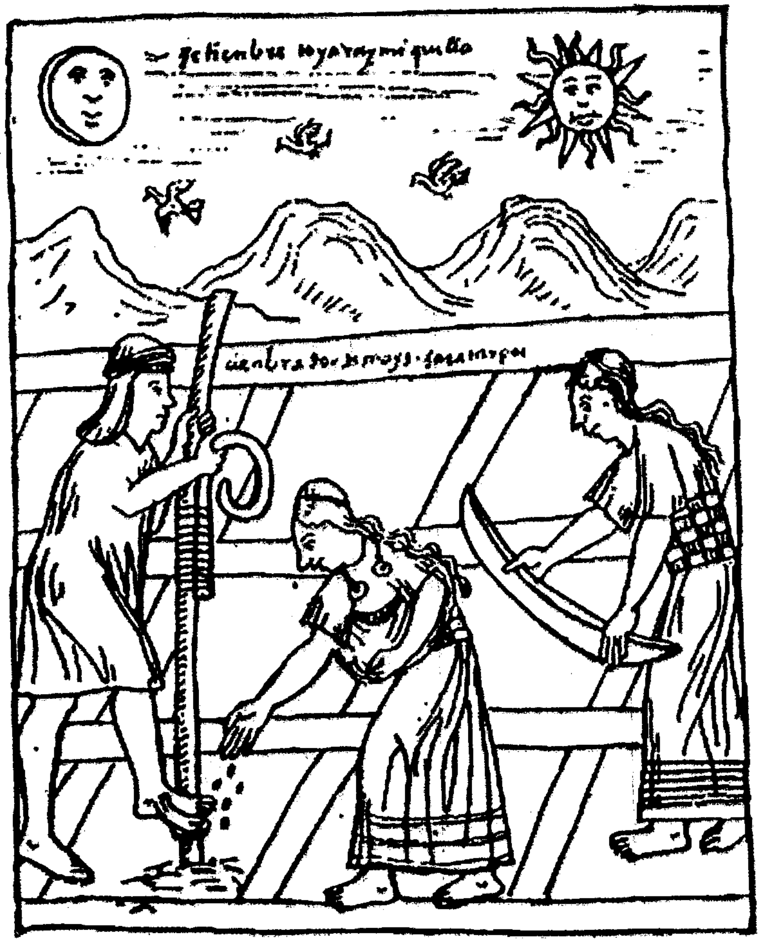

"Calendario Agrícola Incaico – Agricultural Calendar of the Incas"

Drawing by Phelipe Guaman Poma de Ayala, Peru; early 17th century

By courtesy of Rolf Derpsch, Conservation Consultant,
Asunción, Paraguay

NO-TILL FARMING SYSTEMS

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Carbon Sequestration and Environmental Benefits from No-Till Systems

Donald C. Reicosky

Abstract

Agricultural carbon (C) sequestration may be one of the most cost-effective ways to slow processes of global warming. Information is needed on the mechanism and magnitude of gas generation and emission from agricultural soils with specific emphasis on tillage mechanisms. This work reviews the scientific foundation and basic research on tillage-induced carbon losses and environmental benefits of soil carbon. With no tillage, crop residues are left more naturally on the surface to protect the soil and control the conversion of plant C to soil organic matter (SOM) and humus through C cycling. Numerous environmental benefits may result from agricultural activities that sequester soil C and contribute to environmental security. As part of no-regret strategies, practices that sequester soil C help reduce soil erosion and improve water quality and are consistent with more sustainable and less chemically dependent agriculture. While we learn more about soil C storage and its central role in direct environmental benefits, we must understand the secondary environmental benefits and what they mean to production agriculture. Increasing soil C storage can increase infiltration, increase fertility and nutrient cycling, decrease wind and water erosion, minimize compaction, enhance water quality, decrease C emissions, impede pesticide movement and generally enhance environmental quality. The sum of each individual benefit adds to a total package with major significance on a global scale. Incorporating C storage and cycling in conservation planning demonstrates concern for our global resources and presents a positive role for soil C that will have a major impact on our future quality of life.

Introduction

Intensive agriculture has contributed to water contamination from non-point source pollution, erosion, sedimentation and to the greenhouse effect with tillage-induced carbon dioxide (CO_2) losses. Improved tillage management techniques have shown that scientific agriculture can also be a solution to environmental issues in general and, specifically to mitigating the greenhouse effect (Lal et al., 1998). Improved agricultural practices such as direct seeding or conservation tillage have the potential to sequester more carbon (C) in the soil than farming emits through land use and fossil fuel combustion. Thus, a combination of the economic and C-related environmental benefits of enhanced soil management through reduced labor requirements, time savings, reduced machinery and fuel savings with direct seeding has universal appeal. Indirect measures of social benefits will be difficult to quantify as society enjoys a higher quality of life from environmental quality enhancement. Conservation agriculture (CA), working in harmony with nature by using direct seeding techniques that increase soil C, can be of benefit to society and can be viewed as both "feeding and greening the world" for global sustainability.

Soil quality is the fundamental foundation of environmental quality. Soil quality is largely governed by soil organic matter (SOM) content, which is dynamic and responds effectively to changes in soil management, primarily tillage and C input. Maintaining soil quality can reduce problems of land degradation, decreasing soil fertility, and rapidly declining production levels that occur in large parts of the world needing the basic principles of good farming practice. This review will primarily address effects of no till (NT), zero till (ZT), and direct seeding (DS) on soil C and its associated environmental benefits within conservation production systems.

The terminology being developed for such systems is "Conservation Agriculture" (CA). CA implies conformity with all three of the "keys" supporting CA in Figure 1. These three principles are *minimum soil tillage disturbance, continuous plant residue cover* and *diverse crop rotations and/or cover crops.* The foundation underlying the three principles is how they interact with and contribute to soil C, the primary determinant of soil quality. Conservation Agriculture includes concepts of NT, ZT and DS as the ultimate form of CA. These terms are often used interchangeably to denote minimum soil disturbance. Reduced tillage methods (sometimes referred to as conservation tillage) such as strip tillage, ridge tillage, and mulch tillage disturb a small volume of soil and partially mix the residue with the soil are considered intermediate on their soil quality effects. These terms require explicit definition of the tillage equipment and operation characteristics as they relate to soil volume disturbed and degree of soil-residue mixing. The extreme forms of intensive inversion tillage that include the moldboard plow, disk harrow and certain types of powered rotary tillage tools cannot be considered a form of conservation. This review will primarily address effects of NT, CT and DS on soil C and its associated environmental benefits within conservation production systems with emphasis on the three "keys" of CA. Other recent reviews on the role of C sequestration in CA were presented by Robert (2001), Uri (1999), Tebrugge and Guring (1999), Lal et al. (1998) and Lal (2000). Agriculture has an opportunity to offset some CO_2 emissions and will be a small, but significant player in sequestering C.

Why Crop Residue Management?

Cropland offers a huge potential for sequestering C especially when crop residues are managed properly. Crop residue management (CRM) is a widely used cropland conservation practice. Crop residue provides significant quantities of nutrients for crop production. In addition to affecting soil physical, chemical and

biological functions and properties, crop residues also affect water movement, infiltration, runoff and water quality. The decomposition of crop residues can have both positive and negative effects on crop production and the environment. The presence of crop residues on the surface generally results in wetter and cooler conditions, thus favoring disease and pests, and pathogens also multiply with an additional source of energy. Each CRM practice has drawbacks. Proponents of CA aim to increase the positive effects, especially with respect to environmental conditions. Ideally, crop residue management practices should be selected to enhance crop yields with minimal adverse effects on the environment.

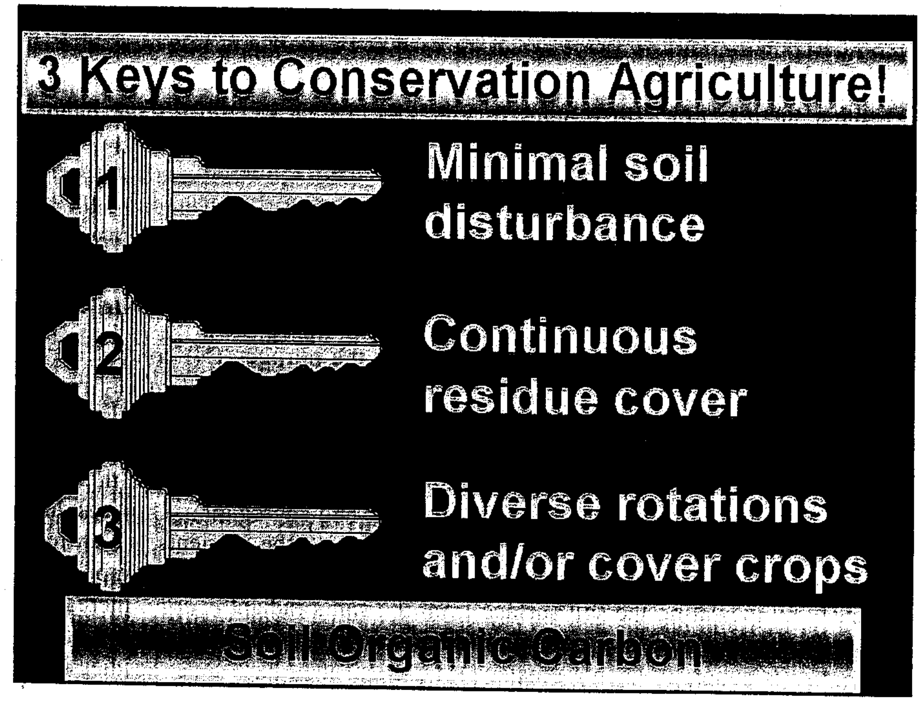

Figure 1. Schematic representation of the three keys of conservation agriculture.

When using conservation tillage methods, most crop residues are retained on the soil surface and not incorporated by tillage, destroyed by burning, or removed for other purposes. Crop residue mulches may increase infiltration by reducing surface sealing and decreasing runoff velocity. Crop residues on soil surfaces are known to reduce both wind and water erosion either directly by affecting the physical force involved in erosion or indirectly by modifying the soil structure through the addition of soil organic matter (SOM). Adopting CRM practices can significantly improve soil quality, reduce soil erosion and runoff, enhance moisture retention, lower summer soil temperatures, reduce the trips across the field, reduce machinery costs and at the same time may increase the net return to the farmer. Technological advancements should help make conservation tillage adaptable to a wider range of conditions, thus enhancing the potential of this practice to conserve soil and water resources and to protect the environment.

Before making crop management recommendations for maximum residue production, basic scientific research should be conducted using information about a site-specific soil, crop and climate. The complexity of conducting research on various aspects of soil conservation and CRM covers many aspects such as:

- •the factors affecting residue decomposition inputs on erosion control,
- •nutrient cycling and plant availability,
- •disease control problems,
- •weed control problems,
- •alternate uses of excess residue,
- •selection of plant varieties for conservation tillage systems,
- •machinery requirements and
- •control of the soil-water-temperature regime.

Conservation, Carbon Cycle, Soil Organic Matter and C Sinks

Crop biomass is generally 40 to 50% C, but the nitrogen (N) content varies considerably within and among species. The C:N ratio, an important key in soil management, also varies. The primary limiting factor for microbial growth in most soils is the C energy source. An abundance of C is added to the soil through crop residues. Since OM is known to maintain soil aggregate stability, the addition of crop residues should improve soil structure and aggregation. Crop residues and tillage management can also affect the leaching of the nutrients, which may pollute groundwater or surface waters. Crop residue influences soil temperature primarily by insulating the soil surface from the sun's radiant energy. Increasing amounts of crop residue on the soil surface reduces evaporation rates. Residue covered soils generally have a greater OM content than bare soils. Studies have shown that soils retain more moisture when residues were retained on the soil surface as compared to residue incorporation.

The term "soil organic matter" (SOM) refers to the sum total of all organic C-containing substances in the soil. Soil organic matter consists of a mixture of plant and animal residues in various stages of decomposition, substances synthesized microbiologically and/or chemically from the breakdown products, and the bodies of live and dead microorganisms and their decomposing remains. The main chemical element in all of these components is C, and, therefore, the terms SOM and C are often used synonymously.

The recent interest in global climate change has prompted many to value all C sources and sinks. Carbon sequestration in terrestrial ecosystems can be defined as the net removal of CO_2 from the atmosphere by crop photosynthesis into stable, long-lived pools of C. The soil organic carbon (SOC) pool is estimated to

compose about two-thirds of the terrestrial biosphere C pool. As stated earlier, cropland is an important component of C sink management. Increasing SOC storage requires increased C input via plant biomass production and decreased C loss as CO_2 from less intensive tillage practices to suppress the decomposition of SOM. Soil organic C storage in cropland soils is determined by the amount and placement of the crop residue as it is returned and the associated tillage systems. As grain and biomass yields increase and less intensive tillage systems are employed, farmers should gradually develop an enhanced long-lived C sink.

Tillage-induced Carbon Dioxide Losses

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 break down of aggregates increasing soil erodibility. Intensive tillage causes soil degradation through C loss and tillage-induced greenhouse gas emissions, mainly CO_2, that impact productive capacity and environmental quality.

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. The tillage studies reported in this review were conducted in West Central Minnesota, U.S.A. on soils high in soil organic C (Reicosky and Lindstrom, 1993, 1995; and Reicosky, 1997, 1998). The CO_2 flux from the tilled surfaces in these studies was measured using a large, portable chamber 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 periods. Briefly, the chamber with the mixing fans running was placed over the tilled surface or the no-tilled surface and data collected for one-second intervals for a total of 60 sec to determine the rate of CO_2 and water vapor increase inside the chamber. The chamber was then raised, calculations completed and the results stored on computer diskette. The data included the time, plot identification, solar radiation, photosynthetic active radiation, air temperature, wet bulb temperature, output of the infrared gas analyzer measuring CO_2 and water vapor concentrations in the same air stream. After the appropriate lag and mixing times, data for a 30-sec calculation window was selected to convert the volume concentrations of water vapor and CO_2 to a mass basis, 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 vapor increase within the chamber from a unit horizontal land area as differentiated from soil surface basis caused by differences in soil roughness. Only treatment differences with respect to tillage methods, tillage type or experimental objectives will be described with the results.

Recent studies involving a dynamic chamber, various tillage methods and associated incorporation of residue in the field indicated major C losses immediately following intensive tillage (Reicosky and Lindstrom, 1993, 1995). The moldboard plow 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 (yielding 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 NT having the least CO_2 loss over a 19-day period. The large gaseous losses of soil C following moldboard plow (MP) compared to relatively small losses with direct seeding (NT) have shown why crop production systems using moldboard plowing have decreased SOM and why NT 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. 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 hour after tillage were two- to four-fold above the pre-tillage values and rapidly declined within 24 hours of cultivation. They concluded that short-term influence on tillage and soil C loss was small under semi-arid conditions in agreement with Roberts and Chan (1990) and Franzluebbers et al. (1995a,b). On the other hand, Reicosky and Lindstrom (1993) concluded that intensive tillage methods, especially moldboard plowing to 0.25 m deep, affected this initial soil flux differently (a larger initial flux due to the physical release of CO_2 from the soil pores immediately after tillage) and suggest improved soil management techniques can minimize agricultural impact on global CO_2 increase. Reicosky (2001b) further demonstrated the effects of secondary tillage methods and post-tillage compaction decreasing the tillage-induced flux. Apparently, the severe soil compaction decreased porosity and limited the CO_2 flux after plow tillage to that of the no-till treatment. Conservation tillage reduces the extent, frequency and magnitude of mechanical disturbance caused by the moldboard plow and reduces the air-filled macropores and slows the rate of C oxidation. Any effort to decrease tillage intensity and maximize residue return should result in C sequestration for enhanced environmental quality.

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 used in row crop production and NT. The highest CO_2 fluxes were from the moldboard plow and subsoil shank tillage. Fluxes from both slowly declined as the soil dried. The least CO_2 flux was measured from the NT 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 that contributed to the vertical gas flux. The narrower and shallower soil disturbance caused less CO_2 loss suggesting that the volume of soil disturbed must be minimized to reduce C loss and impact upon soil and air quality. The results suggest environmental benefits and C storage of strip tillage

over broad area tillage that needs to be considered in soil management decisions.

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

Soil Carbon Management in Conservation Agriculture

Soil organic C represents a key indicator for soil quality, both for agricultural functions (production and economy) and for environmental functions (C sequestration and air quality). Soil organic matter is the main determinant of biological activity because it is the primary energy source for soil fauna and microbes. The amount, diversity and activity of soil fauna and microorganisms are directly related to SOM content and quality. Organic matter and the biological activity that it generates have a major influence on the physical and chemical properties of soils. Soil aggregation and structural stability increase with increasing organic C. These factors in turn enhance the infiltration rate and available water-holding capacity of the soil as well as resistance against erosion by wind and water. Soil organic matter also improves the dynamics and bioavailability of plant nutrients.

Soils contain relatively small amounts of C that could be considered analogous to a catalyst for biological activity where a small amount has a big impact. Farmers are the primary soil managers who have a tremendous responsibility to maintain SOM for environmental benefit of the global population. Thus, farmers who use CA or direct seeding techniques are providing ecosystem services and helping to maintain environmental quality for all of society. Quality food production and economic and environmentally-friendly management practices that are socially acceptable will lead to sustainable production and will be mutually beneficial to farmers and all of society. *Therefore, it is important that C loss from the soil system through historical land use and farming practices be restored to its natural potential by using direct seeding and conservation tillage methods for sustainable production.*

Agricultural crop residues and their proper management can also play a big role in helping society cope with increased greenhouse gas emissions from the burning of fossil fuels. Croplands have the potential to offset a very significant portion of greenhouse gas emissions, but questions about crop residue decomposition research need to be addressed (e.g. What are the effects of various tillage methods on resident decomposition?, What are the effects of residue quality and tillage interactions on residue decomposition?, What are the effects of residue burial position on decomposition?). Properly managed biological C cycling through CA can improve soil productivity and crop production by maintaining or increasing soil C levels (Fig. 2). Two significant advantages of surface residue management are increased C near the soil surface and enhanced nutrient cycling and retention. Greater microbial biomass and activity near the soil surface acts as a reservoir for nutrients needed in crop production and increases structural stability for increased infiltration. In addition to the altered nutrient distribution within the soil profile, changes also occur in the chemical and physical properties of the soil. All of this points to the value of C that starts with crop biomass input. *Under today's economic standards, soil C is priceless for all the social and environmental benefits provided.* While agriculture's contribution to these global change issues will likely be for the short term (25 to 50 years), it will provide society time to develop new technologies and cleaner burning fuels (Lal et al., 1998).

True soil conservation is C management. By properly managing the C in our agricultural ecosystems, we can have less erosion, less pollution, clean water, fresh air, healthy soil, natural fertility, higher productivity, C credits, beautiful landscapes, and sustainability. Dynamic soil quality encompasses those properties that can change over relatively short time periods in response to human use and management and that are strongly influenced by agronomic practices (e.g. soil organic matter, labile soil organic matter fractions, soil structure components, and macro porosity). Soil organic matter is both inherent, as total soil organic matter is related particle size distribution, and dynamic, as it is related to ongoing organic inputs to the soil. A dynamic part of soil C cycling is directly related to the "biological C" cycle (Fig. 2).

Soil C management is the focus of current and future international negotiations and treaties related to global climate change. To manage terrestrial C inventories and fluxes effectively, it is important for agriculture to find a more efficient way to measure and utilize soil C towards development of more efficient ways of offsetting greenhouse gas emissions from industry. In this way, agriculture can increase soil C storage to temporarily help offset the greenhouse gas emissions from industry until cleaner burning fuels are developed. Industrial manufacturing is a big player in the "fossil C" cycle, however it is a small player in the "biological C" cycle. In contrast, agriculture is a big player in the biological C cycle and relatively small player in the fossil C cycle (Fig. 3). These differences between agriculture and industry provide an opportunity to join forces to address the increasing greenhouse gas emissions for all society's benefit. Carbon dioxide in the atmosphere from burning fossil fuels can be extracted by plants into a more manageable form for sequestration. Agriculture and forestry, which manages much of the "biological C" cycle can help offset CO_2 emissions from the "fossil C" cycle that result in production and environmental benefits.

The "biological C" cycle is of the utmost importance in CA and is differentiated from the "fossil C" cycle. Fossil C sequestration entails the capture and engineered storage of C content of fossil fuels prior to its release to the atmosphere. Biological C sequestration entails removal of C from the atmosphere by plants.

Fossil fuels (fossil C) are very old geologically, as much as 200 million years. Biofuels (bio-C) are very young geologically and can vary from 1 to 10 years in age and as a result can be effectively managed for improved C cycling. One example of biological C cycling is the agricultural production of biomass for fuel. The major strength of biofuels is the potential to reduce net CO_2 emissions to the atmosphere. Enhanced C management in CA may make it possible to take CO_2 released from the fossil C cycle and transfer it to the biological C cycle to enhance food, fiber and bio-fuel production as well as for C sequestration for enhancing environmental quality. The social benefits in this scenario require agriculture and industry to work hand-in-hand to research and address CO_2 emissions.

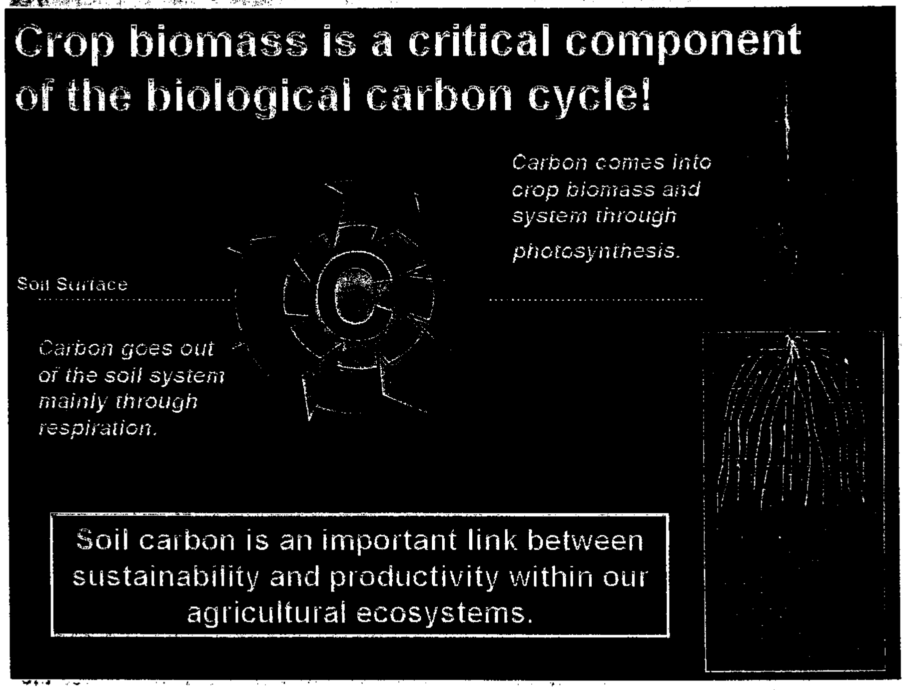

Figure 2. Carbon cycling in crop production systems.

Based upon the soil C losses with intensive agriculture, reversing the decreasing soil C trend with less tillage intensity should be beneficial to sustainable agriculture and society through better control of the global C balance. The literature holds considerable evidence that intensive tillage decreases soil C and supports increased adoption of new and improved forms of conservation tillage or no-till (direct seeding) to preserve or increase storage of soil organic matter (Lal et al., 1998). Better control of the C balance will lead to better harmony between man and nature. The environmental and economic benefits of CA and direct seeding demand their consideration in the development of improved soil C storage practices for sustainable production.

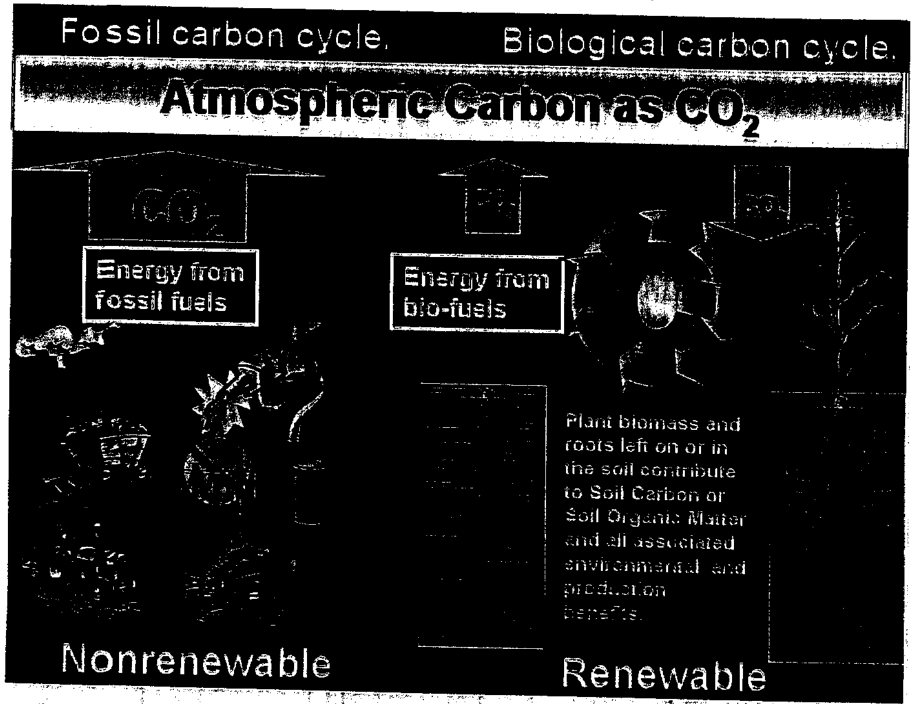

Figure 3. Comparison of CO_2 emissions from fossil and biological carbon cycles.

World soils are an important pool of active C, play a major role in the global C cycle and contribute to changes in the concentration of greenhouse gases in the atmosphere. Agriculture is believed to cause some environmental problems, especially related to water contamination, soil erosion, and greenhouse effect (Houghton et al., 1999; Schlesinger, 1985; Davidson and Ackerman, 1993). Soil contains two to three times as much C as the atmosphere. In the last 120 years, intensive agriculture has caused a C loss between 30 and 50%. By minimizing the increase in ambient CO_2 concentration through soil C management, we reduce the production of greenhouse gases. Recent results suggest scientific agriculture can also lessen environmental problems and mitigate the greenhouse effect. In fact, agricultural practices have the potential to store more C in the soil than farming emits through land use change and fossil fuel combustion (Lal et al., 1998).

Environmental Benefits of Soil Carbon

The direct benefit of CA or DS is the immediate impact on SOM and soil C interactions. Soil organic matter is so valuable for what it does; it can be referred to as "black gold" because of its vital role in physical, chemical and biological properties and processes within the soil system. Agricultural policies are needed to encourage farmers to improve soil quality by storing C that will also lead to enhanced air quality, water quality and increased productivity as well as to help

mitigate the greenhouse effect. Soil C is one of our most valuable resources and may serve as a "second crop" if global C trading systems become a reality. While technical discussions related to C trading are continuing, there are several other secondary benefits of soil C impacting environmental quality that should be considered to maintain a balance between economic and environmental factors.

Soil C is so important that it can be compared to the central hub of a wheel of environmental quality (Fig. 4; Reicosky, 2001a). The wheel represents a circle, which is a symbol of strength, unity and progress. The "spokes" of this wagon wheel represent incremental links to soil C that lead to the environmental improvement that supports total soil resource sustainability. Many spokes make a stronger wheel. Each of the secondary benefits that emanate from soil C contributes to environmental enhancement through improved soil C management. Soane (1990) discussed several practical aspects of soil C important in soil management. Some of the "spokes" of the environmental sustainability wheel are described in following paragraphs.

Increased SOM has a tremendous effect on soil water management because it increases infiltration and the water-holding capacity. The primary role of SOM in reducing soil erodibility is by stabilizing the surface aggregates through reduced crust formation and surface sealing, which increases infiltration (Le Bissonnais, 1990). Enhanced soil water-holding capacity is a result of increased SOM which more readily absorbs water and releases it slowly over the season to minimize the impacts of short-term drought. In fact, certain types of SOM can hold up to 20 times its weight in water. Hudson (1994) showed that for each one percent increase in SOM, the available water-holding capacity in the soil increased by 3.7% of the soil volume. The extra SOM prevents drying and improves water retention properties of sandy soils. In all texture groups, as SOM content increased from 0.5 to 3%, available water-holding capacity of the soil more than doubled. Other factors being equal, soils containing more OM can retain more water from each rainfall event and make more of it available to plants. This result plus the increased infiltration with higher OM and the decreased evaporation with crop residues on the soil surface all contribute to improve water-use efficiency.

Ion adsorption or exchange is one of the most significant nutrient cycling functions of soils. Cation exchange capacity (CEC) is the amount of exchange sites that can absorb and release nutrient cations. Soil organic matter can increase CEC of the soil from 20 to 70% over that of the clay minerals and metal oxides present. In fact, Crovetto (1996) showed that the contribution of the organic matter to the cation exchange capacity exceeded that of the kaolinite clay mineral in the surface 5 cm of his soils. Robert (1996) showed a strong linear relationship between organic C and CEC of his experimental soil. The CEC increased fourfold with an organic C increase from 1 to 4%. The toxicity of other elements can be inhibited by SOM which has the ability to adsorb soluble chemicals. The adsorption by clay minerals and SOM is an important means by which plant nutrients are retained in crop rooting zones.

Figure 4. Environmental sustainability wheel with benefits emanating from the soil C hub.

Soils relatively high in C, particularly with crop residues on the soil surface, are very effective in increasing SOM and in reducing soil erosion loss. Reducing or eliminating runoff that carries sediment from fields to rivers and streams will enhance environmental quality. Under these situations, the crop residue acts as tiny dams that slow the overland flow from the field, allowing the water more time to soak into the soil. Worm channels, macropores and plant root holes left intact increase infiltration (Edwards et al., 1988). Water infiltration is two to ten times faster in soils with earthworms than in soils without earthworms (Lee, 1985). Soil organic matter contributes to soil particle aggregation that makes it easier for the water to move through the soil and enables the plants to use less energy to establish to root systems (Chaney and Swift, 1984). Intensive tillage breaks up soil aggregates and results in a dense soil, making it more difficult for the plants to get nutrients and water required for their growth and production.

The reduction in soil erosion leads to enhanced surface and groundwater quality, another secondary benefit of higher SOM (Uri, 1999). Crop residues on the surface help hold soil particles in place and keep associated nutrients and pesticides on the field. The surface layer of OM minimizes herbicide runoff, and with conservation tillage, herbicide leaching can be reduced as much as half (Braverman et al., 1990). The enhancements of surface and groundwater quality are accrued through the use of conservation tillage and by increasing SOM. Increasing SOM and maintaining crop residues on the surface reduces wind erosion (Skidmore et al., 1979). *Depending on the amount of crop residues left on the soil surface, soil erosion can be reduced to nearly nothing as compared to an unprotected, intensively tilled field.*

Another key factor is that SOM can decrease soil compaction (Angers and Simard, 1986; Avnimelech and Cohen, 1988). Soane (1990) presented different mechanisms where increased SOM can decrease "compactibility": 1) improved internal and external binding of soil aggregates, 2) increased soil elasticity and rebounding capabilities, 3) dilution effect of reduced bulk density due to mixing organic residues with the soil matrix, 4) temporary or permanent existence of root networks, 5) localized change in ion exchange capacity contributed by SOM on soil particle surfaces, and 6) change in soil internal friction. While most soil compaction occurs during the first vehicle trip over the tilled field, reduced weight and horsepower requirements associated with forms of conservation tillage can also help minimize compaction. Additional field traffic required by intensive tillage compounds the problem by breaking down soil structure. The combined physical and biological benefits of SOM can minimize the affect of traffic compaction and result in improved soil tilth.

Maintenance of SOM contributes to the formation and stabilization of soil structure. Another spoke in the wagon wheel of environmental quality is improved soil tilth, structure and aggregate stability that enhance gas exchange properties and aeration required for nutrient cycling (Chaney and Swift, 1984). Critical management of soil airflow with improved soil tilth and structure is required for optimum plant function and nutrient cycling. It is the combination of many little factors rather than one single factor that results in comprehensive environmental benefits from SOM management. The many attributes suggest new concepts on how we should manage the soil for the long-term aggregate stability and sustainability.

A secondary benefit of less tillage and increasing SOM is reduced air pollution. CO_2 is the final decomposition product of SOM and is released to the atmosphere. Research has shown that intensive tillage, particularly the moldboard plow, releases large amounts of CO_2 as a result of physical release and enhanced biological oxidation (Reicosky et al., 1995). With conservation tillage, crop residues are left more naturally on the surface to protect the soil and control the biological C cycle and the conversion of plant C to SOM and humus. Intensive tillage releases soil C to the atmosphere as CO_2 where it can combine with other gases to contribute to the greenhouse effect. Thus a combination of the economic and environmental benefits of NT or DS through reduced labor requirements, time savings, reduced machinery costs and fuel savings has universal appeal. Indirect measures of social benefits as society enjoys a higher quality of life from environmental quality enhancement will be difficult to quantify.

Limits of No-Till or Direct Seeding for Carbon Sequestration

Carbon sequestration through continuous CA is only a short-term solution to the problem of global warming. The amount of C that can be stored in the soil using no-till techniques will plateau in 25 to 50 years (Lal et al., 1998). The time period depends on the specific geographic site, soil and climate parameters, and cropping practices. At some point, a new equilibrium will be reached where there is no further gain in soil C; however, the environmental benefits will continue. In the long term, reducing CO_2 emissions from the burning of fossil fuels by developing alternate energy sources is the only solution. Soil C sequestration and the potential of associated C credit trading will allow major CO_2 emitters time to reduce their emissions, while developing economical long-term solutions. For the next 50 years, however, soil C sequestration can be a cost-effective option that buys society time in which to develop alternate energy options while still providing numerous environmental benefits.

Agricultural policy should play a prominent role in agro-environmental instruments to support a sustainable development of rural areas and respond to society's increasing demand for environmental services. Environmental protection and nature conservation require enhanced management skills that create extra work and cost for the farmers, but in no other sector can so much be achieved for the environment with so little input. We must no longer take for granted the contribution made by farmers to society through ecosystem services and environmental measures, but must compensate them appropriately through stewardship payments. Farmers using conservation techniques stand to gain from protecting the environment because it is in their fundamental economic interest to conserve natural resources for the future. It is in all our economic interests to have healthy and sustainable ecosystems to enhance our quality of life. The true economic benefits can only be determined when we assign monetary values to externalities of environmental quality. It makes more economic sense to take account of nature conservation from the outset than to have to repair damage after it is done, and in many cases the repair may not even be possible. Conservation agriculture can play a major role in sequestering soil C and providing long-term global economic and environmental benefits.

Summary

Conservation agriculture with enhanced soil C management is a triple-win strategy. Agriculture wins with improved food, fiber and biofuel production systems and sustainability. Society wins because of the enhanced environmental quality. The environment wins as improvements in soil, air and water quality are all enhanced with increased amounts of soil C. While we in agriculture learn more about soil C storage and its central role in environmental benefits, all society must understand the secondary environmental benefits of CA (no-till) and what they mean to sustainable production agriculture. Understanding these environmental benefits and getting the conservation practices implemented on the

land will hasten the development of harmony between man and nature while increasing production of food and fiber and offsetting industrial greenhouse emissions. Increasing soil C storage can also increase infiltration, increase fertility, decrease wind and water erosion, minimize compaction, enhance water quality, decrease soil C emissions, impede pesticide movement and generally 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 soil C 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 CA that will have a major impact on global sustainability and our future quality of life.

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Effect of No-Till on Conservation of the Soil and Soil Fertility

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Abstract

Conventional tillage with plow disks and harrows leaving bare soil must no longer be considered recommended practice. Continuous no-till maintaining soil cover with plant residues called Conservation Agriculture (CA) must become the standard practice used by agriculture. Initially, more fertilizer may be required, but, as soil organic carbon (SOC) increases, the soil becomes more productive, requiring the same or even less fertilizer due to the increased values of nitrogen, phosphorus, potassium, calcium, magnesium and also greater pH and cation exchange capacity. Soil cover protects the soil against the impact of raindrops, prevents the loss of water from the soil through evaporation, and also protects the soil from the heating effect of the sun. Good aggregation, abundant surface crop residue, and a biologically active soil are keys to drought-proofing a soil. The utilization of CA with permanent soil cover not only improves soil and water quality for the farmer, but also improves the environment for all. CA has experienced wide application and levels of farmer acceptance on more than 100 million ha worldwide and is gaining even greater interest due to demonstrated increases in production, profitability and sustainability. In order to be successful, practicable, and fail-proof and to achieve widespread adoption of CA, farmers require an adequate level of knowledge to ensure that all aspects of the no-till production system are being considered.

Introduction

Traditionally, farmers practice conventional tillage with ploughs, disks and harrows. They believe that to obtain a uniform and loose seedbed that is weed-free, it is necessary to till the soil. However, ploughing, the mixing of crop residues and other biomass into the soil surface, and the burning of residues, all contribute to the deterioration of the physical quality of soil. In particular, soil structure becomes coarse, massive and platy; soil strength increases, and water infiltration, retention and availability all decrease. Routine tillage with associated soil degradation also has a strong potential to increase the impact of droughts as the soil becomes less fertile, less responsive to fertilizer and less able to infiltrate rainfall or irrigation water. The long-term result of routine tillage is the increased requirement for additional energy inputs (more tillage, fertilizer, chemical and organic amendments, water – particularly irrigation water). More energy is needed to restore the soil ecosystem before it becomes healthy again, and thus can supply the necessary nutrients and soil physical conditions for plant growth