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Impact of conservation agriculture and resource conservation technologies on carbon sequestration–a review

G T PATLE[1], K K BANDYOPADHYAY[2] and D K SINGH[3]

College of Agricultural Engineering and Post Harvest Technology, Gangtok, Sikkim 737 135

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ABSTRACT

Global warming and its consequences are amongst the most serious problems of the present century. Increase in concentration of greenhouse gases (GHGs) in the atmosphere is major cause for global warming. Increase in global concentration of CO_2 is mainly due to fossil fuel consumption, land use change and soil cultivation. Methane and N_2O concentrations are increasing primarily due to dairy and agriculture. Sequestering atmospheric carbon in agricultural soils may partially offset the emission of greenhouse gases from fossil fuel consumption. Conservation agriculture helps in sequestering atmospheric carbon in soil-plant system through change in agricultural operations and management practices. Conservation tillage along with efficient management of inputs, viz. irrigation, fertilizer and pesticides facilitates carbon sequestration in soil-plant system. Land use change and conventional agricultural practices are major contributors to global annual emission of CO_2. Conservation agriculture and recommended management practices (RMPs) collectively are helpful to offset part of the emissions due to unscientific agricultural practices. In India, agriculture contributes about 17 per cent of the country's total GHGs emission. An intensive agricultural practice during the post-green revolution era without caring for the environment has supposedly played a major role towards enhancement of the greenhouse gases. Due to increase in demand for food production the farmers have started growing more than one crop a year through repeated tillage operations using conventional agricultural practices. Increase in carbon emission is the major concern, which is well addressed in kyoto protocol. Nowadays, more emphasis has been given for promotion of conservation agriculture to mitigate the impact of climate change.

Key words: Carbon sequestration, Climate change, Conservation agriculture, GHG emission

One of the major challenges of 21st century is lowering the atmospheric concentration of greenhouse gases (GHGs) at a certain acceptable levels to mitigate the impact of climate change on agriculture and alike sectors due to global warming (Verge *et al.* 2007, Goyal 2004). Increased concentration of key greenhouse gases, viz. carbon dioxide; methane and nitrous oxide in the atmosphere are responsible for global warming (IPCC 2001). Beginning with the industrial revolution the global atmospheric concentrations of these greenhouse gases have increased markedly as a result of human activities (IPCC 2001). The global increase in carbon dioxide concentration is due primarily to fossil fuel consumption; land use and land cover change and deforestation. Similarly, emission of methane and nitrous oxide are primarily due to agriculture (West and Maryland 2002). The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005. It was about 35% higher than a century and a half ago, with the faster growth occurred in the last ten years @1.9 ppm/year in the period 1995-2005 (IPCC 2007). Similarly, the global atmospheric concentration of methane (CH_4) and nitrous oxides (N_2O) has also increased considerably.

According to report of Intergovernmental Panel on Climate Change (IPCC), the global mean surface temperature has increased 0.6 ± 0.2 °C since 1861, and further increase of 1.1 to 6.4 °C is expected by 2100 (IPCC 2007). Kyoto Protocol affirms that part of the CO_2 emissions from fossil-fuel use and from other sources, can be offset by removal of CO_2 from atmosphere via a net increase in the carbon stocks of the biosphere (West and Maryland 2002, Tandon 2008). Soils play a major role in the global carbon(C) budget because they contain more carbon than the atmosphere and plant biomass combined (Wang *et al.* 2010). Sequestering atmospheric carbon in agricultural soils may partially offset

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[1] Assistant Professor (e mail: gtpatle77@gmail.com) Present Address: Division of Agricultural Engineering, Indian Agricultural Research Institute, New Delhi 110 012; [2] Principal Scientist (e mail: kk.bandyopadhyay@gmail.com), Division of Agricultural Physics, Indian Agricultural Research Institute, New Delhi 110 012; [3] Principal Scientist (e mail: dks111@rediffmail.com), Water Technology Centre, Indian Agricultural Research Institute, New Delhi 110 012

fossil fuel emissions (Lal 1999). Conservation agriculture plays a vital role in sequestering carbon in soil-plant system through change in management practices, use of improved cropping systems, less disturbance of soil and hence less disruption of carbon rich soil aggregates and retention of crop residues in soil (Lal and Stewart 2010, Wang *et al.* 2010). Conservation tillage along with efficient management of irrigation, fertilizer and pesticides may increase soil organic carbon by increasing yield and subsequent organic matter (Lal 1999, 2004a).

About 3/4th of the earth's terrestrial carbon is present in the top one meter of soil. Well managed soils have potential to sequester more carbon. Some estimates show that 15% of the fossil fuel emissions of CO_2 could be offset by soil C sequestration alone. Sequestering C in agriculture requires a change in management practices, i e efficient use of pesticides, irrigation, and farm machinery. Lal (2008) reported that soil and crop management now and in the future would play a significant role for sustainable agriculture development. Land use and land cover change and agricultural practices contributes about 20% of the global annual emission of CO_2 (IPCC 2001). But worldwide adoption and promotion of conservation agriculture and recommended management practices (RMPs) have potential to reduce the significant part of green house gas (GHGs) emission through agriculture (Lal 1999, 2004c).

India's mean surface air temperature has increased significantly by about 0.4°C over the past century. According to recent climate model projections, India may experience a further rise in temperature of 1 °C by the year 2050, about four times the rate of warming experienced over the past 100 years (Rae *et al.* 1996). India having a total geographical area of 329 mha produces 4% of global CO_2 emissions and this figure is likely to grow in future. According to the projection given by World Energy Outlook, CO_2 emissions in India would increase @ 4.3% per year and almost tripled between 2005 and 2030 mainly due to energy consumption. Following the IPCC guidelines, methane emissions from rice and livestock are estimated at 17.4 and 12.8 Tg/year, respectively (Rae *et al.* 1996). Agriculture being the mainstream of livelihood of more than 70% peoples in the country, plays a significant role in GHGs emission due to conventional agricultural practices. Due to increase in the demand for food production, the farmers have started growing more than one crop a year which involves repeated tillage resulting in land degradation, unscientific agricultural practices and increase in use of different inputs such as seed, fertilizer, chemicals and agricultural machinery. All these require excessive use of energy thus contributing to the global warming. Now-a-days more emphasis has been given in the country for promotion of conservation agriculture to mitigate the impact of climate change.

Worldwide studies have suggested significant reduction in GHGs emissions through transforming conventional agriculture to conservation agriculture and use of recommended management practices in agriculture (Lal 1999, 2008a, Marland *et al.* 2003, Franzluebbers 2005, Meyer-Aurich *et al.* 2006b). An attempt has been made in this paper to review worldwide studies to assess the impact of conservation agriculture on carbon sequestration relevant to Indian context.

CO_2 level in atmosphere and climate change

Climate change is defined as any change over the time, whether due to natural variability or from human activity. Climate change alters the composition of global atmosphere and causes natural climatic variability. Atmosphere surrounding the earth is made up of nitrogen (78%), oxygen (21%) and the remaining 1%, is made up of trace gases that include carbon dioxide, methane, nitrous oxide and water vapours. These gases, also called greenhouse gases which act as a blanket and trap heat radiating from the earth and make the atmosphere warm. Beginning with the industrial revolution global atmospheric concentrations of these greenhouse gases have increased markedly as a result of human activities (IPCC 2001). Carbon dioxide is mainly responsible for heating the global atmosphere. The concentration was about 280 ppm in the19th century and at present it is 380 ppm and expected to rise to 550 ppm at the end of 21st century. Impact of climate change can be seen on agriculture in terms of shifting of sowing time, decrease in length of growing season, decrease in yield due to increase in temperature, changes in plant metabolic activity and decrease in production and productivity, losses due to flood, drought, famines etc (Kumar *et al.* 2004).

Role of global carbon cycle and carbon pool

Carbon cycle is the basis for greenhouse gas emission and global warming (GW). Knowledge of C cycle and its perturbation by anthropogenic activities is important for developing viable strategies for mitigating climate change. Global carbon cycle is a budgetary statement of different components including pools and fluxes which plays a significant role in identifying sources and sinks of carbon. The future rate of increase in atmospheric CO_2 concentration depends on the anthropogenic activities, the interaction of bio-geochemical and climate processes on the global C cycle and interaction among principal C pools. Carbon is stored in our planet in the following major pools, viz. oceanic pool (38000Pg), geologic pool (5000Pg), pedologic pool/soil C pool (2500Pg), atmospheric pool (760Pg) and biotic pool (560Pg) (Lal 2011). Carbon is stored in ocean in the form of bi-carbonates of dissolved carbon such as calcium carbonate and shells in marine organisms. Geologic pools stores the carbon in the lithosphere as fossil fuels and rock deposits such as limestone, dolomite and chalk etc. Oceanic pool is the largest C pool followed by geologic, pedologic, atmospheric and biotic global C pools. Although ocean stores most of the earth's carbon, soil contains approximately 75% of the carbon pool on land, which is three times more than amount stored in living plants and animals.

Soil carbon storage facts

Carbon is an important part of life on earth. It is found in all living organisms and is the major building block for life on earth and moves through the atmosphere, oceans, plant, soil and earth in short and long term cycles over a time. Carbon pools act as storage houses for large amount of carbon. Any movement of carbon between these carbon pools is called a flux. Some of the important aspects of carbon pools and fluxes are listed below.

1. Soil plays a major role in maintaining balance between global carbon cycle through sequestration of atmospheric carbon as soil organic carbon.
2. Soils store about three times as much carbon as the terrestrial vegetation.
3. Soil C pool comprises soil organic carbon (SOC) and soil inorganic carbon (SIC) pool.
4. Measured rates of soil C sequestration through adoption of recommended management practices (RMPs) range from 50-1000 kg/ha/year.
5. Estimated global potential of SOC sequestration through recommended management practices (RMPs) range from 0.9 ± 0.3 Pg C/year which is $1/4^{th}$ -$1/3^{rd}$ of annual increase in atmospheric CO_2 rate (3.3 Pg C/year).
6. Cumulative C sequestration potential is 30-60 Pg over 25-50 year.
7. SOC concentration is low in the soils of arid region and high in the soils of temperate region and is much more in the organic or peat soil. SOC is more in cool and moist than warm and dry regions (Lal 2004c). There is great possibility to sequester more SOC in cool and temperate regions and SIC in dry arid regions.

Principle behind the process of carbon sequestration

Carbon sequestration may be defined as the long-term storage of carbon in oceans, soils, vegetation and geologic formations. Carbon exists in many forms, predominately as plant biomass, soil organic matter, and as carbon dioxide (CO_2) gas in the atmosphere and dissolved in seawater. Through the process of photosynthesis, plants assimilate carbon and return some of it to the atmosphere through respiration. The carbon that remains as plant tissue is then consumed by animals or added to the soil as litter when plants die and decompose. The primary way by which carbon is stored in the soil is as soil organic matter (SOM). SOM is a complex mixture of carbon compounds, consisting of decomposing plant and animal tissue, various microbes and carbon associated with soil minerals. Carbon can remain stored in soils for millennia, or be quickly released back into the atmosphere. Climatic conditions, natural vegetation, soil texture, and drainage, all affect the amount and length of time carbon is stored.

Importance of carbon sequestration

Carbon sequestration builds soil fertility, improves soil quality, improves agronomic productivity, protect soil from compaction and nurture soil biodiversity. Increased organic matter in soil, improves soil aggregation, which in turn improves soil aeration, soil water storage, reduces soil erosion, improves infiltration, and generally improves surface and groundwater quality. This enhanced soil health, facilitates use of agricultural inputs in an efficient manner and helps in sustaining agricultural productivity at higher level. It is also helpful in the protection of streams, lakes, and rivers from sediment, runoff from agricultural fields, and enhanced wildlife habitat. Besides these, it has major roles in mitigating GHG gas emissions and tackling the effects of climate change.

What is Conservation Agriculture?

Conservation agriculture (CA) is scientific practice of agriculture utilizing resource conservation/efficient technologies to save and conserve the natural resources, increase the production and productivity while concurrently conserving the environment. Principle of conservation agriculture can be stated considering the three main processes as described by FAO.

1. Minimal soil disturbance: disturbed area must be less than 15 cm wide or 25% of cropped area (whichever is lower). No periodic tillage that disturbs a greater area then aforementioned limits.
2. Soil cover: Ground cover must be more than 30%.
3. Crop rotation: Rotation should involve at least three different crops. However, monocropping is not an exclusion facto.

Conservation Agriculture (CA) aims

1. To conserve, improve and make more efficient use of natural resources.
2. To integrate the management of available soil, water and biological resources combined with external inputs.
3. It contributes to environmental conservation as well as to enhanced and sustained agricultural production.
4. It can also be referred to as resource-efficient/resource effective agriculture.

Forms of conservation agriculture

Major forms of conservation agriculture includes

- Minimum, reduced or no tillage
- Crop and pasture rotation
- Contour farming and strip cropping
- Cover and green manure cropping
- Fertility management
- Erosion control
- Agro-forestry and alley cropping
- Organic and biodynamic farming
- Stubble mulching
- Integrated nutrient management (INM)

- Integrated pest management (IPM)
- Irrigation management

Benefits of conservation agriculture

Benefits of CA are of several folds. Direct benefits to farmers include reduced cost of cultivation through savings in labour, time and farm power, fuel and improved use efficiency resulting in reduced use of inputs. More importantly, CA practices reduce resource degradation. Gradual decomposition of surface residues improves soil organic matter status, biological activity and diversity and contributes to overall improvement in soil quality. CA is a way to reverse the processes of degradation inherent in conventional agricultural practices involving intensive cultivation, burning and/or removal of crop residues, etc. CA leads to efficient use of water and nutrients by improving nutrient balance and availability, infiltration and retention by the soil, reducing water loss due to evaporation and improving the quality and availability of ground and surface water.

Conservation agriculture and resource conservation technologies (RCTs)

Conservation agriculture and RCTs are meaningly same with little difference. RCTs are those practices applied in agriculture which enhance resource or input-use efficiency. For example new varieties that use nitrogen more efficiently may be considered RCTs. Zero or reduced tillage practices that save fuel and improve plot-level water productivity may also be considered RCTs, as may land leveling practices that help save water. In contrast, conservation agriculture practices will only refer to the RCTs with the following characteristics:

- Soil cover, particularly through the retention of crop residues on the soil surface
- Sensible, profitable crop rotations
- A minimum level of soil disturbance

Role of conservation agriculture in SOC sequestration is possible either by maximizing the carbon input or minimizing the soil carbon loss. Various management approaches to sequester carbon from atmosphere to biosphere are suggested by Franzlubbers (2008) for maximizing the carbon input (Table 1). Carbon sequestration rate varies with plant characteristics, rotation sequence, type and frequency of tillage, fertilizer management in terms of rate, timing and placement of fertilizers in the soils and integrated management of pest and nutrients, crop and livestock etc.

Table 1 Different conservation methods for carbon sequestration

Conservation method	Characteristics
Plant selection	✓ Species, cultivar, variety ✓ Growth habit (perennial/annual) ✓ Rotation sequence ✓ Biomass energy crops
Tillage	✓ Type ✓ Frequency
Fertilization	✓ Rate, timing, placement ✓ Organic amendments
Integrated management	✓ Pest control ✓ Crop/livestock systems

*Source:*Franzluebbers (2008)

Different field practices, farm operations and agricultural input used in the process of crop production emits significant amount of CO_2 to the atmosphere (Lal 2004b). Gifford (1984) has classified agricultural practices into primary, secondary and tertiary sources with reference to their C emission capacity. Primary sources of C emissions are either due to mobile operations (e g tillage, sowing, intercultural, harvesting and transport) or stationary operations (e g pumping water, grain drying and milling). Secondary sources of C emission comprise manufacturing, packaging and storing fertilizers and pesticides. Tertiary sources of C emission include acquisition of raw materials and fabrication of equipment and farm buildings, etc. Therefore, reducing emissions implies enhancing use efficiency of all these inputs by decreasing losses, and using other C-efficient alternatives (Lal 2004b). Emissions of CO_2 from agriculture are generated from three sources: machinery used for cultivating the land, production and application of fertilizers and pesticides, and the SOC that is oxidized following soil disturbance (Lal 2004b, West and Marland 2002). More intensive land use might involve more fuel, farm machinery and agrochemicals and the production, packaging, transportation and application of these requires significant energy resources leading to an increase in GHG emissions (Vlek *et al.* 2003, Chauhan *et al.* 2005, Maraseni *et al.* 2010a,b, Maraseni and Cockfield 2011). Use of fertilizers and pesticides applied varies among crop types, crop rotations, and tillage practices. Lal (2004b) reported that C emissions 2-20 kg CE/ha for different tillage operations, 1-1.4 kg CE/ha for spraying chemicals, 2-4 kg CE/ha for seeding and 6-12 kg CE/ha for combine harvesting. Similarly, estimates of C emissions in kg CE/kg for different fertilizer nutrients are 0.9-1.8 for N, 0.1-0.3 for P_2O_5, 0.1-0.2 for K_2O.

Impact of irrigation on carbon emission

In India irrigation has played key role in achieving the green revolution. After independence irrigated area has increased from 22 mha to 87.26 mha in which groundwater has made significant contribution in increasing agriculture production in India. Its importance can be realized by the facts that about 61 per cent of net irrigated area in the country is irrigated by groundwater (CWC 2010). However, large scale development and utilization of groundwater in various parts of India has caused depletion of groundwater resources resulting in increase of gray and dark areas in the country. Groundwater irrigation is a very C intensive practice. Pumping of water from aquifers requires lot of energy for lifting the water. Emission of CO_2 is mainly through consumption of diesel/petrol. The energy required to pump water depends on numerous factors including total dynamic head (based on water lift, pipe friction, and system pressure), the water flow rate and the pumping system efficiency (Whiffen 1991, Franzluebbers and Francis 1995). The energy use depends on the water table depth or the lift height. The supplemental irrigation used for crop production ranges from 250 to 500 mm per season (Franzluebbers and Francis 1995). The C emission ranged from 7.2 to 425.1 kg CE/ha for 25 cm of irrigation and from 53.0 to 850.2 kg CE/ha for 50 cm of irrigation. Schlesinger (1999) estimated C emission from irrigation at 220-830 kg CE/ha/year. Follett (2001) estimated C emission by pump irrigation at 150–200 kg CE/ha/year depending on the source of energy. Tube wells are commonly used for irrigation in Punjab, India. Energy use depends on the water table depth, which in some areas is falling at the rate of 0.5 m/year. In comparison, irrigation of winter wheat in Punjab, India, by tube well was estimated to emit 3–25 kg CE/ha (Singh *et al.* 1999).

Impact of agrochemicals on carbon emission

Use of agrochemicals in agricultural production has increased tremendously in India during the green revolution period. Agrochemicals include nitrogenous, phosphoric and potasic fertilizers including many micro-nutrients (plant growth regulators) required for plant growth and chemicals in the form of herbicides, insecticides, fungicides. The production, packaging, storage and transportation of these agrochemicals require energy and thus they contribute to GHG emissions (Bhat *et al.* 1994). Improper use can be a major environmental hazard and a principal source of pollution. Pimentel (1980) estimated that energy required for production, formulation, packaging and transport of various pesticides (Mcal/kg of the active ingredient) ranged from 63 to 100 for fungicides, 61 to 87 for insecticides and 28 to 65 for herbicides. The average energy required for production of pesticides was 67 Mcal/kg of a.i. West and Marland (2002) estimated 4.4, 4.6 and 4.8 kg CE/kg a.i. for production, packaging and transport of herbicides, insecticides and fungicides. Similar to fertilizers, identifying strategies of integrated pest management (IPM) is important to reducing C emissions from pesticide use. Lal (2004b) reported C emission in relation to production, packaging, storage and distribution of fertilizers as 0.9-1.8 kg CE/kg N, 0.1-0.3 kg CE/kg P_2O_5, 0.1-0.2 kg CE/kg K_2O and 0.03-0.23 kg CE/ kg of $CaCO_3$. Helsel (1992) reported that out of the total energy used in agriculture globally, 51% is expended in farm machinery manufacturing and 45% in the production of chemical fertilizer. Verge *et al.* 2007 reported that more than 50% of the applied N is either lost through leaching into the soil or released into the atmosphere as nitrous oxide (N_2O) which has 298 times more global warming potential than CO_2 (IPCC 2007). Resource conservation technologies (RCTs) can play a vital role in reducing the quantum of these agrochemicals in agriculture and on the other hand GHG emissions due to production, packaging, storage, transportation.

Impact of N-fertilizer application on N_2O emissions

N_2O is responsible for 6% of observed global warming (Dalal *et al.* 2003). Most of the N_2O emissions come from N fertilizer usage and soil disturbances. Lack of oxygen or limited oxygen supply in the soil or high oxygen demand due to more carbon food in the soil causes micro-organisms to utilize nitrate (NO_3) and nitrite (NO_2) instead of oxygen. As a result of this de-nitrification process, the applied N-fertilizer is released as N_2O into the atmosphere (Dalal *et al.* 2003). The IPCC set a default emission factor of 1.25% N_2O–N emissions/kg of applied N. The level of emissions is directly related to N-fertilizer amounts; the higher the N fertilizer use, the greater the emissions of N_2O and thus the higher the CO_2e feed back to the atmosphere.

Impact of tillage on carbon emission

Tillage is defined as the mechanical manipulation of soil performed for seed bed preparation. This prime field operation involves maximum energy, time and cost. Direct and indirect emission of CO_2 takes place during the tillage operations in term of fossil fuel consumption and due to soil disturbance, respectively. Consumption of fuel is the major source of CO_2 emission during seed bed preparation and sowing of the seeds. Conventional tillage usually involves the use of ploughing, while reduced tillage involves using disks or chisels, without the use of plough. No-till leaves the soil undisturbed. Many studies carried all over the world has reported that the fuel requirement varies with the depth of ploughing, soil types, nature of operation, type of implement used, horse power requirement and speed of tractor (Schrock *et al.* 1985, Bowers 1989, Rautare 2003, Lal 2004b). Koller (1996) reported that the diesel fuel consumption was 49.4 l/ha for moldboard plow, 31.3 l/ha for chisel plow, 28.4 l/ha for disk plow, 25.2 l/ha for ridge plant and 13.4 l/ha for no-till system of seedbed preparation. Thus, reduction in fuel consumption in comparison with plough-based tillage system was 37% for chisel plow, 43% for disk plow, 49% for ridge plant and 73% for no-till. Each liter of diesel produces 2.698 kg CO_2e during its combustion and thus the total GHG emissions during the production and combustion of one liter of diesel is 3.15 kg CO_2e.

The data in Table 2 show that the average C emission is 15.2 kg CE/ha for moldboard plowing, 11.3 kg CE/ha for sub-soiling, 8.3 kg CE/ha for heavy tandem disking, 7.9 kg CE/ha for chiseling, 5.8 kg CE for standard disking, 4.0 kg CE/ha for cultivation and 2.0 kg CE/ha for rotary hoeing.

Conservation tillage and carbon sequestration

Several studies compare soil organic carbon (SOC) in conventional and conservation tillage systems. The results

Table 2 Tillage operations and average C emission

Tillage operation	Equivalent carbon emission (kg CE/ha)	
	Range	Mean SD
Moldboard plowing	13.4–20.1	15.2±4.1
Chisel plowing	4.5–11.1	1 7.9±2.3
Heavy tandem disking	4.6–11.2	8.3±2.5
Standard tandem disking	4.0–7.1	5.8±1.7
Sub-soiler	8.5–14.1	11.3±2.8
Field cultivation	3.0–8.6	4.0±1.9
Rotary hoeing	1.2–2.9	2.0±0.9

Source: Lal 2004b

Table 3 Average net carbon flux for US with changes in tillage practices

	Conventional tillage (kg C/ha/year)	No-tillage (kg C/ha/year)
C emission from soil	0	–337
C emission from farm machinery	+69	+23
C emissions from agricultural inputs	+99	+114
Net C flux	+168	–200
Relative net C flux	0	–368

Source: West and Marland (2002)

from analysis suggest that switching from conventional cultivation to zero till would clearly reduce on-farm emissions. VandenBygaart *et al.* (2003) found that reduced tillage increases the amount of carbon sequestered by an average of 320-150 kg C/ha in 35 studies of western Canada and that the removal of fallow enhanced soil carbon storage by 150-60 kg C/ha based on 19 Studies. West and Marland (2002) reported that carbon emission from conventional tillage (CT), reduced tillage (RT) and no tillage (NT) were respectively 72.02, 45.27, 23.26 kg C/ha in case of corn cultivation and 67.45, 40.70, 23.26 kg C/ha for soybean cultivation based on annual fossil fuel consumption and CO_2 emission from agricultural machinery. Thus there was 67.70% and 65.41% reduction in CO_2 emission as compared to conventional tillage for corn and soybean cultivation respectively. West and Marland (2002) reported that no-till emitted less CO_2 from agricultural operations than did conventional tillage and estimated that net relative C flux, following a change from CT to NT on non-irrigated crops was –368 kg ha. Mosier *et al.* (2006) reported that based on soil C sequestration, only NT soils were net sinks for GWP and economic viability and environmental conservation can be achieved by minimizing tillage and utilizing appropriate levels of fertilizer.

West and Marland (2002) estimated the average net C flux for U.S. at +168 kg C/ha/year due to CT practices. The net C flux following a change from CT to NT was –200 kg C/ha/year. Thus, the total change in the flux of CO_2 to the atmosphere, following a change from CT to NT on non-irrigated crops, was expected to be about –368 kg C/ha/year (Table 3).

In India, zero-till drills, strip till drills, roto till drills are used for direct drilling of wheat after paddy. Comparative study of zero till, strip trill and roto-till was carried out and their performance was compared with conventional tillage (Table 4). In no-till plots, fuel consumption was found to be 11.30 l/ha as compared to 34.62 l/ha by conventional method resulting in fuel saving of 24 l/ha. There was 67 % saving in fuel due to no-tillage as compared to conventional method (Table 4). Jat (2007) for rice-wheat system reported that the crop yield was comparable under flat bed and raised bed sown wheat and paddy and was equal to the yield obtained by conventional method.

For promotion and adoption of conservation agriculture(CA) on large scale, research is being carried out in India by Indian Council of Agricultural Research (ICAR), State Agricultural Universities (SAUs) and CIMMYT's Rice-wheat consortium. A good number of machines such as no-till drill, strip till drill, raised bed planter, laser land leveler, straw cutter cum incorporator, straw baler, farm residue collector, straw combine have been developed and are being propagated (Tandon 2008). Lal (2004) reported that, conversion of conventional tillage to minimum tillage or no tillage practices can lead to drastic reductions in C emissions.

Impact of tillage and crop rotations on carbon sequestration

Crop rotations with combination of tillage sequestered

Table 4 Comparative performance of Conservation tillage methods with conventional tillage method

Particular	No-tillage seeding	Strip tillage seeding	Seeding with roto–till drill	Conventional tillage (3 passes + leveling)
Time required(h/ha	3.23 (70.15)*	4.17(61.46)	3.45(68.1)	10.82
Fuel used (l/ha)	11.30(67.36)	17.80(49.45)	13.80(60.14)	34.62
Operational energy (MJ/ha)	648.96(67.16)	1001.76(49.31)	783.60(60.34)	1976.11
Cost of operation Rs/ha	639.54(66.39)	979.95(48.50)	807.30(57.58)	1903.04

*Numbers in parentheses indicate percentage saving compared to conventional tillage.
Source: Routray (2003)

more soil carbon compared to monocropping under different climatic conditions (Meyer-Aurich *et al.* 2006, Yang and Kay 2001, Sainju *et al.* 2006, Mandal *et al.* 2007, Campbell *et al.* 1995.

Meyer-Aurich *et al.* (2006) conducted the experiment with two levels of tillage and eight different corn-based crop rotations. Continuous alfalfa rotation had the highest sequestration rates at 513 kg C/ha/year. Studies showed that soils cultivated with continuous corn and the rotations involving cereals had carbon levels between the highs noted for rotations with alfalfa and the lows for rotations with soybeans. The integration of legumes into corn-based cropping systems provides multiple benefits, including higher yields, cost savings, carbon sequestration, and the mitigation of GHGs. Meyer-Aurich *et al.* (2006) reported highest carbon storage after 20 years where alfalfa was planted continuously and lowest in the corn–corn–soybean– soybean rotation. Carbon storage of soils in the corn–corn–alfalfa–alfalfa rotation was significantly higher than in the corn–corn–soybean–soybean rotation. Rotations, which included cereals and red clover, had soil carbon levels which were between those observed for continuous alfalfa and a corn–corn–soybean–soybean rotation. The continuous alfalfa rotation had the highest sequestration rates at 513 kg C/ha/year than soils cultivated with continuous corn.

Cropping and pasture systems were compared for soil organic C in Georgia. Soil organic C was greater near the soil surface under pasture than under conservation-tilled cropland, which was greater than under conventional-tilled cropland. In several field experiments, crop rotation including legume crops found to be more beneficial for carbon sequestration. Under zero-tillage simulated carbon sequestration was generally much higher and was estimated to reach 0.83Mg C/ha/year in a winter cereal–spring cereal–rape rotation (Fig 1).

Impact of RMPs on carbon sequestration

Lal (2004a) has suggested following recommended management practices over traditional practices in order to soil organic sequestration (Table 5.). Therefore, conversion to restorative land uses (e g afforestation, improved pastures) and adoption of recommended management practices (RMP) can enhance SOC and improve soil quality. Important RMP for enhancing SOC include conservation tillage, mulch farming, cover crops, and integrated nutrient management including use of manure and compost, and agro-forestry.

Agro-forestry has importance as a carbon sequestration strategy because of carbon storage potential in its multiple plant species and soil as well as its applicability in agricultural lands and in reforestation. Proper design and management of agro-forestry practices can make them effective carbon sinks (Montagnini and Nair 2004, Bhadwal and Singh 2002). Average carbon storage by agroforestry practices has been estimated as 9, 21, 50, and 63 Mg C/ha in semiarid, sub-humid, humid, and temperate regions. For smallholder agroforestry systems in the tropics, potential C sequestration rates range from 1.5 to 3.5 Mg C/ha/yr (Montagnini and Nair 2004). Another indirect avenue of C sequestration is through the use of agro-forestry technologies for soil conservation, which could enhance C storage in trees and soils. Agro forestry systems with perennial crops may be important carbon sinks.

Doraiswami *et al.* (2007) reported that rate of soil erosion was highest with conventional tillage and it reduced with

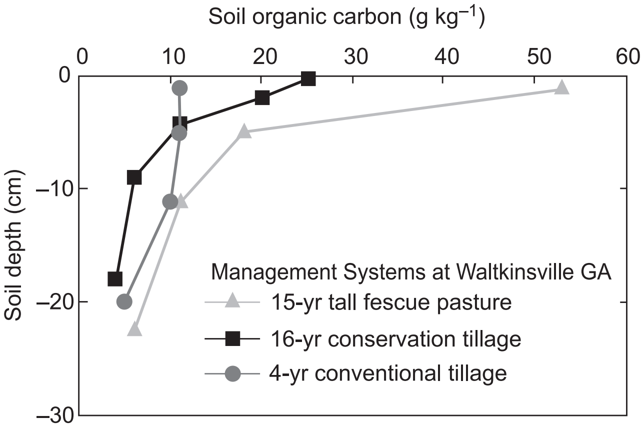

Fig 1 Distribution of soil organic C under conventional tillage, conservation tillage, and pasture
Source: Franzluebbers (2008)

Table 5 Comparison between traditional methods and recommended management practices

Traditional methods	Recommended management practices (RMPs)
Biomass burning and residual removal	Residue return as surface mulch
Conventional tillage and clean cultivation	Conservation tillage, no till and mulch farming
Bare/idle fallow during off-season	Growing cover crops during off-season
Continuous monoculture	Crop rotations with high density
Low input subsistence farming and soil fertility mining	Judicious use of off-farm input
Intensive use of chemical fertilizers	Integrated nutrient management with compost, bio-solids and nutrient cycling, precision farming
Intensive cropping	Integrated trees and livestock with crop production
Surface flood irrigation	Drip, furrow or sub irrigation
Indiscriminate use of pesticides	Integrated pest management
Cultivating marginal soils	Conservation reserve programme, restoration of degraded soils through land use change

Source: Lal (2004a)

adoption of ridge tillage. Further ridge tillage with increased fertilizer and crop residues lowers the rate of erosion and consequently increased SOC at the end of 25th year (Table 6). Ghosh *et al.*(2009) reported that soil quality management in the fragile ecosystem of North-East India should include permanent pasture grasses, particularly, setaria, congosignal, and Makunia having better soil binding through an extensive root system. These grasses improved soil physical properties and reduced soil erosion by ~33% and also signified ecological benefits through C-sequestration. Pathak *et al.* (2011) reported that combination of NPK+FYM have good potential in C sequestration in Indian soils and mitigating GHG emission without any additional cost. It also increased yield. Thus FYM application was a 'win–win' technology increasing farm income and also sequestering C.

Impact of tillage and crop residues on carbon sequestration

The impacts of conservation tillage and crop residues combination have shown the remarkable potential in C sequestration as compared to conservation tillage alone. Conservation agriculture, based on the use of crop residue mulch and no till farming can sequester more SOC through conserving water, reducing soil erosion, improving soil structure, enhancing SOC concentration, and reducing the rate of enrichment of atmospheric CO_2 (Lal 2004a). Doraiswamy *et al.* (2007) found that ridge tillage in combination with fertilizer and crop residue is very effective in SOC sequestration through erosion control. Crop rotations alone with conventional tillage can increase the rate of carbon sequestration, and with conservation tillage the rate is much higher than earlier (Gaisera *et al.* 2009). Franzluebbers (2008) reported that greater soil organic C accumulation under pastures than under annual crops due to longer growing periods, more extensive root system, and less soil disturbance. Ghimire *et al.* (2008) reported that SOC sequestration could be increased with minimum tillage and surface application of crop residue and SOC sequestration was highest in top 0-5 cm soil depth irrespective of the tillage and crop residue management practices. Suman *et al.* (2009) reported that changes in residue management and incorporation of organic manures may help in carbon sequestration by restoring soil organic carbon (SOC). Sugarcane cropping (one plant + four ratoons) increased SOC by 2.3–17.1 tonnes/ ha over initial content with different treatments at the end of five years study.

Table 6 Effect of management practices on soil erosion and SOC sequestration

Management practices	Erosion (Mg/ha/yr)	Soil Organic C (Mg/ha/yr)
Conventional tillage (CT)	16.5	–0.023
CT with increased fertilizer	15.0	–0.006
Ridge tillage (RT)	6.6	0.001
RT with increased fertilizer	5.9	0.027
RT with fertilizer and residues	3.5	0.086

Source: Doraiswamy *et al.* (2007)

Effectiveness of conservation agricultural system in terms of soil organic carbon (SOC) sequestration has described by Franzluebbers (2008). In all three scenarios, SOC sequestration under conservation agriculture was 0.15 Mg C/ ha/yr. However, compared to conventional system, SOC sequestration rate increased to 0.25 Mg C/ha/yr in Scenario A due to declined rate of SOC by 0.10 Mg C/ha/yr under conventional agricultural practices following degradation from a previously elevated condition. In Scenario B (the most often presumed condition), SOC sequestration was same under conservation agriculture as that observed without comparison with conventional agriculture because soil organic C under conventional agriculture was at a steady-state condition. In Scenario C, SOC sequestration was improved under conventional agriculture by other practices similar to that under conservation agriculture (Fig 2).

The soil (0-50cm depth) retained 8.24 kg C/m^3 under no-tillage practice, which was significantly higher than under conventional tillage treatment (7.86 kg C/m^3). Crop residue treatment in no-tillage soils sequestered significantly higher amount of SOC than any other treatments in the top 15 cm soil depths (Ghimire *et al.* 2008) (Table 7). Thus it was revealed that SOC sequestration could be increased with minimum tillage and surface application of crop residue. Crop residue served as a source of carbon for these soils especially in upper soil depths. No-tillage practice minimizes exposure of SOC from oxidation, ensuring higher SOC sequestration in surface soils of no-tillage with crop residue application.

David *et al.*(2009) estimated annual N_2O and CH_4 emissions from different tillage treatments and their global

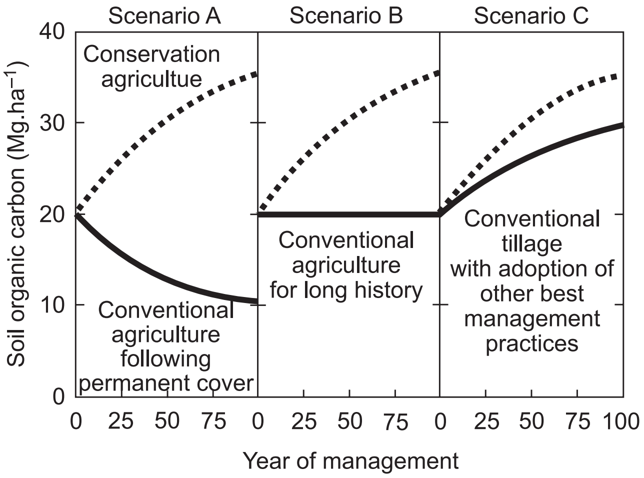

Fig 2 SOC content under conservation agriculture and different baseline of conventional agriculture (*Source:* Franzluebbers 2008)

Table 7 SOC affected by interaction of tillage × crop residue management on different soil depth of Nepal

Soil depth (cm)	Soil organic carbon(kg/cm^2)				LSD
	CT		N T		
	Mo	M1	Mo	M1	
0-5	11.01	12.12	12.73	14.23	1.72
5-10	8.53	10.83	10.08	10.94	1.72
10-15	7.13	9.26	10.11	8.06	1.72
15-30	4.63	5.73	5.80	4.82	1.72
30-50	4.43	4.90	4.69	3.99	1.72
0-50	7.15	8.57	7.81	8.68	0.77

CT, Conventional tillage; NT, no tillage

Mo, No crop residue M1 crop residue@ 4 tonnes/ha for each crop in the rotation

Source: Ghimire *et al.* 2008

warming potential (GWP) and observed that annual N_2O flux was significantly more from chisel till(CT) (1.96 kg N_2O-N/ha/year than MT (1.82 kg) and NT (0.94 kg N_2O-N/ha/year treatment (Table 8). The N_2O emitted were equivalent to 1690, 1825 and 875 kg CO_2 e/ha/year for CT, MT, NT. Net CO_2 emission and global warming potential were in NT was 48 and 52% lower than those from MT and CT respectively (Table 8).

Tillage generally disrupts aggregation and exposes particulate organic matters (POM) which decompose quickly by microbial action. Reduced C sequestration in chisel till compared to no tillage (NT) is due to differences in aggregates and aggregate associated carbon. Study revealed that concentration of fine iPOM (intra aggregate POM) was less in chisel till (CT) compared to NT macro aggregates. On a whole soil basis, fine iPOM C was 51% less in CT than NT and accounted for 21% total carbon difference between NT and CT. The concentration of free light fraction (LF) was not affected by tillage but was on average 45% less in CT than native vegetation (Six *et al.* 1999). Lal (2004a) reported that permanent pasture has the highest C sequestration potential (Table 9).

Table 8 Annual N_2O and CH_4 emissions from different tillage treatments and their global warming potential (GWP)

Treatment	Nitrous oxide (kg/ ha/year)		Total GWP (kg/ha/year)		Methane ((kg/ha/year)
	N_2O	CO_2 (equiv.)	CH_4	CO_2 (equiv.)	
Moldboard till (MT)	1.82	1 690.3	2.76	84.6	1 775
Chisel till (CT)	1.96	1 824.6	2.27	69.6a	1 894
No-till (NT)	0.94	874.5	0.32	9.81	865

Source: David *et al.* (2009)

Table 9 Estimates of global soil carbon sequestration potential

Land use	Soil carbon sequestration potential (Pg C/year)
World cropland	0.43-0.57
Desertification control	1.0
Desertification control	0.2-0.4
Soils of tropics	0.28- 0.54
World soil	0.4-0.8
Permanent pasture	1.87

Source: Lal (2004a)

Obstacles to adoption of conservation agriculture by farming community

- SOC sequestration requires input of crop residues/bio-solids and fertilizers/manures to enhance biomass production. However there is alternate competing demands of these inputs
- Sometimes it becomes difficult to handle crop residues during sowing and other farm operations
- Farmers may have to incur extra expenditure, at least at the initial stage, while adopting conservation agricultural practices
- There are challenges to manage weeds under conservation agricultural practices
- Increased cost for herbicides are involved to control weeds and there may involvement of additional expenditure
- There are challenges to update farm machinery to cater to the need of conservation agricultural practices

Conclusions

From above reviews, it is concluded that agriculture significantly impacts the environment and practicing conservation agriculture and other resource conservation technologies can play a significant role in SOC sequestration by increasing soil carbon sinks, reducing GHG emissions, and sustaining agricultural productivity at higher level. Conservation agriculture sequesters maximum soil organic carbon near soil surface layer. Adoption of conservation agriculture with use of crop residues mulch, efficient crop rotation and no till farming and efficient use of of agricultural inputs help to conserve moisture, reduce soil erosion and enhance SOC sequestration. Rate and amount of SOC sequestration differ with soil types, depths; land use and land cover and varies from one region to another. Sequestration of carbon in soil can improve soil health and improvement in soil health will help in improving input use efficiency in agriculture. Thus sequestering carbon in soil and biota can mitigate climate change as a win-win strategy.

In future research work may be carried out in the following aspects to unravel the details of soil management practices on carbon sequestration.

- Standardization of soil organic C sequestration rate and their cost effectiveness under various RMPs
- Combine study of field sampling and simulation modeling for better estimates of soil organic carbon
- Determination of cost of soil C sequestration under different land uses and soil/vegetation/water management practices.
- Standardization of site specific conservation agricultural practices for enhancing carbon sequestration and crop yield.

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