect of conservation tillage on seeding accuracy and soil moisture content in corn cultivation. *Ind. J. Fund. Appl. Life Sci.*, 2014, **4**, 342–346.
58. Sławiński, C., Cymerman, J., Witkowska-Walczak, B. and Lamorski, K., Impact of diverse tillage on soil moisture dynamics. *Int. Agrophys.,* 2015, **26**, 301–309.
59. Shaxson, T. F. and Barber, R. G., Conservation agriculture. In *Optimizing Soil Moisture for Plant production. The Significance of Soil Porosity* (eds Shaxson, T. F. and Barber, R. G.), FAO Soils Bulletin 79, Rome, 2003, pp. 1–107.
60. Lopez, M. V., Arrue, J. and Sanchez-Giron, L. V. A., Comparison between seasonal changes in soil water storage and penetration resistance under conventional and conservation tillage systems in Aragon. *Soil Till. Res.*, 1996, **37**, 251–271.
61. Alvarez, R. and Steinbach, H. S., A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in Argentine Pampas. *Soil Till. Res*., 2009, **104**, 1–15.
62. Thierfelder, C., Amezquita, E. and Stahr, K., Effects of intensifying organic manuring and tillage practices on penetration resistance and infiltration rate. *Soil Till. Res*., 2005, **82**, 211–226.
63. Bescansa, P., Imaz, M. J., Virto, I., Enrique, A. and Hoogmoed, W. B., Soil water retention as affected by tillage and residue management in semiarid Spain. *Soil Till. Res*., 2006, **87**, 19–27.
64. Obi, M. E. and Nnabude, P. C., The effect of different management practices on the physical properties of a sandy loam soil in southern Nigeria. *Soil Till. Res.*, 1988, **12**, 81–90.
65. Celik, I., Effects of tillage methods on penetration resistance, bulk density and saturated hydraulic conductivity in a clayey soil conditions. *J. Agric. Sci.*, 2011, **17**, 143–156.
66. McGarry, D., Bridge, B. J. and Radford, B. J., Contrasting soil physical properties after zero and traditional tillage of an alluvial soil in the semi-arid subtropics. *Soil Till. Res.*, 2000, **53**, 105–115.
67. Bhattacharyya, R., Prakash, V., Kundu, S. and Gupta, H. S., Effect of tillage and crop rotations on pore size distribution and soil hydraulic conductivity in sandy clay loam soil of the Indian Himalayas. *Soil Till. Res.*, **86**, 129–140.
68. Sauer, T. J., Clothier, B. E. and Daniel, T. C., Surface measurements of the hydraulic properties of a tilled and untilled soil. *Soil Till. Res.*, 1990, **15**, 359–369.
69. Karlen, D. L. *et al*., Long-term tillage effects on soil quality. *Soil Till. Res.*, 1994, **32**, 313–327.
70. Miller, J. J., Sweetland, N. J., Larney, F. J. and Volkmar, K. M., Unsaturated hydraulic conductivity of conventional and conservation tillage soils in southern Alberta. *Can. J. Soil Sci.*, 1998, **78**, 643–648.
71. Evett, S. R., Peters, F. H., Jones, O. R. and Unger, P. W., Soil hydraulic conductivity and retention curves from tension infiltrometer and laboratory data. In *Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media* (eds van Genuchten, M. T., Leij, F. J. and Wu, L.), Part 1, US Soil Salinity Lab, Riverside, CA, 1997, pp. 541–551.
72. Cameira, M. R., Fernando, R. M. and Pereira, L. S., Soil macropore dynamics affected by tillage and irrigation for a silty loam alluvial soil in southern Portugal. *Soil Till. Res.*, 2003, **70**, 131–140.
73. Sharratt, B., Zhang, M. and Sparrow, S., Twenty years of tillage research in subarctic Alaska I. Impact on soil strength, aggregation, roughness, and residue cover. *Soil Till. Res.*, 2006, **91**, 75–81.
74. Logsdon, S. D. and Kaspar, T. C., Tillage influences as measured by ponded and tension infiltration. *J. Soil Water Conserv.*, 1995, **50**, 571–575.
75. Sumathi, I. and Padmakumari, O. P., Modelling infiltration under ponded and simulated rainfall conditions. *Indian J. Soil Conserv.*, 2000, **28**, 98–102.
76. Barzegar, A. R., Yousefi, A. and Daryashenas, A., The effect of addition of different amounts and types of organic materials on soil physical properties and yield of wheat. *Plant Soil*, 2002, **247**, 295–301.
77. Pansak, W., Hilger, T. H., Dercon, G., Kongkaew, T. and Cadisch, G., Changes in the relationship between soil erosion and N loss pathways after establishing soil conservation systems in uplands of Northeast Thailand. *Agric. Ecosyst. Environ*., 2008, **128**, 167–176.
78. Fuentes, M. *et al.*, Fourteen years of applying zero and conventional tillage, crop rotation and residue management systems and its effect on physical and chemical soil quality. *Eur. J. Agron*., 2009, **30**, 228–237.
79. Vidhana, A. L. P., Effect of deep ploughing on the water status of highly and less compacted soils for coconut (*Cocos nucifera* L.) production in Sri Lanka. *Soil Till. Res.*, 2009, **103**, 350–355.
80. Freebairn, D. M., Gupta, S. C., Onstad, C. A. and Rawls, W. J., Antecedent rainfall and tillage effects upon infiltration. *Soil Sci. Soc. Am. J.*, 1989, **53**, 1183–1189.
81. Christian, T., Edgar, A. and Karl, S., Effects of intensifying organic manuring and tillage practices on penetration resistance and infiltration rate. *Soil Till. Res.*, 2006, **82**, 211–226.
82. Moret, D. and Arrue, J. L., Characterizing soil water-conducting macro-and mesoporosity as influenced by tillage using tension infiltrometry. *Soil Sci. Soc. Am. J.*, 2006, **71**, 500–506.
83. Qin, H. L., Gao, W. S., Ma, Y. C., Yang, S. Q. and Zhao, P. Y., Effects of no-tillage on soil properties affecting wind erosion during fallow in Ecotone of north China. *Acta Ecol. Sin.*, 2007, **9**, 3778–3784.
84. Licht, M. A. and Al-Kaisi, M., Strip-tillage effect on seedbed soil temperature and other soil physical properties. *Soil Till. Res.*, 2005, **80**, 233–249.
85. Oliveira, J. C. M. *et al.*, Soil temperature in a sugar-cane crop as a function of the management system. *Plant Soil*, 2001, **230**, 61–66.
86. Dahiya, R., Ingwersen, J. and Streck, T., The effects of mulching and tillage on the water and temperature regimes of a loess soil: Experimental findings and modeling. *Soil Till. Res.*, 2007, **96**, 52–63.
87. Gupta, S. C., Larson, W. E. and Linden, D. R., Tillage and surface residue effects on soil upper boundary temperatures. *Soil Sci. Soc. Am. J.*, 1983, **47**, 1212–1218.
88. Kaspar, T. C., Erbach, D. C. and Cruse, R. M., Corn response to seed-row residue removal. *Soil Sci. Soc. Am. J*., 1990, **54**, 1112–1117.
89. Azooz, R. H., Lowery, B., Daniel, T. C. and Arshad, M. A., Impact of tillage and residue management on soil heat flux. *Agric. Forest Meteorol.*, 1997, **84**, 207–222.
90. Rao, K. P. C., Steenhuis, T. S., Cogle, A. L., Sri, N. S. T., Yule, D. F. and Smith, G. D., Rainfall infiltration and runoff from an Alifisol in semi-arid India. I. No-till systems. *Soil Till. Res.*, 1998, **48**, 51–59.
91. Rockstrom, J., Barron, J. and Fox, P., Water productivity in rainfed agriculture: Challenges and opportunities for smallholder farmers in drought prone tropical agro-systems*.* Paper presented at an IWMI Workshop, Colombo, Sri Lanka, 12–14 November 2001.
92. Simon, J. V. D. and Klocke, N. L., Tillage and crop residue removal effects on evaporation, irrigation requirements, and yield.

In Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, 21–22 February 2012; CPIA, 760 N. Thompson, Colby, Kansas.
93. Lindstrom, M. J., Effects of residue harvesting on water runoff, soil erosion and nutrient loss. *Agric. Ecosyst. Environ*., **16**, 103–112.
94. FAO, The economics of conservation agriculture. Rome, Food and Agriculture Organization of the United Nations, 2001.
95. Thierfelder, C. and Wall, P. C., Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil Till. Res*., 2009, **105**, 217–227.
96. Munyati, M., Conservation tillage for sustainable crop production: Results and experiences from on-station and on-farm research in Natural Region 2 (1988–1996). *Zimbabwe Sci. News*, 1997, **31**, 27–33.
97. Ailincai, C., Jitareanu, G., Bucur, D., Ailincai D., Raus, L. and Filipov, F., Effects of cropping systems on water runoff, soil erosion and nutrient loss in the Moldavian Plateau, Romania, In *Advances in Studies on Desertification* (eds Romero Diaz A. *et al.*), Murcia University, Spain, 2009, pp. 143–146.
98. Rosner, J., Zwatz, E., Klik, A. and Gyuricza, C., Conservation tillage systems-soil-nutrient-and herbicide loss in lower Austria and the Mycotoxin Problem. In Proceedings of 15th International Congress of ISCO, Geographical Research Institute, Budapest, Hungary, 18–23 May 2008, pp. 205–210.
99. Carroll, C., Halpin, M., Burger, P., Bell, K., Sallaway, M. M. and Yule, D. F., The effect of crop type, crop rotation, and tillage practice on runoff and soil loss on a Vertisol in central Queensland. *Aust. J. Soil Res*., 1997, **35**, 925–940.
100. Baker, J. M., Ochsner, T. E., Venterea, R. T. and Griffis, T. J., Tillage and soil carbon sequestration – what do we really know? *Agric. Ecosyst. Environ.*, 2007, **118**, 1–5.

Received 9 July 2015; revised accepted 24 June 2016

doi: 10.18520/cs/v112/i01/52-61