No-tillage Seeding in Conservation Agriculture

Second Edition

C.J. Baker, K.E. Saxton, W.R. Ritchie, W.C.T. Chamen, D.C. Reicosky, M.F.S. Ribeiro, S.E. Justice and P.R. Hobbs

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C.J. Baker and K.E. Saxton

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17 Reduced Environmental Emissions and Carbon Sequestration

Don C. Reicosky and Keith E. Saxton

While tillage agriculture contributes significant greenhouse gases detrimental to the atmosphere, no-tillage agriculture will reduce them by both storing new SOM and reducing the oxidation of existing SOM.

Introduction

Agriculture affects the condition of the environment in many ways, including impacts on global warming through the production of 'greenhouse gases', such as CO_2 (Robertson *et al.*, 2000). In 2004, the US Environmental Protection Agency (EPA) estimated that agriculture contributed approximately 7% of the US greenhouse gas emissions (in carbon equivalents, CE), primarily as methane (CH_4) and nitrous oxide (N_2O). While agriculture represents a small but relevant source of greenhouse gas emissions, it has the potential, with new practices, to also act as a sink by storing and sequestering CO_2 from the atmosphere in the form of soil carbon (Lal, 1999). Estimates of the potential for agricultural conservation practices to enhance soil carbon storage range from 154 to 368 million metric tons (MMTCE), which compare to the 345 MMTCE of reduction proposed for the USA under the Kyoto Protocol (Lal *et al.*, 1998). Thus, agricultural systems can be manipulated for the dual benefits of reducing greenhouse gas emissions and enhancing carbon sequestration. The influence of agricultural production systems on greenhouse gas generation and emission is of interest as it may affect potential global climate change. Agricultural ecosystems can play a significant role in production and consumption of greenhouse gases, specifically, CO_2.

Conservation tillage reduces the extent, frequency and magnitude of mechanical disturbance caused by the mouldboard plough, reduces the air-filled macropores and slows the rate of carbon oxidation. Any effort to decrease tillage intensity and maximize residue return should result in carbon sequestration for enhanced environmental quality.

Tillage-induced Carbon Dioxide Emissions

Tillage or soil preparation has been an integral part of traditional agricultural production. Tillage is also a principal agent resulting in soil perturbation and subsequent modification of the soil structure with soil degradation. Intensive tillage can adversely affect soil structure and cause excessive breakdown of aggregates, leading to potential soil movement via erosion. Intensive tillage causes soil degradation through carbon loss and tillage-induced greenhouse gas emissions, mainly CO_2, which have an impact on productive capacity and environmental quality.

Intensive tillage decreases soil carbon. The large gaseous losses of soil carbon following mouldboard ploughing compared with relatively small losses with no-tillage have shown why crop production systems using mouldboard ploughing have resulted in decreased SOM and why no-tillage or direct-seeding crop production systems are stopping or reversing that trend (Reicosky and Lindstrom, 1993). Reversing the trend of decreased soil carbon with less tillage intensity will be beneficial to agriculture as well as the global population through better control of the global carbon balance (Reicosky, 1998).

Emission measurements

The tillage studies reported in this chapter were conducted in west central Minnesota, USA, on rich soils high in soil organic carbon (Reicosky and Lindstrom, 1993, 1995; Reicosky, 1997, 1998). The CO_2 flux from the tilled surfaces in these studies was measured using a large, portable chamber, described by Reicosky (1990) and Reicosky *et al.* (1990), in the same manner as described by Reicosky and Lindstrom (1993) and Reicosky (1997, 1998). Measurements of CO_2 flux were generally initiated within 1 minute after the tillage pass and continued for various times. The CO_2 flux from the soil surface was measured using the large, portable chamber described by Reicosky and Lindstrom (1993).

Briefly, the chamber, with mixing fans running, was placed over the tilled surface or the no-tilled surface, the chamber lowered and data collected for 1 s intervals for a total of 60 s to determine the rate of CO_2 and water vapour increases inside the chamber. The chamber was then raised, calculations completed and the results stored on computer floppy disk.

The data included the time, plot identification, solar radiation, photosynthetically active radiation, air temperature, wet bulb temperature, output of the infrared gas analyser measuring CO_2 and water vapour concentrations in the same airstream. After the appropriate lag and mixing times, data for a 30 s calculation window were selected to convert the volume concentrations of water vapour and CO_2 to a mass basis and then regressed as a function of time using linear and quadratic equations to estimate the gas fluxes. These fluxes represent the rate of CO_2 and water vapour increase within the chamber from a unit horizontal land area as differentiated from a soil surface basis caused by differences in soil roughness. Only treatment differences in respect of tillage methods, tillage type or experimental objectives are described, with the results.

Tillage and residue effects

Recent studies, involving the dynamic chamber described above, various tillage methods and associated incorporation of residues in the field, indicated major carbon losses immediately following intensive tillage (Reicosky and Lindstrom, 1993, 1995). The mouldboard plough had the roughest soil surface, the highest initial CO_2 flux and maintained the highest flux throughout the 19-day study. High initial CO_2 fluxes were more closely related to the depth of soil disturbance that resulted in a rougher surface and larger voids than to residue incorporation. Lower CO_2 fluxes were caused by tillage associated with low soil disturbance and small voids, with no-tillage having the least amount of CO_2 loss during 19 days.

The large gaseous losses of soil carbon following mouldboard ploughing (MP) compared with relatively small losses with no-tillage (NT) or direct seeding have shown why crop production systems using mouldboard ploughing have decreased SOM and why no-tillage or direct-seeding crop production systems are stopping or reversing that trend. The short-term cumulative CO_2 loss was related to the soil volume disturbed by the tillage tools. Lower CO_2 fluxes were caused by tillage associated with low soil disturbance and small voids, with no-tillage having the least amount of CO_2 loss during 19 days. Similarly, Ellert and Janzen (1999) used a single pass with a heavy-duty cultivator that was relatively shallow and a small dynamic chamber to show that fluxes from 0.6 hours after tillage were two- to fourfold above the pre-tillage values and rapidly declined within 24 hours of cultivation. They concluded that short-term influences on tillage and soil carbon loss were small under semi-arid conditions, in agreement with Franzluebbers *et al.* (1995a, b).

On the other hand, Reicosky and Lindstrom (1993) concluded that intensive tillage methods, especially mouldboard ploughing to 0.25 m deep, affected this initial soil flux differently and suggested that improved soil management techniques can minimize the agricultural impact on global CO_2 increase. Reicosky (2001b) further demonstrated the effects of secondary tillage methods and post-tillage compaction in decreasing the tillage-induced flux. Apparently, severe soil compaction decreased porosity and limited the CO_2 flux after plough tillage to that of the no-tillage treatment.

This concept was further explored when Reicosky (1998) determined the impact of strip tillage methods on CO_2 loss after five different strip tillage tools were used in row-crop production and no-tillage. The highest CO_2 fluxes were from mouldboard plough and subsoil shank tillage. Fluxes from both slowly declined as the soil dried. The least CO_2 flux was measured from the no-tillage treatment. The other forms of strip tillage were intermediate, with only a small amount of CO_2 detected immediately after the tillage operation. These results suggested that the CO_2 fluxes appeared to be directly and linearly related to the volume of soil disturbed. Intensive tillage fractured a larger depth and volume of soil and increased aggregate surface area available for gas exchange, which contributed to the vertical gas flux. Narrower and shallower soil disturbance caused less CO_2 loss, suggesting that the volume of soil disturbed must be minimized to reduce carbon loss and the impact on soil and air quality. The results also suggest that the environmental benefits and carbon storage of strip tillage compared with broad-area tillage need to be considered in soil management decisions.

Reicosky (1997) reported that average short-term CO_2 losses 5 hours after the use of four conservation tillage tools were only 31% of that of the mouldboard plough. The mouldboard plough lost 13.8 times as much CO_2 as the soil area not tilled, while different conservation tillage tools lost an average of only 4.3 times. The benefits of residues on the soil surface to minimize erosion and smaller CO_2 loss following conservation tillage tools are significant and suggest progress in developing conservation tillage tools that can enhance soil carbon management. Conservation tillage reduces the extent, frequency and magnitude of mechanical disturbance caused by the mouldboard plough and reduces the large air-filled soil pores to slow the rate of gas exchange and carbon oxidation.

Reicosky *et al.* (2002) have shown that removal of maize stover as silage for 30 years of continuous maize, compared with returning the residue and removing only the grain, resulted in no difference in the soil carbon content after 30 years of mouldboard ploughing. Fertility level had no observable effect on CO_2 losses. The tillage-induced CO_2 flux data represented the cumulative gas exchange for 24 h for all treatments.

The pre-tillage CO_2 flux from the same area not tilled averaged 0.29 g $CO_2/m^2/h$ for the high-fertility plots at the start of measurements. This contrasts with the largest cumulative flux after tillage of 45 g $CO_2/m^2/h$ on a low-fertility grain plot. The CO_2 flux showed a relatively large initial flux immediately after tillage and then rapidly decreased 4 to 5 hours after tillage. The CO_2 flux decrease continued as the soil lost CO_2 and dried out to 24 hours, when values were lower but still substantially higher than those from the no-tillage treatment. The flux 24 h after tillage on the same plots above was approximately 3 g $CO_2/m^2/h$, considerably higher than the pre-tillage value.

The temporal trend was similar for all treatments, suggesting that the physical release controlled the flux rather than the imposed experimental treatments. The consistency of the C : N ratio across all four treatments suggests little effect of residue removal or addition and that mouldboard ploughing masked the effects of residue removal as silage or grain removal and above-ground stover returned. Intensive tillage with the mouldboard plough overshadowed any residue management aspects and resulted in essentially the same lower carbon content at the end of 30 years. The results suggest that intensive tillage with a mouldboard plough may overshadow any beneficial effect of residue management (return or removal) that might be considered in a cropping system.

Strip tillage and no-tillage effects on CO_2 loss

The impact of broad-area tillage on soil carbon and CO_2 loss suggests possible improvements with mulch between the rows and less intensive strip tillage to prepare a narrow seedbed, as well as no-tillage. Reicosky (1998) quantified short-term tillage-induced CO_2 loss after the use of strip tillage tools and no-tillage. Various strip tillage tools, spaced at 76 cm, were used and gas exchange measured with a large portable chamber. Gas exchange was measured regularly for 6 hours and then at 24 and 48 hours. No-tillage had the lowest CO_2 flux during the study and mouldboard ploughing had the highest immediately after tillage, which declined as the soil dried. Other forms of strip tillage had an initial flush related to tillage intensity, which was intermediate between these extremes, with both the 5 and 24 hour cumulative losses related to the soil volume disturbed by the tillage tool.

Reducing the volume of soil disturbed by tillage should enhance soil and air quality by increasing soil carbon content. These results suggest that soil and environmental benefits of strip tillage should be considered in soil management decisions. Limited tillage can be beneficial and do much to improve soil and air quality, minimize runoff to enhance water quality and minimize the greenhouse effect. The energy savings represent an additional economic benefit associated with less disturbance of the soil. The results suggest environmental benefits of strip tillage over broad-area tillage, which need to be considered when making soil management decisions.

The CO_2 flux as a function of time for each tillage method for the first 5 hours showed that mouldboard ploughing had the highest flux, which was as large as 35 g $CO_2/m^2/h$ and then rapidly declined to 6 g $CO_2/m^2/h$ 5 hours after tillage. The second largest CO_2 flux was 16 g $CO_2/m^2/h$ following subsoil shanks, which also slowly declined. The least CO_2 flux was measured from the no-tillage treatment, with an average flux of 0.2 g $CO_2/m^2/h$ for the 5 hour period. Other forms of strip tillage were intermediate and only a small amount of CO_2 was detected immediately after some tillage operations, which ranged from 3 to 8 g $CO_2/m^2/h$ and gradually declined to approach no-tillage values within 5 hours. These results suggest a direct relationship between the magnitude of the CO_2 flux that appears to be related to the volume of soil disturbed.

The cumulative CO_2 losses calculated by integrating the flux as a function of time for both 5 and 24 h periods showed similar trends. The values for 24 hours may be subject to error due to the long time between the last two measurements and tillage-induced drying, which may have caused the tilled treatments to dry out faster than the no-tillage treatments. The cumulative flux for the first 5 hours after tillage for mouldboard ploughing was 59.8 g CO_2/m^2, decreasing to 31.7 g CO_2/m^2 for the subsoil shank to a low of 1.4 g CO_2/m^2 for the no-tillage treatment. The strip tillage methods had slightly more CO_2 loss than no-tillage. Similarly, the cumulative data for the 24 h period reflect the same trend, the maximum release by mouldboard ploughing, 159.7 g CO_2/m^2, decreasing to 7.2 g CO_2/m^2 for no-tillage. The other forms of strip tillage were intermediate between these, which paralleled the 5 hour data. The results suggest that cumulative CO_2 loss was directly related to the soil volume disturbed by the tillage tool. The narrower and shallower soil disturbance caused less CO_2 loss.

The cross-sectional areas of the soil disturbed by the tillage were estimated from field measurements drawn to scale, using graphical techniques. The drawings were then cut out and run through an area meter. The cumulative CO_2 fluxes for 24 hours were then plotted as a function of these soil areas disturbed and showed a nearly linear relationship between the 24 hour cumulative CO_2 flux and the soil volume disturbed by tillage. These results suggest that intensive tillage fractured a larger depth and volume of soil and increased aggregate surface area available for gas exchange. This increased soil porosity and area for gas exchange contributed to the vertical flux, which was largest following mouldboard ploughing.

The results of short-term CO_2 loss from the strip tillage study for row crops suggest that, to minimize the impact of tillage on soil and air quality, the volume of soil disturbed must be minimized. Tilling the soil volume necessary to get an effective seedbed and leaving the remainder of the soil protected and undisturbed to conserve water and carbon to minimize soil erosion and CO_2 loss should be the preferred strategy. Limited tillage can be beneficial and do much to improve soil and air quality, minimize runoff to enhance water quality and minimize the greenhouse effect. The energy savings represent an additional economic benefit associated with less disturbance of the soil (West and Marland, 2002; Lal, 2004). The results suggest that the environmental benefits of strip tillage over broad-area tillage need to be considered when making soil and residue management decisions.

The concept that each soil has a finite carbon storage capacity is being revisited. This has important implications for soil productivity and the potential of using soil to enhance soil carbon storage and reduce greenhouse gases in the atmosphere. Most agricultural and degraded soils can provide significant potential sinks for atmospheric CO_2. However, soil carbon accumulation does not continue to increase with time with increasing carbon inputs but reaches an upper limit or carbon saturation level, which governs the ultimate limit of the soil carbon sink (Goh, 2004). The relation between no-tillage and conservation tillage in the way they affect soil carbon stocks is open to further debate and definition of carbon pools.

The relationship between tillage-induced changes in soil structure and subsequent effect on carbon loss was reviewed by Six *et al.* (2002) within the framework of a newly proposed soil C-saturation concept. They differentiated SOM that is protected against decomposition by various mechanisms from that which is not protected and discussed implications of changes in land management for processes that affected carbon release. This new model defined a soil C-saturation capacity, or a maximum soil carbon storage potential, determined by the physicochemical properties of the soil, and was differentiated from models that suggested soil carbon stocks increased linearly with carbon inputs. Presumably, this carbon saturation capacity will be soil-, climate- and management-specific. This causes a change in the thinking about carbon sequestration and that a soil-dependent natural limit may exist in both natural and managed systems.

Superimposed on this analysis is the role of glomalin, a sticky substance produced by fungal hyphae that helps glue soil aggregates together (Nichols and Wright, 2004). No-tillage is one management practice that has been successful in increasing the hyphal fungi that produce glomalin. The next researchable challenge will be to determine if the carbon saturation and glomalin over the entire profile in no-tillage and conservation tillage systems are substantially different. Presumably with less tillage-induced breakdown of soil aggregates, no-tillage may have an advantage over other forms of conservation tillage. The final answer awaits further research.

Carbon Sequestration Using No-tillage

Conservation agriculture is receiving much global focus as an alternative to the use of conventional tillage systems and as a means to sequester soil organic carbon (SOC) (Follett, 2001; Garcia-Torres *et al.*, 2001). Conservation agriculture can work under many situations and is cost-effective from a labour standpoint. More importantly, the practices that sequester soil organic carbon contribute to environmental quality and the development of a sustainable agricultural system. Tillage or other practices that destroy SOM or cause loss and result in a net decrease in soil organic carbon do not result in a sustainable agriculture. Sustainable agricultural systems involve those cultural practices that increase productivity while enhancing carbon sequestration. Crop residue management, conservation tillage (especially no-tillage), efficient management of nutrients, precision farming, efficient management of water and restoration of degraded soils all contribute to a sustainable agriculture.

Kern and Johnson (1993) calculated that conversion of 76% of the cropland planted in the USA to conservation tillage could sequester as much as 286 to 468 MMTCE over 30 years and concluded that US agriculture could become a net sink for carbon. Lal (1997) provided a global estimate for carbon sequestration from conversion of conventional to conservation tillage that was as high as 4900 MMTCE by 2020. Combining economics of fuel cost reductions and environmental benefits derived by converting to conservation tillage are positive first steps for agriculture towards decreasing carbon emissions into the atmosphere.

Soil tillage practices are of particular significance for the carbon status of soils because they affect carbon dynamics directly and indirectly. Tillage practices that invert or considerably disturb the surface soil reduce soil organic carbon by increasing decomposition and mineralization of biomass due to increased aeration and mixing plant residues into the soil, exposing previously protected soil organic carbon in soil aggregates to soil fauna, and by increasing losses due to soil erosion (Lal, 1984, 1989; Dick *et al.*, 1986a, b; Blevens and Frye, 1993; Tisdall, 1996). Conversely, long-term no-tillage or reduced tillage systems increase soil organic carbon content of the soil surface layer as a result of various interacting factors, such as increased residue return, less mixing and soil disturbance, higher soil moisture content, reduced surface soil temperature, proliferation of root growth and biological activity and decreased risks of soil erosion (Lal, 1989; Havlin *et al.*, 1990; Logan *et al.*, 1991; Blevens and Frye, 1993; Lal *et al.*, 1994a, b).

Cambardella and Elliott (1992) observed for a loam soil that the soil organic carbon content in the 0 to 20 cm depth was 3.1, 3.5, 3.7 and 4.2 kg/m^2 for bare fallow, stubble mulch, no-tillage and native sod, respectively. They observed that tillage practices can lead to losses of 40% or more of the total soil organic carbon during a period of 60 years. Edwards *et al.* (1992) observed that conversion from mouldboard plough tillage to no-tillage increased soil organic carbon content in the 0 to 10 cm layer from 10 g/kg to 15.5 g/kg in 10 years, an increase of 56%. Lal *et al.* (1998) stated:

> A summary of the available literature indicates that the soil organic carbon sequestration potential of conversion to conservation tillage ranges from 0.1 to 0.5 metric tons ha^{-1} yr^{-1} for humid temperate regions and from 0.05 to 0.2 metric tons ha^{-1} yr^{-1} for semi arid and tropical regions.

They further estimated that the soil organic carbon increase may continue over a period of 25 to 50 years, depending on soil properties, climate conditions and management.

Carbon sequestration in the soil has benefits beyond removal of CO_2 from the atmosphere. No-tillage cropping reduces fossil fuel use, reduces soil erosion and enhances soil fertility and water-holding capacity. Beneficial effects of conservation tillage on soil organic carbon content, however, may be short-lived if the soil is ploughed, even after a long time under conservation tillage (Gilley and Doran, 1997;

Stockfisch *et al.*, 1999). Stockfisch *et al.* (1999) concluded that organic matter stratification and accumulation as a result of long-term minimum tillage were completely lost by a single application of inversion tillage in the course of a relatively mild winter. Tillage accentuates carbon oxidation by increasing soil aeration and soil residue contact, and accelerates soil erosion by increasing exposure to wind and rain (Grant, 1997). Several experiments in North America have shown more soil organic carbon content in soils under conservation tillage compared with plough-tillage seed beds (Doran, 1980; Doran *et al.*, 1987; Rasmussen and Rohde, 1988; Havlin *et al.*, 1990; Tracy *et al.*, 1990; Kern and Johnson, 1993; Lafond *et al.*, 1994; Reicosky *et al.*, 1995).

Similar to the merits of no-tillage reported in North America, Brazil and Argentina (Lal, 2000; Sa *et al.*, 2001), several studies have reported a high potential for soil organic carbon sequestration in European soils. In an analysis of 17 European tillage experiments, Smith *et al.* (1998) found that the average increase of soil organic carbon, with a change from conventional tillage to no-tillage, was 0.73 ± 0.39% per year and that soil organic carbon may reach a new equilibrium in approximately 50 to 100 years. Analysis of some long-term experiments in Canada (Dumanski *et al.*, 1998) indicated that soil organic carbon can be sequestered for 25 to 30 years at a rate of 50 to 75 g carbon/m^2/year, depending on the soil type in well-fertilized Cherozem and Luvisol soils cropped continuously to cereals and hay. Analysis of these Canadian experiments focused on crop rotations, as opposed to tillage, and is unique in that it considered rates of carbon sequestration with regard to soil type.

On a global basis, West and Post (2002) suggested that soil carbon sequestration rates with a change to no-tillage practices can be expected to have a delayed response, reach a peak sequestration rate in 5 to 10 years, and then decline to nearly 0 in 15 to 20 years, based on regression analysis. This agrees with a review by Lal *et al.* (1998), based on results from Franzluebbers and Arshad (1996) showing that there may be little or no increase in soil organic carbon in the first 2 to 5 years after a change in management practice, followed by a large increase in the next 5 to 10 years. Campbell *et al.* (2001) concluded that wheat rotation systems in Canada will reach an equilibrium, following a change to no-tillage, after 15 to 20 years, provided average weather conditions remained constant. Lal *et al.* (1998) estimated that rates of carbon sequestration may continue over a period of 25 to 50 years. The different estimates of carbon sequestration may be expected partly based on different rotations and rotation diversity.

Nitrogen Emissions

Cropping systems and nitrogen fertilization affect plant biomass production, partially controlling input of organic carbon to the SOM stocks. Agriculture alters the terrestrial nitrogen cycle as well. Through nitrogen fertilization, annual cropping, monocropping and improper water management, nitrogen is more prone to being lost to both ground- or surface water and the atmosphere. N_2O, a common emission from agricultural soils, is a potent greenhouse gas (310 times more potent than CO_2), which has increased its atmospheric concentration by 15% during the past two centuries (Mosier *et al.*, 1998). Reductions can be achieved through improved nitrogen management, as well as with irrigation water management, because N_2O is generated under both aerobic conditions (where nitrification occurs) and anaerobic conditions (where denitrification occurs) in the soil.

Due to the tightly coupled cycles of carbon and nitrogen, changes in rates of carbon sequestration and terrestrial ecosystems will directly affect nitrogen turnover processes in the soils and biosphere–atmosphere exchange of gaseous nitrogenous compounds. Some data suggest that increasing N_2O emissions may be closely linked to increasing soil carbon sequestration (Mosier *et al.*, 1991; Vinther, 1992; McKenzie *et al.*, 1998;

Robertson *et al.*, 2000). If no-tillage is a truly viable management practice, it must mitigate the overall impact of no-tillage adoption by reducing the net global warming potential determined by the fluxes of all the greenhouse gases, including N_2O and CH_4.

Six *et al.* (2004) assessed potential global warming mitigation with the adoption of no-tillage in temperate regions, by compiling all available data reporting differences in fluxes of soil-derived C, N_2O and CH_4 between conventional tillage and no-tillage systems. Their analysis indicated that, at least for the first decade, switching from conventional tillage to no-tillage would generate enhanced N_2O emissions for humid environments and somewhat lower emissions for dry environments, which would offset some of the potential carbon sequestration gains; and that, after 20 years, N_2O emissions would return to or drop below conventional tillage fluxes. They found that N_2O emissions, with a high global warming potential, drive much of the trend in net global warming potential, suggesting that improved nitrogen management is essential to realize the full benefits from carbon storage in the soil for the purposes of global warming mitigation. They suggested caution in the promotion of no-tillage agriculture to reduce greenhouse gas emissions and that the total radiative forcing needs additional consideration beyond just the benefit of carbon sequestration. They suggested that it is critical to investigate the long-term as well as short-term effects of various nitrogen management strategies for long-term reduction of N_2O fluxes under no-tillage conditions. These results suggest the need for more basic research on N_2O emissions during the transition from conventional tillage to no-tillage and after equilibrium conditions have been achieved to adequately quantify the carbon-offsetting effects in global warming potential.

In Brazil, most, but not all, studies indicate that the introduction of zone tillage increases SOM (Bayer *et al.*, 2000a, b; Sa *et al.*, 2001). Sisti *et al.* (2004) evaluated changes in soil carbon in a 13-year study comparing three different cropping rotations under zone tillage and conservation tillage in a clayey Oxisol soil sampled to 100 cm. They found that, under a continuous sequence of winter wheat and summer soybean, the stock of soil carbon to 100 cm under zone tillage was not significantly different from that under conservation tillage. However, in rotations with a vetch crop, soil carbon stocks were significantly higher under zone tillage than under conservation tillage. They concluded that the contribution of nitrogen fixation by the legume crop was the principal factor responsible for the observed carbon accumulation in the soil under zone tillage. The results demonstrate the role of diverse crop rotations, especially including legumes supplying organic nitrogen under zone tillage, in the accumulation of soil carbon. The dynamic nature of the carbon : nitrogen ratio may require additional organic nitrogen to increase carbon sequestration at depth. Sisti *et al.* (2004) found that much of the nitrogen gain was at depths below the plough layer, suggesting that most of the accumulated soil carbon was derived from crop root residues.

Further work in Brazil reflects the importance of soil and plant management effects on soil carbon and nitrogen losses to 1 m depth (Diekow *et al.*, 2004). They evaluated carbon and nitrogen losses during a period of conventional cultivation that followed on native grassland and 17-year no-tillage cereal- and legume-based cropping systems with different nitrogen fertilization levels to increase carbon and nitrogen stocks. With nitrogen fertilization, the carbon and nitrogen stocks of the oat/maize rotation were steady with time. However, they found increased carbon and nitrogen stocks due to higher residue input in the legume-based cropping systems. The long-term no-tillage legume-based cropping systems and nitrogen fertilization improved soil carbon and nitrogen stocks of the previously cultivated land to the original values of the native grassland. Nitrogen and legume residues in a rotation were more effective for building soil carbon stocks than inorganic nitrogen from fertilizer applied to the grass crop in the rotation. In addition, legume nitrogen does not require the cost of using fossil fuel to manufacture nitrogen fertilizer. The dominant soil change took place in the surface layer; however, deeper layers were important for carbon and nitrogen storage, which leads to improved soil and environmental quality.

The literature holds considerable evidence that intensive tillage decreases soil carbon and supports the increased adoption of new and improved forms of conservation tillage or direct seeding to preserve or increase SOM (Reicosky *et al.*, 1995; Paul *et al.*, 1997; Lal *et al.*, 1998). Based on the soil carbon losses with intensive agriculture, reversing the decreasing soil carbon trend with less tillage intensity should be beneficial to agriculture and the global population by gaining better control of the global carbon balance (Houghton *et al.*, 1983; Schlesinger, 1985). The environmental and economic benefits of conservation tillage and direct seeding demand their consideration in the development of improved management practices for sustainable production. However, the benefits of no-tillage for soil organic carbon sequestration may be soil- or site-specific, and the improvement of soil organic carbon may be inconsistent on fine-textured and poorly drained soils (Wander *et al.*, 1998). Six *et al.* (2004) indicated a strong time dependency in the greenhouse gas (GHG) mitigation potential of no-tillage agriculture, demonstrating that greenhouse gas mitigation by adoption of no-tillage is much more variable and complex than previously considered.

Policy of Carbon Credits

The increase in greenhouse gas concentrations in the atmosphere is a global problem that requires a global solution (Kimble *et al.*, 2002; Lal, 2002). Concern about negative effects of climate warming resulting from increased levels of greenhouse gases in the atmosphere has led nations to establish international goals and policies for reductions of these emissions. Initial targets for reductions are stated in the Kyoto Protocol of the United Nations Framework Convention on Climate Change, which allows trading credits that represent verified emission reductions and removal of greenhouse gases from the atmospheres (United Nations Framework Convention on Climate Change Secretariat, 1997).

Emissions trading may make it possible to achieve reductions in net greenhouse gas emissions for far less cost than without trading (Dudek *et al.*, 1997). Storing carbon in soils using conservation agriculture techniques can help offset greenhouse gas emissions while providing numerous environmental benefits, such as increasing site productivity, increasing water infiltration and maintaining soil flora and fauna diversity (Lal *et al.*, 1998; Lal, 2002). Storing carbon in forests may also provide environmental benefits resulting from increased numbers of mature trees contributing to carbon sequestration (Row *et al.*, 1996). While carbon is a key player for agriculture in solving the problem of global warming, a critical caveat is that other greenhouse gases change with changes in land use, including CH_4 and N_2O. We must look at the net global warming potential, not only for carbon in future trades but global warming potential credits, rather than carbon credits alone.

As interest in soil carbon sequestration grows and international carbon trading markets are developed, it is important that appropriate policies be developed that will prevent the exploitation of soil organic carbon and at the same time replace the lost carbon and establish its value (Walsh, 2002). Policies are needed that will encourage the sequestration of carbon for all environmental benefits that will evolve (Kimble *et al.*, 2002). Making carbon a commodity necessitates determining its market value and doing so with rational criteria.

Both farmers and society will benefit from sequestering carbon. Enhanced soil quality benefits farmers, but farmers and society in general benefit from erosion control, reduced siltation of reservoirs and waterways, improved air and water quality and biodegradation of pollutants and chemicals. Farmers need to be compensated for the societal benefits of carbon sequestration and the mechanisms that develop will allow for carbon trading and maintaining property rights. One important criterion in developing the system is the measurement and verification of the carbon options for sequestration that must be developed and the importance of making policymakers aware of these procedures and the technical difficulties. The use of international carbon credit market mechanisms is intended to help meet the challenge of climate change and future carbon constraints, which enable sustainable development and at the lowest social cost.

Carbon credit accounting systems must be transparent, consistent, comparable, complete, accurate and verifiable (IPCC, 2000). Other attributes for a successful system include global participation and market liquidity, linking of different trading schemes, low transaction costs and rewards for early actions to voluntarily reduce emissions before regulatory mandates are put in place. Characterizing the relationships between soil carbon and water quality, air quality and all the other environmental benefits should be an easy sell to get social acceptance of this type of agriculture. The largest impediment is the educational processes directed at the policymakers and food-consuming public, which require further enhancement.

A growing number of organizations around the world are implementing voluntary projects that are climate-beneficial as a means to improve efficiency and reduce operating costs and risk. Businesses and institutions throughout the world are realizing that the benefits of good environmental management far outweigh the cost, both now and in the future, of good corporate management, which includes strategies to reduce greenhouse gas emissions, risk exposure and costs and to enhance overall competitive operations. Multinational organizations are participating in carbon energy credit trading markets in order to avoid future compliance costs and to protect their global franchise in the face of increasing concern over global warming (Walsh, 2002). In the evolution towards a global economy and as concerns over global environmental impacts increase, CO_2 emission management will become a factor in the planning and operations of industrial and government entities all over the world, creating challenges and opportunities for those who are able to recognize and capitalize on them.

The global ecosystem services provided by farmers and other landowners could provide a source of carbon-emission credits to be sold to carbon emitters and hence provide an additional source of income for farmers, particularly no-tillage farmers. Trade in carbon credits has the potential to make conservation agriculture more profitable and enhance the environment at the same time. The potential for carbon credits has attracted considerable attention of farmers and likely buyers of the carbon credits. However, it is difficult to stay fully informed about developing carbon credits because of their technical complexity and the pace of development on this subject. Rules for trading in carbon credits are not yet agreed upon, but international dialogue is under way to develop a workable system and rules for trading. The number of organizations working on developing a carbon trading system suggests that some type of international mechanism will evolve and that carbon credit trading will become a reality.

Information is rapidly becoming available on publicly traded carbon credits; however, little information is available on privately traded contracts. A great deal of uncertainty exists at this time as to which companies will emerge as reliable sources of high-quality information and entities that can handle trading in a fair and reliable manner. Potential suppliers and buyers of carbon credits are urged to proceed with caution because many of the issues central to carbon credit markets and trade are yet to be clarified. We must convince policymakers, environmentalists and industrialists that soil carbon sequestration is an additional important benefit of adopting improved and recommended conservation agricultural production systems. This option stands on its own, regardless of the threat of global climate change from fossil fuels.

Conservation agricultural practices (especially no-tillage) can help to mitigate global warming by reducing carbon emissions from agricultural land and by sequestering carbon in the soil through regulatory, market incentive and voluntary or educational means (Lal, 2002). Public policy can encourage adoption of these practices. For the present, there is a degree of uncertainty for investors and potential investors in forest-related carbon sinks over the specific rules that will apply to implementation of the sinks provisions of the Kyoto Protocol. Investors and potential investors in carbon sinks need to be aware that there is uncertainty at the international level. Administration and transaction costs could play a key role in determining the success of any carbon credit trading system. Costs in these areas are expected to be minimized through improved techniques and services for measuring and reporting sequestered carbon, private-sector consultants, economies of scale and the emergence of market mechanisms and strategies such as carbon pooling or aggregating. There are risks involved in selling carbon credits in advance of any formalized international trading system and those participating in early trading need to clarify responsibilities and obligations. However, care should be taken in the design of these policies to ensure their success, to avoid unintended adverse economic and environmental consequences and to provide maximum social benefit.

Summary of Reduced Environmental Emissions and Carbon Sequestration

While we learn more about soil carbon emissions, soil carbon storage and their central roles in environmental benefits, we must understand the secondary environmental benefits of no-tillage and what they mean to sustainable production agriculture. Understanding these environmental benefits directly related to soil carbon and getting the conservation practices implemented on the land will hasten the development of harmony between humans and nature while increasing production of food, fibre and biofuels.

Reducing soil carbon emissions and increasing soil carbon storage can increase infiltration, increase fertility, decrease wind and water erosion, minimize compaction, enhance water quality, impede pesticide movement and enhance environmental quality. Increased levels of greenhouse gases in the atmosphere require all nations to establish international and national goals and policies for reductions. Accepting the challenges of maintaining food security by incorporating carbon storage in conservation planning demonstrates concern for our global resources and our willingness to work in harmony with nature. This concern presents a positive role for no-tillage, which will have a major impact on global sustainability and our future quality of life.