Climate Change and Terrestrial Carbon Sequestration in Central Asia

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CHAPTER 15

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

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1 INTRODUCTION

Conservation agriculture (CA) 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. The CA 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 (GHGs). Intensification of agricultural production has been an important factor influencing GHG emission and affecting the water balance. Agricultural activities contribute to carbon dioxide (CO_2) emissions released to the atmosphere through the combustion of fossil fuel, soil organic matter (SOM) decomposition and biomass burning. Improved CA practices, especially in water-limited areas, have great potential to increase soil organic carbon (SOC) sequestration, available water storage, and decrease net emissions of CO_2 and other GHGs.

World soils, an important pool of active C, play a major role in the global C cycle and contribute to changes in the concentration of GHGs in the atmosphere (Lal et al., 1998). Intensive agriculture is believed to cause some environmental problems, especially related to water use, water contamination, soil erosion and greenhouse effect (Houghton et al., 1999; Schlesinger, 1985; Davidson and 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%. Minimizing the increase in ambient CO_2concentration through soil C management, reduces the production of GHGs and minimizes potential for climate change. 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 et al., 1998).

There is a vast potential for C sequestration in dryland ecosystems of Central Asia (Lal, 2004). With limited rainfall, much of the land area is irrigated resulting in secondary salinization and desertification suggesting that present land use and management systems are not sustainable. An important strategy of soil C sequestration is to reverse soil degradation. The CA and phytoremediation of degraded soils and ecosystems are important options in enhancing crop production and C sequestration. The CA with residue mulch can increase the available water storage in the root zone by increasing infiltration and decreasing soil temperature, reducing evaporation losses and improving water use efficiency (WUE). Lal's (2004) estimates of the potential of soil C sequestration in the Central Asian countries indicate a range of 10 to 23 $\mathrm{Tg\,C\,yr^{-1}}$ over 50 years. To achieve this amount of C sequestration, improved management practices will require less fallowing. Karbozova-Saljnikov et al. (2004) concluded that a frequent fallow system cultivated four to five times for weed control during the season depletes SOM via accelerated mineralization.

The potentially mineralizable C was inversely proportional to the frequency of the fallow period and was highest in continuous wheat system. They found the nitrogen (N) dynamics were closely related to the recent influence of plant residues while C dynamics was more related to the long-term residue addition. These results agree with those by Campbell and Zentner (1993) in similar climatic areas of the Canadian prairies.

The SOC is a major determinant of soil quality and is the fundamental foundation of environmental quality in water-limited areas. 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. The close coupling of the water, N and C cycles is discussed along with the duel role of crop residues for C input and soil water evaporation reduction. Throughout the following discussion, the terms "SOC" and "SOM content" are used synonymously. (See other recent reviews on the role of C sequestration in conservation agriculture presented by Reicosky et al. (1995), Robert (2001), Uri (1999), Tebrugge and Guring (1999), Lal et al. (1998) and Lal (2000)).

2 KEY ROLE OF SOIL CARBON (SOIL ORGANIC MATTER)

The SOM generated from crop residues, is the main determinant of biological activity because it is the primary energy source. The primary chemical in SOM 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 related to SOM content and quality. Both SOM and the biological activity that it generates, have a major influence on the physical and chemical properties of the soil. Soil aggregation and soil structure stability increases with increase in SOM and surface crop residues. These factors in turn increase the infiltration rate and available water-holding capacity (WHC) of the soil as well as resistance against erosion by wind and water. The SOM also improves the dynamics and bio-availability of main plant nutrient elements.

3 WATER-C-N LINKAGES IN CONSERVATION AGRICULTURE

In water-limited areas ($<$400 mm of annual rainfall), like many of the Central Asian countries, water and C management are interdependent. All farming systems reflect in some way the fact that photosynthetic productivity involves simultaneous water loss through transpiration by plants. In areas where water supply is limiting, several basic strategies are relied on to bring crops to maturity within the available supply. One strategy is to insure that a large portion of the available water goes to transpiration, a second is to achieve high level of production per unit of transpiration, and the third involves achieving a balance between seasonal water use and seasonal supply. As part of this balance, farming practices must also contend with the losses of water through runoff, percolation, and evaporation from the soil surface. It is in managing this water that conservation agriculture has the greatest opportunity for enhancing crop biomass production and soil C storage.

The exchange of the two main gases of interest, CO_2 and water vapor, are so critically important and related to solar-energy-dependent processes for C fixation and soil storage. The critical link between water and C starts with the process of photosynthesis represented by the chemical formula given below.

$$6CO_2 + 6H_2O \xrightleftharpoons{\text{Light energy}} C_6H_{12}O_6 + 6O_2$$

CO_2 comes through the stomata into the leaf via photosynthesis and water vapor goes out through the stomates to the atmosphere via transpiration. The combination of CO_2 plus water in the presence of light with chlorophyll in the plant leaves yields a sugar or carbohydrate plus oxygen. This is the start of the C cycle in agricultural ecosystems as a part of the global C cycle. These carbohydrates are transformed into many different chemical compounds and structures that make photosynthesis so important to the existence of life on earth. Water availability is a major factor in plant productivity because of the linkage of CO_2 and H_2O flux through the plant stomatal openings. Water transports nutrients from the soil into the plant and acts as a solvent for transport of various chemical compounds within the plant.

The reverse of photosynthesis is respiration where the plant material is oxidized and CO_2 is released to the atmosphere. Water is essential, along with optimum temperatures, for respiration which is the oxidation of the plant material and SOM. Efficient agricultural water use is critical in an era of increasing competition for limited water resources that in turn reflects the biomass productivity as a precursor for SOC input. So it is clear that water is an important factor critical for C fixation in the plant material and subsequent input into the soil C pools. This is where tillage and residue incorporation have a negative impact on SOM and has resulted in 30–60% soil C loss in the last 150 years of intensive agriculture in the US. Returning the respired CO_2 to the atmosphere completes the final part of the global C cycle. The C and water cycles are intimately coupled with strong interdependence on each other and in dry and warm climates, soil C sequestration continues to be a major scientific challenge.

In general, dry matter production and water use are more closely correlated than grain yield and water use (Ritchie, 1983). The information on yield and water use relationships enables predictions of crop yield that then can be used to estimate C yield for soil C input. There is little question that soil water supply for transpiration causes major variation in crop yields and biomass. The relationship between transpiration and total dry matter production of plants under field conditions is generally the same for plants grown in containers provided the dry matter production of plants in the fields is limited by the availability of water. Thus by knowing the seasonal transpiration, it is possible to estimate the amount of biomass that may be generated by specific crops and with that information it is possible to calculate potential C input to the soil system. The strong linear relationship supports the concept that biomass production is primarily water limited, which also implies that C input to the soil is water limited. Power et al. (1961) observed that biomass yields of wheat were linearly related to evapotranspiration and were affected by phosphorus (P) fertilization. Biomass yields, hence C input, can be easily calculated from grain yield and straw:grain ratio often referred to as the harvest index (HI). The evapotranspiration efficiency (Power et al., 1961), that is the slope of the line of biomass versus water use, was about 1.89 and 2.13 kg biomass m^{-3} water as a result of the P fertilization treatment. Jensen and Sletten (1965) showed similar effects of nitrogen (N) application. Effective nutrition is a part of C fixation through its impact on photosynthesis and biomass accumulation. Knowledge of these relations is essential to estimate the C input based on seasonal rainfall data within different geographic regions.

The devastating effects of water stress on plant productivity have been recognized since the beginning of agriculture. The central question with respect to C sequestration is the nature of the ratio of biomass productivity to crop water use and its inherent variability. Dry matter production rates under water-stress conditions are a function of source and sink activity (size and strength). As water stress develops, reductions occur in both leaf area and photosynthetic rate, reducing the total assimilating capacity of the plant (Hsiao, 1973). In essentially every case, whole-plant C assimilation capacity declines as water stress develops. The resultant effect on biomass yield depends on the relative contribution of newly assimilated C, compared with the utilization of previous accumulated dry matter. Much remains to be accomplished in terms of increasing photosynthesis and crop productivity to meet future C input demands. By understanding the order of limitations in crop growth and development in determining the degree of genetic variability in existing crop species, it is possible to develop higher-yielding, more stress-tolerant varieties which can enhance soil C accumulation.

Soil water deficits may affect photosynthate utilization by altering either the efficiency with which the photosynthate converted to new growth or the rate of photosynthesis used in maintenance of existing dry matter. The production of photosynthetically active leaf area by field crops is one of the most important factors affecting crop activity (Hsiao, 1973). The reduced rate of leaf area accumulation usually associated with growth in dry land environments may be associated with smaller sized leaves or with the production of fewer leaves. In addition, plant-water deficits may alter light interception through effects on the display and duration of the green leaf area.

The close linkage of the water and C cycles is clear, but the linkage of these two cycles extends to the N cycle. All three cycles are closely coupled in agricultural production systems. Intensive tillage can disrupt all three cycles because it buries the crop residue that when left on the surface can serve many other functions. Sometimes additional N may be required for high residue crops to assist in residue control by providing the optimum C:N ratio for crop residue decomposition. The belowground root biomass and exudates of legumes play a significant role in providing energy for the soil fauna and for modifying the subsurface soil physical properties (Wilts et al., 2004). However, there are limited management opportunities for these forms of C and N.

Water deficit can simultaneously reduce N acquisition and advance the onset of foliar senescence. The efficient use of water for crop production can also be enhanced in the semi-arid areas by adding fertilizer to deficient soils. This technique usually increases the total aboveground biomass without increasing total water use. Added fertilizer shifts the balance between soil and plant evaporation more toward plant evaporation. There is a strong relationship between water availability and N-fertilizer responses and that changing one of these factors can greatly affect responses to the other. Smika et al. (1965) showed how native grass production responded to N fertilization as available water supplies vary when the water supply was very limited; grass production was low and little response to N fertilizer occurred at any N rate. As available water supply increased, yield from unfertilized grass increased. However, as the rate of annual N fertilizer increased, the slopes of the regression lines relating yield to available water also increased. Thus, while N rate had very little effect on a biomass production when water supply was limited, responses of several thousand kg ha^{-1} of biomass were recorded when adequate water was available. Similar responses to increased water were very modest with no N fertilizer, but increased greatly as the rate of N fertilizer increased. Thus, water has both direct and indirect effects on biomass production and requires close coordination with N fertilizer rates for optimal biomass and C production.

4 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 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 breakdown of aggregates making it vulnerable to erosion. Intensive tillage causes soil degradation through C loss and tillage-induced GHG 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 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 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) showed why crop production systems using moldboard plowing 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_2fluxes 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 tillage. 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.

Plowing or excessive tillage is another factor that exacerbates the problem of soil degradation and reduces the SOM pool. Plowing depletes the SOM pool increasing mineralization and the risks of soil erosion. Reicosky (1997) reported that average short-term C loss from four conservation tillage tools was 31% of the CO_2 loss from the moldboard plow. The moldboard plow lost 13.8 times more CO_2 as the soil not tilled while conservation tillage systems averaged about 4.3 times more CO_2 loss. The smaller CO_2 loss from conservation tillage systems 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.

The C loss associated with intensive tillage is also associated with soil erosion and degradation that can lead to increased soil variability and decreased yield. Tillage erosion or tillage-induced translocation, the net movement of soil downslope through the action of mechanical implements and gravity forces acting on the loosened soil, has been observed for many years. Papendick et al. (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 contribute to this problem (Grovers et al., 1994; Lobb and Kachanoski, 1999). Soil translocation from moldboard plow tillage can be greater than soil loss tolerance levels (Lindstrom et al., 1992; Grovers et al., 1994; Lobb, Kachanoski and 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 et al. (1992) reported 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 et al. (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 ^{137}Cs, 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 SOC related to lower soil productivity (Schumacher et al., 1999).

5 CROP RESIDUES AND EVAPORATION

Water management is an integral part of any agricultural production system. Changes in total crop water use may occur through modification of crop residue management. To use the limited water resources more efficiently for crop production, it is important to develop new technology for effectively capturing and retaining rainfall using available resources. Agricultural residues serve dual purposes, one minimizing soil evaporation with improved residue management and second, residues are the primary form of soil C input. Crop residues improve soil and water conservation when retained on the surface (Unger, 1994). However, the residues are usually destroyed or incorporated with the soil through the use of intensive tillage methods.

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 to 12 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 effects on soil water profiles following 34 days of drying in field experiments where no tillage treatment that maintained surface residue cover resulted in more water storage in the soil profile below a depth of 5 cm. Smika and Unger (1986) and Unger et al. (1988) provide excellent reviews of the effects of reduced tillage and increased residues on water conservation. Thus, with improved crop residue management and less tillage, soil physical conditions improve with time after initiation of conservation tillage (Peterson et al., 1998). Emphasis on improved residue management and less intensive tillage systems in conservation agriculture combines the beneficial effects of water conservation and soil C enhancement important in water-limited areas.

A major advantage of maintaining crop residue on the soil surface, especially in subhumid and semiarid regions, is improved soil water conservation (Steiner, 1994). This is a result of reduced runoff of surface water and improved soil surface condition that allows more time for and permits greater water infiltration. Crop residues also reduce evaporation, which reduces the loss of stored water. Improved water conservation with less intensive tillage is also an important in humid regions where the short-term drought can severely limit crop yields on soils that have low water-holding capacities. As SOM levels increase, soil physical factors such as aggregate stability, bulk density and porosity that affect water infiltration and flow are positively influenced.

The manner in which the residue is left on the surface can play a big role in controlling water loss through evaporation. Residue that lays flat, provides continuous surface coverage and reduces evaporation much more than upright residue of the same mass. Residue lying in strips, like that found in strip till or following planting operations with aggressive residue managers, is less effective in reducing evaporation in comparison with complete residue coverage. The way the residue is left on the surface can have a big role in infiltration and soil water recharge. Stubble left upright over winter is important to snow catchments and water conservation in much of the Great Plains of the USA. Greb et al. (1967) reported that snow-melt moisture is more than 66% effective in moisture storage compared with 0 to 15% effectiveness of moisture from a July rainstorm. In addition, crop residue can reduce soil freezing, provide infiltration channels into the soil, and reduce the evaporation rate from the wetted soil as the snow melts. Mannering and Meyer (1961) demonstrated the value of the form of the crop residues on runoff and soil losses. They evaluated corn stalks as left by the corn picker (check treatment), stalks that were shredded, and stocks that were shredded and disked once. Runoff with the check and shredded corn stalk treatment was intermediate, but shredding the corn stalks decreased soil losses to about one half of those of the check. Although runoff was not affected, the study showed that increasing the surface coverage by shredding was an effective soil-loss control practice.

Crop residue on the soil surface reduces evaporation. Most of the evaporation occurs when the soil is wet, within a few days after rain or irrigation. The residue insulates the wet soil from solar energy and reduces evaporation. In instances where the soil is wetted more frequently, as in the case of sprinkler irrigation, evaporation increases and crop residue can control evaporation. Todd et al. (1991) measured mean daily evaporation from soil under a corn canopy during the growing season at North Platte, Nebraska, USA to document the effects of residue on soil evaporation in irrigated corn. The wheat straw residue (13.4 Mg ha^{-1}) left lying flat on the surface, produced complete cover and reduced soil evaporation by 50 to 64 mm during the growing season. While these results may have limited practical use, they do identify potential water savings and C input from biomass production accomplished with improved residue management in rainfall-limited areas.

Unger and Parker (1968) studied the effectiveness of stubble-mulch farming on water conservation during the fallow period. They found that mulches conserved water during long, dry periods. Evaporation from soil over a 16-week period was reduced 57% by straw applied and mixed with the soil surface, and 19% by straw buried 30 mm deep. Other findings showed a significant increase in fallow moisture efficiency with 1.68 and 6.72 Mg ha^{-1}of surface straw mulch, compared with bare fallow.

Removal of crop residues likewise affects soil nutrient availability and water relations. Barnhart et al. (1978) showed that continued removal of corn silage from an Iowa soil resulted in decreased SOM and total N content, when compared with plots where grain only was removed. Similarly, Reicosky et al. (2002) found that 30 years of fall moldboard plowing reduced the SOC whether the aboveground corn biomass was removed for silage or whether the stover was returned and plowed into the soil. Their results suggest that no form of residue management will increase SOC content as long as the soil is moldboard plowed. Hooker et al. (2005) also found that within a tillage treatment, residue management had little effect on SOC in the surface soil layer (0–5 cm). Tillage tended to decrease the SOC content, although only no till combined with stover return to the soil resulted in an increase in SOC in the surface layer compared with moldboard plowed treatments.

Removal of crop residues exposes the soil to water and wind erosion. Larson et al. (1978) calculated that removal of crop residues from Minnesota corn land would result in the removal of substantial amounts of N directly in the crop residues in addition to the N loss in accelerated soil erosion. Such losses of N over a period of years would eventually reduce fertility levels and reduce WUE. Understanding the SOC dynamics in bioenergy crops is important since C sequestration can influence biomass production, ecosystem sustainability, soil fertility, and soil structure. Continued crop residue removal for biofuels also raises concern about the long-term sustainability of this management system (Wilhelm et al., 2004).

Increasing SOM content has been considered effective for increasing its available water-holding capacity. Smaller additions of crop residue can result in smaller increases in water retention, but is often more practical to grow the materials in place. Returning most or all the crop residues from well-managed, high-residue crops to the soil should maintain or gradually increase SOM; thus, increasing water-storage capacity over a long period. Generally, this requires reduced tillage intensity or no tillage at all and increased cropping intensity (Peterson et al., 1998).

6 ENVIRONMENTAL BENEFITS OF SOIL C

The main benefit of CA or direct seeding is the immediate impact on SOM and soil water interactions. The SOM 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 which also leads to enhanced air quality, water quality and increased productivity as well as to help mitigate the greenhouse effect. The SOC is one of the 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 SOC impacting environmental quality that should be considered to maintain a balance between economic and environmental factors.

The importance of SOC 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 SOC that lead to the environmental improvement that supports total soil resource sustainability. Many spokes make a stronger wheel. Each secondary benefit resulting from SOC conservation management contributes to an overall improvement of environmental quality. 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.

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). 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 (Jones et al., 1994). 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). The SOM 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 the root systems

(Chaney and Swift, 1984). 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. Increased water-holding capacity plus the increased infiltration with higher SOM and decreased evaporation with crop residues on the soil surface all contribute to improve crop 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. SOM 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 SOM to CEC exceeded that of the kaolinite clay mineral in the surface 5 cm. Robert (1996; 2001) reported a strong linear relationship between organic C and CEC of his experimental soil. The CEC increased four-fold with an SOC increase in SOC 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.

Soil erosion leads to degraded surface and ground water quality. Another secondary benefit of higher SOM is decrease in 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 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 the unprotected, intensively tilled field.

The SOM can decrease soil compaction (Angers and Simard, 1986; Avnimelech and Cohen, 1988). Soane (1990) presented different mechanisms where soil "compactibility" can be decreased by increased in 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) created temporary or permanent root networks; (5) localized change electrical charge of soil particles surfaces, and (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 also 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 effect of traffic compaction and improve 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 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 to manage the soil for the long-term aggregate stability and sustainability.

7 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 in water-limited areas of Central Asia.

Numerous environmental benefits and enhanced water-use efficiency result from agricultural activities that sequester soil C and contribute to crop production and environmental security. Increase in surface residues and soil C increases infiltration, decreases runoff, increases water-holding capacity, and decreases 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 residue management and soil C storage and their central role in direct environmental benefits, we must understand the secondary environmental benefits and what they mean to production agriculture. Increasing soil C storage in water-limited areas can 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 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.

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