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Revegetation and Carbon Cycling in China's Loess Plateau

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Abstract

Agricultural soil carbon (C) sequestration may be one of the most cost-effective ways to slow down processes of global warming. Revegetation in land use planning is a tangible demonstration of C cycle management. Carbon management has many implications for erosion control. This review emphasizes the critical role of soil C as part of revegetation in conservation agriculture for decreasing soil erosion. Plants capture carbon dioxide (CO_2) and fix C in the grain or in vegetative biomass. The biomass protects the soil and serves as an energy source for the soil biology. Practices that sequester soil C help reduce soil erosion and improve water quality for rain-limited areas in China. Intensive tillage releases soil C to the atmosphere as CO_2, where it combines with other gases to contribute to the greenhouse effect. Conservation agriculture leaves crop residues on the surface to protect the soil and control the conversion of plant C to soil organic matter (SOM) and humus. Increasing soil C storage can increase infiltration, 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. Revegetation strategies for erosion control will also help mitigate global climate change by reducing C emissions to the atmosphere. Because plant biomass is a manageable form of C and because of the direct benefits of C in the ecosystem, we must talk directly about C management and C cycling. Incorporating C storage in conservation planning demonstrates concern for our global resources.

摘要

对农业的土壤实施碳素分离可能是减缓全球变暖进程的最成功有效的方法之一。对计划编制中使用的土地的植被再造是碳循环管理切实事例。碳管理在腐蚀管理中拥有很多的含义。这篇评论强调土壤中的碳作为农业保护中减少土壤腐蚀的植被再造部分的重要角色。植物从谷物或与植物生长有关的生物中获取二氧化碳及固定碳。这些生物保护土壤并且也是土壤生物的能量来源。隔绝土壤中碳的实践可以减少土壤腐蚀和为中国降雨有限的地区改善水质。密集的耕地将土壤中的碳元素以二氧化碳的形式释放出来，二氧化碳又与别的气体一起形成了温室效应。农业保护将谷物的残存物遗留在土地表面来保护土壤和控制植物由碳转化为土壤有机物和腐殖土。增加土壤中碳的储量可以增加渗透活动，土壤肥沃度，营养成分的回收，减少风和水的腐蚀，最小化紧束状态，提高水质，减少碳元素散发，阻止杀虫剂的运动，提高环境的质量。这个植被再造战略还可以通过减少碳元素散发到大气来减缓世界气候的变化。因为植物内生物数量的碳元素形式是可以

控制的，又因为生态系统中的碳有着直接的益处，我们必须直接谈论碳元素的管理与回收。在保护计划中结合碳存储表现了对全球资源的关注。

1 Introduction

China's Loess Plateau is characterized by some of the most extensive soil erosion in the world. The ecological devastation present in this region is influenced by many factors in addition to the very nature of the soil. Loess is noted as being among the most erosion prone soils in the world. Of all the factors contributing to soil erosion in the region, including desertification, wind erosion, violent rain storms, and earthquakes, the most significant one has been irrational land use (Fu et al. 1999). Conservation agriculture that enhances carbon (C) cycling is proposed as a change from traditional agriculture to manage agricultural land and enhance environmental quality in a more sustainable way. The main pillars of conservation agriculture are minimum soil disturbance, continuous crop residue cover, and the use of cover crops and/or diverse crop rotations. The purpose of this article is to review current knowledge of two of the three main topics in this book – combating soil erosion and rebuilding vegetation, as related to C management in conservation agriculture. This work emphasizes the critical role of soil C for decreasing soil erosion and maintaining environmental quality, and stresses the need for field research using conservation agriculture. While many examples are from other parts of the world, the principles and concepts will apply equally to the Loess Plateau in developing land use policies.

2 Revegetation and Carbon Cycling

Revegetation in land use planning is a tangible demonstration of managing the C cycle. Carbon management through revegetation has many implications for erosion control. Plants capture CO_2. The fixed C in vegetative biomass protects the soil and serves as an energy source for the soil biology. Photosynthesis produces plant biomass which is 40 to 45 % C in the carbohydrates along with several other nutrient elements. The living plant used for revegetation (grass, crops, shrubs, trees) provides a protective biomass surface over the soil and a distributed root biomass network in the soil that enables the development of biopores important in many soil and plant functions. Plant roots hold the soil in position and prevent it from being blown or washed away (Li et al. 1993; Li 1995). Part of the C in the root system stays within the physical structure of the roots, but a substantial amount of C is secreted into the soil through exudation, rhizo-deposition, and the formation of mucilage.

The material exuded becomes the primary energy source for soil fauna and microbes and is quickly utilized as part of the biological nutrient cycling process.

3 Agriculture and the Carbon Cycle

Over the past 150 years, the amount of CO_2 in the atmosphere has increased by 30 %. A direct relationship between increased levels of greenhouse gases in the atmosphere, especially CO_2, and rising global temperatures has been put forward by eminent scientists and research institutes and is now widely held to be possible (IPCC 2001). One proposed method to reduce atmospheric CO_2 build-up is to increase the global storage of C in soils (Lal et al. 1998). Additional benefits to this solution are the potential for simultaneous enhancement in agricultural production and ecosystem services. Soil C sequestration through conservation agriculture may be one of the most economical ways to reduce C emissions. Soil organic C is a valuable resource, and it is a renewable resource, from which we can gain many environmental benefits by increasing its levels (Reicosky 2001). Society needs to look at agriculture as part of the solution to an increasing concern, namely global climate change.

Agriculture contributes to water contamination from sedimentation and the greenhouse effect with tillage-induced CO_2 losses. Improved tillage management techniques have shown that scientific agriculture can help solve these environmental issues in general, and specifically mitigate the greenhouse effect (Lal et al. 1998). Improved agricultural practices such as direct seeding or conservation tillage have the potential to sequester more C in the soil than farming emits through land use and fossil fuel combustion. Conservation agriculture promises a combination of the economic benefits of enhanced soil management through reduced labor requirements, time savings, reduced machinery, and fuel savings with direct seeding, and the environmental benefits listed above. Indirect social benefits as society enjoys a higher quality of life from environmental quality enhancement will be difficult to quantify.

4 Soil Carbon Management in Conservation Agriculture

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 soils, natural fertility, higher productivity, beautiful landscapes, and sustainability. Dynamic soil quality encompasses those properties that can change over relatively short periods of time in response to human use and management and that are strongly influenced by agronomic practices (e.g. soil organic matter (SOM), labile soil organic matter fractions, soil structure components, and macro porosity). Soil organic matter is both inherent and dynamic; as a whole, it is related to particle size distribution, and yet it is also dependent on continued inputs of organic matter to the soil.

Soil C as part of the (living) biological carbon cycle is of utmost importance in conservation agriculture and can be differentiated from "fossil C." Biological C sequestration means removal of C from the atmosphere by a sole agent – plants. Fossil fuels (fossil C) are very old geologically, dating back several million years; biofuels (bio C) in contrast are very young geologically; their age may vary from only a few months to several hundred years (wood). As a result, biofuels can be effectively managed for improved C cycling. One example of biological C cycling is agricultural production. The major strength of biofuels is their potential to reduce net CO_2 emissions to the atmosphere. In fact, enhanced C management in conservation agriculture may take CO_2 released from fossil fuels and transfer it back into the biological C cycle.

5 Environmental Benefits of Soil Carbon Sequestration

The main benefit of conservation agriculture is the immediate impact it has on soil organic matter and soil C interactions (Reicosky 2001). Soane (1990) discussed practical aspects of soil C management: In agricultural production systems, many decisions are based on farmer experience and economic considerations. However, environmental concerns demand for a balance between economic and environmental factors and have recently caused soil organic matter management to rise to a high-level priority.

The most important soil and environmental properties which are affected positively by increased soil C (soil organic matter) are:

- *Soil water holding capacity*. The primary role of SOM in reducing soil erodibility is to stabilize the surface aggregates through reduced crust formation and surface sealing and thus increase infiltration (Le Bissonnais 1990). Increased SOM allows more water to be absorbed by the soil. In fact, certain types of SOM can hold up to 20 times their weight in water. Hudson (1994) showed that for each 1 % increase in SOM, the available water holding capacity in the soil increases by 3.7 % of the soil volume. In his experiments, extra SOM prevented drying and improved water retention properties of sandy soils. As SOM content increased from 0.5 to 3 %, available water capacity in soils of different texture groups more than doubled. Soils containing more organic matter could retain more water from each rainfall event and made more of it available to plants.

- *Biological activity and infiltration.* Domínguez et al. (2004) evaluated the leaching of water and nitrogen (N) in plots with varying earthworm populations in a corn system. They found the total flux of N in soil leachates was 2.5-fold greater in plots with increased earthworm population than in those with lower populations. Although these results were dependent on rainfall amounts, they indicate that earthworms can increase the leaching of water and inorganic N to greater depths in the profile, potentially increasing N leaching from the system. Leaching losses were lower on the organically fertilized plots, which was attributed to higher immobilization potential. Worm channels, macropores and plant root holes left intact also 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 plant to use less energy to establish its root system (Chaney & Swift 1984). Intensive tillage breaks up soil aggregates and results in a dense soil, making it more difficult for the plant to reach nutrients and water required for its growth and production.

- *Cation exchange capacity (CEC).* Ion adsorption or exchange is one of the most significant nutrient cycling functions of soils. CEC is the amount of exchange sites that can absorb and release nutrient cations. Soil organic matter can increase CEC of soil from 20 to 70 % over that of the clay minerals and metal oxides present. Robert (1996) showed that there exists a strong linear relationship between organic C and CEC. In his experiments, the CEC increased four-fold with an organic C increase in soil from 1 to 4 %. The toxicity of other elements can be inhibited by organic C, 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 compaction.* SOM can decrease soil compaction (Angers & Simard 1986; Avnimelech & Cohen 1988). Soane (1990) presented mechanisms and functions of increased SOM which lower soil "compactibility": (i) improved internal and external binding of soil aggregates, (ii) increased soil elasticity and rebounding capabilities, (iii) dilution effect of reduced bulk density due to mixing of organic residues with the soil matrix, (iv) temporary or permanent existence of root networks, (v) localized change of electrical charges of soil particle surfaces, and (vi) changed soil internal friction. As 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 minimize its impact.

- *Soil erosion*. Reduction in soil erosion leads to enhanced surface and ground water quality. Soils relatively high in C, particularly with crop residues on the soil surface, are very effective in reducing soil erosion loss. 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. Water coming in contact with organic material can be absorbed by the soil (see above), so that runoff will be reduced. Depending on the slope and amount of crop residues left on the soil surface, soil erosion can be reduced to nearly zero as compared to the unprotected, intensively tilled field.

- *Water quality*. Crop residues left on the field in conservation agriculture bind nutrients and pesticides associated with soil particles. Organic matter on the surface minimizes herbicide runoff, reducing it as much as half (Braverman et al. 1990). While surface and ground water quality in surrounding areas improve through increased SOM, the latter will increase further as a result of these improved conditions – the process is reciprocal. (Skidmore et al. 1979). All 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. This result plus the increased infiltration with higher organic matter and the decreased evaporation with crop residues on the soil surface all contribute to improved crop water use efficiency and water quality.

- *Soil tilth*. Maintenance of SOM contributes to the formation and stabilization of soil structure or soil tilth. Improved soil tilth is yet another spoke in the wheel of environmental quality advances brought forth by increased SOM; it enhances the soil's gas exchange properties and aeration required for nutrient cycling (Chaney & Swift 1984).

This work illustrates the critical role of soil C as part of revegetation in conservation agriculture for decreasing soil erosion and maintaining environmental quality; it stresses the need for field research using these techniques. Rather than one single factor, it is the combination of many factors that results in comprehensive environmental benefits from increased SOM. These many attributes suggest new concepts on how we should manage soil for long-term aggregate stability and sustainability that ultimately lead to enhanced environmental quality

6 Conservation Agriculture and Tillage Erosion

Tillage has been an integral component of global crop production for centuries. Recent studies, however, indicate that huge amounts of C are lost under intensive tillage regimes. Reicosky and Lindstrom (1993) found the moldboard plow to be heading the bill of C loss, measured by initial and overall CO_2 flux after tillage. CO_2 emissions were related to the roughness of soil surface, the depth of soil disturbance, and the size of soil pores created by the plow. No-tillage had the least amount of CO_2 loss. It was inferred therefore that improved soil management techniques such as strip tillage or forms of conservation tillage can minimize agricultural impact on global CO_2 increase.

The study of tillage has evolved into a science built on an understanding of the relationships between tillage and soil physical properties, crop growth, pests, soil erosion, and, most recently, C sequestration. The recognition of two processes associated with tillage has the potential to dramatically change future tillage research (Lobb et al. 2000). These processes are tillage translocation and tillage erosion (Lindstrom et al. 1992; Govers et al. 1994; Lobb et al. 1995; Poesen et al. 1997). Tillage translocation is the displacement of soil by tillage tools expressed as a mass of soil moved forward or laterally relative to the direction of tillage. The translocation of soil by tillage varies greatly within landscapes as a result of several factors, including the design and operation of tillage implements and the topographic and soil properties of landscapes. The consequence of this variation in translocation is net soil redistribution or "leveling" resulting in tillage erosion. Typically, tillage results in a progressive downslope movement of soil, causing severe soil loss on upper slope positions and accumulation in lower slope positions. Visual evidence of tillage erosion includes loss of organic-rich topsoil and exposure of subsoil at the summit of ridges and knolls, as well as undercutting of field boundaries (fence lines, hedgerows, terraces, etc.) on the downslope side and burial on the upslope side.

Although intensive tillage on steep slopes in the Loess Plateau for the last 50 years has been considered the major reason for accelerated soil erosion (Qiangguo 2002), its effect on soil quality has never been directly measured. In their 2001 study, Li and Lindstrom found a significant positive relationship between soil nutrients and soil accumulation from tillage on steep slopes and terraces. Soil redistribution by tillage, according to them, provided short-term soil quality benefits in the lower slope positions as evidenced by small increases in soil organic matter and available nutrients within the plow layer. The long-term effects of such accumulation by intensive tillage were researched in a follow-up study by Li et al. in 2004. They conducted 50 plowing operations over a five-day period, using a donkey-drawn moldboard plow on a steep backslope in the Loess Plateau, and measured topographic changes, soil organic matter changes, and nutrient content changes along a downslope transect after groups of ten tillage events. The results contradicted the positive first study: whereas soil redistribution by intensive tillage, carrying off the tilled layer from the upper slope, resulted in a temporary improvement of soil quality in the lower slope, the continuous accumulation of soil material above the initial soil surface led to degraded soil quality here too. Intensive tillage, it was proven, created conditions for severe erosion and soil loss.

The moldboard plow has been identified as a major contributor to tillage erosion throughout the world, but all tillage implements will invariably contribute to this problem (Govers et al. 1994; Lobb & Kachanoski 1999). Soil translocation from tillage operations can even be greater than currently accepted soil loss tolerance levels (Lindstrom et al. 1992; Govers et al. 1994; Lobb et al. 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) showed that soil movement from annual moldboard plowing on a convex slope in southwestern Minnesota, U.S.A, could result in a soil loss of approximately 30 t ha^{-1} yr^{-1}. Lobb et al. (1995), in southwestern Ontario, Canada, estimated soil loss from a shoulder position to be 54 t ha^{-1} yr^{-1} when tilled in a sequence of moldboard plow, tandem disk, and C-tine cultivator. In this case, tillage erosion, as estimated through resident Cesium137, accounted for at least 70 % of the total soil loss. Tillage speed increased the rate of tillage erosion nonlinearly.

The relationship between soil productivity and tillage erosion is complex. The degree to which crop yield losses are related to soil is a function of several interacting factors, including soil physical, chemical, and biological properties; landscape position; crop grown; management practices; and weather conditions before and during the growing season. Schumacher et al. (1999) used modeling procedures to show that tillage erosion caused soil loss from the shoulder position, while soil loss from water erosion occurred primarily in the mid to lower backslope position. The decline in overall soil productivity was greater when both processes were combined compared to either process acting alone. Water erosion contributed to nearly all the decline in soil productivity in the backslope position when both tillage and water erosion processes were combined. The net effect of soil translocation from the combined effects of tillage and water erosion was an increase in spatial variability of crop yield and a likely decline in overall soil productivity (Schumacher et al. 1999). A similar analysis is needed for the Loess Plateau.

7 Carbon Sequestration Policies and Perspectives

The increase in greenhouse gas concentrations in the atmosphere is a global problem that requires a global solution (Kimble et al. 2002; Lal 2002). Concerns about negative effects of climate warming have led governments to establish goals and policies for reductions of emissions. Initial targets are stated in the Kyoto Protocol to the United Nations Framework Convention on Climate Change (1997). The Protocol allows nations to trade credits representing verified emission reductions and removal of greenhouse gases from the atmosphere. This scheme is likely to achieve reductions in net greenhouse gas emissions for far less cost than without trading (Dudek et al. 1997). Storing C in soils using conservation agriculture techniques can help offset greenhouse gas emissions while providing numerous environmental benefits (Lal et al. 1998; Lal 2002). Storing C in forests multiplies these benefits by increased numbers of mature trees contributing to C sequestration (Row 1996).

As interest in soil C sequestration grows and C trading markets take shape all over the world, it is important that appropriate policies be developed, which prevent the exploitation of soil organic C, and, at the same time, replace the lost C (Walsh 2002). International policies are needed that will encourage the sequestration of C for all environmental benefits that will evolve (Kimble et al. 2002). Making C a commodity necessitates determining its market value and doing so with rational criteria. Enhanced soil quality only benefits farmers, but farmers and Society together benefit from erosion control, reduced siltation of reservoirs and waterways, improved air and water quality, and biodegradation of pollutants and chemicals. Farmers need to be compensated for the societal benefits of C sequestration, and the mechanisms that develop must allow for trading C and maintaining property rights.

One important criterion in developing the system is the measurement and verification of C options for sequestration. Policymakers have to be made aware of these procedures and the technical difficulties surrounding their set-up. Carbon credit accounting systems must be transparent, consistent, comparable, complete, accurate, and verifiable (IPCC 2000). Other attributes for a successful system include global participation and market liquidity, the linking of different trading schemes, low transaction costs, and rewards for early actions to voluntarily reduce emissions before regulatory mandates are put in place. Characterizing the relationships between soil C and water quality, air quality, and all the other environmental benefits should be an easy sell to get social acceptance of conservation agriculture. The largest impediment is the educational processes directed at policymakers and the food consuming public; they require further enhancement within China.

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

Conservation agriculture practices can help mitigate global warming by reducing C emissions from agricultural land and sequestering C in the soil. Public policy can encourage adoption of these practices through regulatory, market incentive, and voluntary or educational means (Lal 2002). For the present, there is a degree of uncertainty for investors and potential investors in forest-related C sinks over the specific rules that will apply to implementation of the sink provisions of the Kyoto Protocol. Administration and transaction costs could play a key role in determining the success of any C credit trading system. They can be minimized through improved techniques and services for measuring and reporting sequestered C, private sector consultants, economies of scale, and the emergence of market mechanisms and strategies such as C pooling or aggregating. There are risks involved in selling C credits in advance of any formalized international trading system and those participating in early trading need to clarify responsibilities and obligations. Care should be taken in the design of such policies to ensure their success and to avoid unintended adverse economic and environmental repercussions for a maximum social benefit.

8 Recommendations

Science and technology play an important role in creating sound scientific knowledge for sustainable use of land resources, but the integration and diffusion of this knowledge into the respective social and policy frameworks is just as critical for the planning and implementation of sustainable land use. Integrated participatory educational programs on the importance of revegetation for soil C as well as C and N cycling in agricultural and forest systems must be implemented. The development of regional on-farm research programs and demonstrations for farmers and the public to illustrate the potential economic and environmental benefits of conservation agriculture are an important part of erosion control. Farmer-led regional conservation organizations with emphasis on no-tillage and direct seeding for both large and small scale farms are desirable.

The following specific recommendations are aimed at implementing socially acceptable and environmentally friendly production systems that employ the principles and concepts of conservation agriculture within the soil and climate constraints of the Loess Plateau.

1) Develop improved soil management plans that decrease tillage intensity and the volume of soil disturbed, and enhance the soil physical, chemical and biological properties.
2) Develop improved vegetation and crop residue management practices that yield continuous residue cover to protect the soil surface.
3) Encourage cropping systems that maintain vegetation cover during heavy rainfall periods.
4) Utilize diverse crop rotations and cover crops to maximize soil carbon and nitrogen input in combination with agro-forestry and perennial species with dense root systems to protect the soil from erosive forces.
5) Develop comprehensive integrated crop production systems that encompass management aspects for optimum grain yield and environmental protection.

References

Angers, D.A. and Simard, R.R., 1986. Relationships between organic matter content and soil bulk density. Relations entre la teneur en matière organique et la masse volumique apparente du sol. *Canadian Journal of Soil Science* 66: 743-746.

Avnimelech, Y. and Cohen, A., 1988. On the use of organic manures for amendment of compacted clay soils: Effects of aerobic and anaerobic conditions. *Biological Wastes* 29: 331-339.

Fu, B.J., Chen, L.D., Ma, K.M., and Zhou, H.F, 1999. The effect of land-use structure on the distribution of soil nutrients in the hilly area of the Loess Plateau, China. *Chinese Science Bulletin* 44: 732-737.

Braverman, M.P., Dusky, J.A., Locascio, S.J., and Hornsby, A.G., 1990. Sorption and degradation of thiobencarb in three Florida soils. *Weed Science* 38(6): 583-588.

Cai, Q.G., 2002. The relationships between soil erosion and human activities on the Loess Plateau. In Yuren, J. (Ed.), *Sustainable utilization of global soil and water resources*. Proceedings of the 12th ISCO Conference, Beijing, P.R. China, 26-31 May 2002, Vol. 1. 22 May 2006 http://www.tucson.ars.ag.gov/isco/isco12/volume_1.html

Chaney, K. and Swift, R.S., 1984. The influence of organic matter on aggregate stability in some British soils. *Journal of Soil Science* 35: 223-230.

Domínguez, J., Bohlen, P.J., and Parmelee, R.W., 2004. Earthworms increase nitrogen leaching to greater soil depths in row crop agroecosystems. *Ecosystems* 7(6): 672-685.

Dudek, D.J., Goffman, J., and Wade, S.M., 1997. Emissions trading in non-attainment areas: Potential, requirements, and existing programs. In Kosobud, R.F. and Zimmermann, J.M. (Eds.), *Market-based approaches to environmental policy: Regulatory innovations to the fore*. New York: Van Nostrand Reinhold, 151-185.

Edwards, W.M., Shipitalo, M.J., and Norton, L.D., 1988. Contribution of macroporosity to infiltration into a continuous corn no-tilled watershed: Implications for contaminant movement. *Journal Contaminant Hydrol.* 3: 193-205.

Govers, G., Vandaele, K., Desmet, P.J.J., Poesen, J., and Bunte, K., 1994. The role of tillage in soil redistribution on hillslopes. *European Journal of Soil Science* 45: 469-478.

Hudson B.D., 1994. Soil organic matter and available water capacity. *Journal of Soil Water Conservation* 49(2): 189-194.

Intergovernmental Panel on Climate Change (IPCC), 2001. *A report of working group I of the Intergovernmental Panel on Climate Change*. Summary for policymakers. 22 May 2006 http://www.ipcc.ch

IPCC, 2000. *Land use, land use change, and forestry*. Special report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Kimble, J.M., Lal, R., and Follett, R.R., 2002. Agricultural practices and policy options for carbon sequestration: What we know and where we need to go. In Kimble, J.M. et al. (Eds.), *Agricultural practices and policies for carbon sequestration in soil*. Boca Raton, Florida: CRC Press, 495-501.

Lal, R., 2002. Why carbon sequestration in agricultural soils? In Kimble, J.M. et al. (Eds.), *Agricultural practices and policies for carbon sequestration in soil*. Boca Raton, Florida: CRC Press, 21-30.

Lal, R., Kimble, J.M., Follet, R.F., and Cole, V., 1998. *Potential of U.S. cropland for carbon sequestration and greenhouse effect mitigation*. Chelsea, Michigan: Ann Arbor Press, 128.

Le Bissonnais Y., 1990. Experimental study and modeling of soil surface crusting processes. In Bryan, R.B. (Ed.), *Soil erosion: Experiments and models*. Cremlingen-Destedt: Catena Verlag, 13-28.

Lee, K.E., 1985. *Earthworms: Their ecology and relationship with soils and land use*. New York: Academic Press.

Li, Y., 1995. *Plant roots and soil anti-scouribility on the Loess Plateau*. Beijing: Science Press.

Li, Y. and Lindstrom, M.J., 2001. Evaluating soil quality-soil redistribution relationship on terraces and steep slopes. *Soil Science Society of America Journal* 65:1500-1508.

Li, Y., Tian, G., Lindstrom, M.J., and Bork, H.R., 2004. Variation of surface soil quality parameters by intensive donkey-drawn tillage on steep slope. *Soil Science Society of America Journal* 68: 907-913.

Li, Y., Zhu, X.M., Xu, X.Q., and Tian, J.Y., 1993. Studies on the relationships between plant roots and the anti-scouribility of soils. *Journal of Soil and Water Conservation* 7(3): 11-18.

Lindstrom, M.J., Nelson, W.W., and Schumacher, T.E. 1992. Quantifying tillage erosion rates due to moldboard plowing. *Soil Tillage Research* 24: 243-255.

Lobb, D.A. and Kachanoski, R.G., 1999. Modeling tillage translocation using steppe, near plateau, and exponential functions. *Soil Tillage Research* 51: 261-277.

Lobb, D.A., Lindstrom, M.J., Quine, T.A., and Govers, G., 2000. Tillage at the threshold of the 21st century: New directions in response to tillage translocation and tillage erosion. In *Proceedings of the 15th ISTRO Conference*, Fort Worth, Texas, U.S.A, 2-7 July 2000. (CD-ROM computer file)

Lobb, D.A., Kachanoski, R.J., and Miller, M.H., 1995. Tillage translocation and tillage erosion on shoulder slope landscape positions measured using 137Cesium as a tracer. *Canadian Journal of Soil Science* 75: 211-218.

Poesen, J., Wesenael, B., Govers, G., Martinez-Fernadez, J., Desmet, B., Vandaele, K., Quine, T., and Degraer, G., 1997. Patterns of rock fragment cover generated by tillage erosion. *Geomorphology* 18: 193-197.

Reicosky, D.C., 2001. Conservation agriculture: Global environmental benefits of soil carbon management. In Garcia-Torres et al. (Eds.), *Conservation agriculture: A worldwide challenge*. Cordoba: XUL, 3-12.

Reicosky, D.C., 1998. Strip tillage methods: Impact on soil and air quality. In Mulvey, P. (Ed.), *Environmental benefits of soil management*. Proceedings of ASSSI National Soils Conference, Brisbane, Queensland, Australia, 27-30 April 1998. Brisbane: ASSSI, 56-60.

Reicosky, D.C. and Lindstrom, M.J., 1993. Fall tillage method: Effect on short-term carbon dioxide flux from soil. *Agronomy Journal* 85: 1237-1243.

Robert, M., 1996. Aluminum toxicity – A major stress for microbes in the environment. In Huang, P.M. (Ed.), *Environmental impacts*. Vol. 2: Soil component interaction. Boca Raton, Florida: CRC Press, 227-242.

Row, C., 1996. Effects of selected forest management options on carbon storage. In Sampson, R.N.

and Hair, D (Eds.), *Forest and global change*. Vol. 2: Forest Management Opportunities for Mitigating Carbon Emissions. Washington, D.C.: American Forests, 59-90.

Schumacher, T.E., Lindstrom, M.J.; Schumacher, J.A., and Lemme, G.D., 1999. Modeling spatial variation and productivity due to tillage and water erosion. *Soil Tillage Research* 51: 331-339.

Skidmore, E.L., Kumar, M., and Larson, W.E., 1979. Crop residue management for wind erosion control in the Great Plains. *Journal of Soil Water Conservation* 34: 90-94.

Smith, O.H., Petersen, G.W., and Needelman, B.A., 2000. Environmental indicators of agroecosystems. *Advances in Agronomy* 69: 75-97.

Soane B.D., 1990. The role of organic matter in soil compactibility: A review of some practical aspects. *Soil Tillage Research* 16: 179-202.

United Nations Framework Convention on Climate Change, 1997. *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. Bonn, Germany: United Nations Framework Convention on Climate Change Secretariat.

Walsh, M.J. 2002. Growing the market: Recent developments in agricultural sector carbon trading. In Kimble, J.M. et al. (Eds.), *Agricultural practices and policies for carbon sequestration in soil*. Boca Raton, Florida: CRC Press, 375-385.