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Conservation agriculture: Environmental benefits of reduced tillage and soil carbon management in water limited areas

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Summary

Agricultural carbon (C) sequestration may be one of the most cost effective ways to slow processes of global warming and enhance plant available water. Numerous environmental benefits and enhanced water use efficiency result from agricultural activities that sequester soil C and contribute to crop production and environmental security. Surface residues and soil C increase infiltration, decrease runoff, increase water-holding capacity and decrease evaporation. As part of no-regret strategies, practices that sequester soil C also 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. Enhancing soil C storage can increase fertility and nutrient cycling, increase available water holding capacity, 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 regional scale. Incorporating C storage in conservation planning in areas of limited water resources 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.

Key words: *Soil organic matter, soil quality, conservation tillage, zero tillage, carbon sequestration, water conservation*

Introduction

Conservation agriculture aims to conserve, improve and make more efficient use of natural resources through integrated management of available soil, water and biological resources combined with external inputs. Conservation agriculture contributes to global environmental conservation as well as to enhanced and sustained agricultural production and can play a central role in global agricultural policy. Food security and sustainability are important for all citizens. Agriculture, the major industry for food and fiber production, is known to cause emission and storage of greenhouse gases. Intensification of agricultural production has been an important factor influencing greenhouse gas emission and affecting the water balance. Agricultural activities contribute to carbon dioxide (CO_2) emissions to the atmosphere through the combustion of fossil fuel, soil organic matter (SOM) decomposition and biomass burning. Improved conservation agricultural practices have great potential to increase soil carbon (C) sequestration, available water storage, and decrease net emissions of CO_2 and other greenhouse gases that contribute to global environmental security.

World soils are an important pool of active C and play a major role in the global C cycle and have contributed to changes in the concentration of greenhouse gases in the atmosphere. Agriculture is believed to cause some environmental problems, especially related to water use, water contamination, soil erosion and greenhouse effect (Houghton, Hackler & Lawrence, 1999; Schlesinger, 1985; Davidson & Ackerman, 1993). The 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 minimize the production of greenhouse gases and minimize potential for climate change. 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 agriculture releases through land use change and fossil fuel combustion (Lal, Kimble, Follet & Cole, 1998).

Soil C is a major determinant of soil quality and is the fundamental foundation of environmental quality. Soil quality is largely governed by SOM content, which is dynamic and responds effectively to changes in soil management, primarily tillage and C input. This review will primarily address soil C and water conservation as they relate to environmental benefits. Throughout the following discussion, the terms "soil C" and "SOM content" are used synonymously. (See other recent reviews on the role of C sequestration in conservation agriculture were presented by Robert (2001), Uri (1999), Tebrugge & Guring (1999), Lal et al. (1998) and Lal (2000).)

Key role of soil carbon (soil organic matter)

Soil organic matter (SOM), generated from crop residues, is the main determinant of biological activity because it is the primary energy source. The primary chemical in soil organic matter is C that represents a key indicator for soil quality, both for agricultural functions (production and economy) and for environmental functions (C sequestration and air quality). The amount, diversity and activity of soil fauna and microorganisms are directly

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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 the soils. Soil aggregation and stability of soil structure increases with increasing organic C and surface crop residues. These factors in turn increase 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 bio-availability of main plant nutrient elements. Crop residues on the surface also decrease soil evaporation, thus leaving more water for plants.

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 each have a tremendous responsibility to maintain SOM for environmental benefit of the global population. Thus, farmers who use conservation agriculture or direct seeding techniques are providing ecosystem services and helping to maintain environmental quality for society. Quality food production and economic and environmentally-friendly management practices that are socially acceptable will lead to sustainable production and be mutually beneficial to farmers and society. It is important, therefore, that C loss from the soil system through historical land use of farming practices be restored to its natural potential using direct seeding and conservation tillage methods for sustainable production.

Carbon sources and sinks in agricultural systems

Agricultural systems contribute to C emissions through several mechanisms including direct use of fossil fuels in farm operations, indirect use of energy inputs for manufacturing chemicals (typically fertilizers), irrigation and grain drying and through intensive tillage of soils resulting in the loss of SOM. With conservation agriculture techniques, soils can accumulate C to offset other C losses. Thus, the soil can be converted from a "source" of C to a "sink" for C with improved soil and crop management.

Preliminary assessments indicate that soil C sequestration can be a tool to offset C emissions from burning fossil fuels. We in agriculture play a significant role because of the large amount of soil C in the C cycle within agricultural production systems. The limited use of crop rotations combined with intensive tillage decreases soil quality and soil organic matter. Any operation that removes or incorporates crop residue contributes to the decline of soil C through increased biological oxidation. The drive to maximize profit in food and fiber production has created environmental problems that have slowly crept up on conventional agriculture and now requires new knowledge, research and innovation to overcome these concerns.

A case for conservation agriculture and zero tillage

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 loosens soil, enhances the release of soil nutrients for crop growth, kills the weeds that compete with crop plants for water and nutrients and modifies the circulation of water and air within the soil. Intensive tillage can adversely affect soil structure and cause excessive break down of aggregates leading to potential soil movement via erosion. Intensive tillage causes soil degradation through C loss and tillage-induced greenhouse gas emissions that impact productive capacity and environmental quality. Intensive tillage also causes a substantial short-term increase in soil evaporation to rapidly deplete the surface layer.

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 & 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 that resulted in a rougher surface and larger voids than to residue incorporation. Lower CO_2 and water fluxes were caused by tillage associated with low soil disturbance and small voids with no-till having the least amount of CO_2 and water loss during 19 days. The large gaseous losses of soil C following moldboard plowing compared to relatively small losses with direct seeding (no-till) have shown why crop production systems using moldboard plowing have decreased SOM and why no-till 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. This concept was explored when Reicosky (1998) determined the impact of strip tillage methods on CO_2 and water loss after five different strip tillage tools and no-till. 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 no-till 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 and water loss suggests that the volume of soil disturbed must be minimized to reduce C loss and impact on soil and air quality. The results suggest environmental benefits and water 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 C loss from four conservation tillage tools was 31% of the CO_2 from the moldboard plow. The moldboard plow lost 13.8 times more CO_2 as the soil not tilled while conservation tillage tools averaged about 4.3 times more CO_2 loss. The smaller CO_2 loss from conservation tillage tools was significant and suggests progress in equipment development for enhanced 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. With tillage depths of 30 to 45 cm and adequate soil water, the long-term differences in evaporation were negligible.

Carbon loss associated with intensive tillage is also associated with soil erosion and degradation that can lead to increased soil variability and yield decline. Tillage erosion or tillage-induced translocation, the net movement of soil down slope through the action of mechanical implements and gravity forces acting on the loosened soil, has been observed for many years. Papendick, McCool, & Krauss (1983) reported original topsoil on most hilltops had been removed by tillage erosion in the Paulouse region of the Pacific Northwest of the USA. The moldboard plow was identified as the primary cause, but all tillage implements will contribute to this problem (Grovers et al., 1994; Lobb & Kachanoski, 1999). Soil translocation from moldboard plow tillage can be greater than soil loss tolerance levels (Lindstrom, Nelson & Schumacher, 1992; Grovers et al., 1994; Lobb, Kachanoski & Miller, 1995; Poesen et al., 1997). Soil is not directly lost from the fields by tillage translocation, rather it is moved away from the convex slopes and deposited on concave slope positions. Lindstrom, Nelson & Schumacher (1992) showed that soil movement on a convex slope in southwestern Minnesota, USA could result in a sustained soil loss level of approximately 30 t ha^{-1} yr^{-1} from annual moldboard plowing. Lobb, Kachanoski & Miller (1995) estimated soil loss in southwestern Ontario, Canada from a shoulder position to be 54 t ha^{-1} yr^{-1}from a tillage sequence of moldboard plowing, tandem disk and a C-tine cultivator. In this case, tillage erosion, as estimated through resident Cesium137, accounted for at least 70% of the total soil loss. The net effect of soil translocation from the combined effects of tillage and water erosion is an increase in spatial variability of crop yield and a likely decline in soil C related to lower soil productivity (Schumacher, Lindstrom, Schumacher & Lemme, 1999).

Environmental benefits of soil carbon

The main benefit of conservation agriculture or direct seeding is the immediate impact on SOM and soil water interactions. Soil organic matter is so valuable for what it does in soil, 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.

The importance of soil C can be compared to the central hub of a wagon wheel. 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 that 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 capacity of the soil more than doubled. Other factors being equal, soils containing more organic matter can retain more water from each rainfall event and make more of it available to plants. Increased water holding capacity plus the increased infiltration with higher organic matter and decreased evaporation with crop residues on the soil surface all contribute to improve crop water use efficiency.

Reduced tillage and crop residue management systems were initially developed to protect the surface from wind and water erosion, but they also increased soil water storage under a wide range of climates and cropping systems. Unger (1978) showed that high wheat residue levels resulted in increased storage of fallow season precipitation, which subsequently produced higher sorghum grain yields in the field studies in the Southern Great Plains of the USA. High residue levels of 8 to12 Mg ha^{-1} resulted in about 80 to 90 mm more stored soil water at planting and about 2.0 Mg ha^{-1} more of sorghum grain yield than a no residue treatment. Similarly, Smika (1976) showed pronounced tillage affects on soil water profiles following 34 days of drying in field experiments where no tillage treatment that maintain surface residue cover resulted in more water storage in the soil profile below a depth of 5 cm. Excellent reviews of the effects of reduced tillage and increased resides on water conservation are given by Smika and Unger (1986) and Unger, Langdale & Papendick (1988). Emphasis on improved residue management and less intensive tillage systems in conservation agriculture combines the beneficial effects of water conservation and soil carbon enhancement important in water limited areas.

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 clay minerals and metal oxides present. In fact, Crovetto (1996) showed that the contribution of organic matter to cation exchange capacity exceeded that of the kaolinite clay mineral in the surface 5 cm of his soils. Robert (1996 & 2001) showed a strong linear relationship between organic C and CEC of his experimental soil. The CEC increased four-fold 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.

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 down the water runoff 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, Shipitalo & Norton, 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 & 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.

Soil erosion leads to degraded surface and ground water quality. Another secondary benefit of higher SOM is decreased water and wind erosion (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 organic matter 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 ground water 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, Kumar & Larson, 1979). Depending on the amount of crop residues left on the soil surface, soil erosion can be reduced to nearly nothing as compared to the unprotected, intensively tilled field.

Soil organic matter can decrease soil compaction (Angers & Simard 1986; Avnimelech & Cohen, 1988). Soane (1990) presented different mechanisms where soil "compactibility" can be decreased by increased SOM content: 1) improved internal and external binding of soil aggregates; 2) increased soil elasticity and rebounding capabilities; 3) diluted 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 electrical charge of soil particles surfaces, 6) changed 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 the gas exchange properties and aeration required for nutrient cycling (Chaney & Swift, 1975). 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. Carbon dioxide 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 minimize evaporation with more controlled 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 benefits of conservation tillage through reduced labor requirements, time saved and reduced machinery costs and conserved fuel combined with the water conservation benefits listed above appeals universally. Indirect measures of social benefits as society enjoys a higher quality of life from environmental quality enhancement will be difficult to quantify. Conservation agriculture, using direct seeding techniques, can benefit society and can be viewed as both "feeding and greening the world" for global sustainability.

Policies for carbon and water management

Agricultural policy should play a prominent role in agro-environmental instruments to support a sustainable development of rural areas with limited water 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 to society by farmers through 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 repair damage after it is done, and in many cases the repair may not even be possible. Conservation agriculture without intensive tillage can play a major role in sequestering soil C and conserving soil water providing long-term global economic and environmental benefits.

Conservation agriculture with enhanced soil C and water management is a win-win strategy. Agriculture wins with improved food and fiber 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 that result in increased water use efficiency. The win-win scenario will increase productivity, improve soil quality and mitigate the greenhouse effect with major impact on our future quality of life.

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