Tillage and Gas Exchange

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INTRODUCTION

Agriculture is the economic foundation of rural America and has a major influence on components of industry, world trade, and global ecology. In traditional agricultural production, tillage of the soil has been an integral part of the production process. Tillage is the mechanical manipulation of soil and crop residue to prepare a seedbed where crop seeds are planted, sprout, take root, and grow into plants to produce grain. Intensive tillage loosens soil, buries crop residue, enables the soil to warm and dry, enhances release of soil nutrients for crop growth, kills the weeds that compete with crop plants for water and nutrients, facilitates root growth in compacted soil, and improves the flow of water and air within the soil. The enhanced gas exchange affects the processes that impact the accumulation and loss of soil carbon (C) in agricultural systems. Tillage increases water infiltration and increases the soil porosity, especially large pores, which allows greater movement of soil gases through the soil. Diffusion allows movement of gases into or out of the soil from higher to lower concentrations.

Concern for environmental quality and tillage-induced greenhouse gas emissions (carbon dioxide, methane, nitrous oxide) requires new knowledge to minimize agriculture's impact on the environment. In the United States, the moldboard plow has been a significant symbol of agriculture over the past 150 years and now is being reevaluated in many parts of the world as new conservation tillage techniques are developed and researched.

CROP PRODUCTION AND SOIL CARBON LOSS

The link between global warming and atmospheric carbon dioxide (CO_2), a greenhouse gas, has heightened interest in soil C storage, as soil organic matter, in agricultural production systems. Agricultural soils and agricultural production play an important role in C sequestration or storage and thus can help mitigate global warming.[1] Intensive tillage has mineralized or oxidized 30% and 50% of the native soil C or soil organic matter since the pioneers brought the soils into cultivation. Tillage processes and mechanisms leading to C loss are directly linked to soil productivity, soil properties, and environmental issues.[2] Soil C dynamics can have an indirect affect on climate change through net absorption or release of CO_2 from soil to the atmosphere in the natural C cycle. In agriculture, C comes into the system through photosynthesis and is returned to the atmosphere as CO_2 through human and microbial respiration. Good soil C management is vital because of its role in maintaining soil fertility, physical properties, and biological activity required for food production. Good soil C management is also needed to partially offset greenhouse gas emissions from manufacture and use of acid fertilizers, liming, fossil fuels, and the release of more potent nitrous oxide and methane from agricultural systems. Minimizing agriculture's impact on the global increase of CO_2 requires that we sequester and maintain high C levels in soil.

TILLAGE-INDUCED CO_2 LOSS

Tillage affects soil microbial activity, organic matter decomposition, and soil C loss in agricultural systems. Much of the C is lost as CO_2, which is the end product of microbial feeding on soil organic matter. Reicosky and Lindstrom[3] showed major short-term gaseous loss of C, immediately after tillage, which partially explains long-term C loss from tilled soils. Gas exchange was measured using a large, portable chamber to determine CO_2 loss from various types of tillage. Moldboard plow was the most intensive tillage and caused more CO_2 loss than less intensive tillage methods. No till or no soil disturbance lost the least amount of CO_2 suggesting minimal environmental impact. Moldboard plowing loosens and inverts soil and allows rapid CO_2 loss and oxygen entry. It also incorporates and mixes residues to enhance microbial decomposition and respiration (oxidation).[4] Stirring the soil in tillage is analogous to stirring the coals in a fire. Plowing accelerates microbial decomposition and soil aggregate breakdown to cause decreased soil C content in the surface layer. Ellert and Janzen[5] and Rochette and Angers[6] found similar results for different soils and less intensive tillage methods.

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Reicosky[7] reported that average short-term CO_2 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 pores or holes in the soil to slow the rate of gas exchange and C oxidation.

Strip tillage tools are designed to minimize soil disturbance. Different strip tillage tools and moldboard plow were compared to quantify short-term tillage-induced CO_2 loss relative to tillage intensity.[8] Less intensive strip tillage reduced soil CO_2 losses. No till had the lowest CO_2 loss, and moldboard plow had the highest immediately after tillage. Forms of strip tillage had an initial soil CO_2 loss related to tillage intensity intermediate between the extremes of plowing and no till. The cumulative CO_2 losses for 24 hours were directly related to the soil volume disturbed by the tillage tool. Reducing the volume of soil disturbed by tillage should enhance soil and air quality by increasing the soil C content and suggests that soil and environmental benefits of strip tillage be considered in soil management decisions. The CO_2 released immediately after moldboard plowing suggests little C sequestration. Conservation tillage methods that leave most of the crop residue on the surface with limited soil contact yield better C sequestration to enhance environmental quality.

MECHANICS OF GAS EXCHANGE

Tillage affects all physical soil conditions, especially aeration[9]. Tillage can drastically change the configuration, continuity, and size of soil pores. The moldboard plow is probably the most efficient implement to loosen a large volume of soil and to break up dense, massive soil clods into smaller units. After plowing, all plants and plant residues are buried and partially mixed into the soil, simplifying subsequent tillage and planting operations.

Several tillage-related factors affect soil gas exchange, especially the soil porosity and air permeability. The exchange of air between the soil and the atmosphere is bidirectional and can occur by two different mechanisms called diffusion and convection. In diffusion, the moving force is the gradient of partial pressure or concentration of the specific gas that causes the unevenly distributed molecules to randomly migrate from a zone of high concentration to low concentration. In convection, also called mass flow, the moving force consists of a gradient of total gas pressure and results in the entire mass of air streaming from a zone of high pressure to a zone of low pressure. Barometric pressure changes, soil temperature gradients, and wind gusts over the loosened soil surface can create pressure differences between soil air and the external atmosphere, thereby inducing convective flow into or out of the soil. Whether diffusion or mass flow is the dominant gas flow mechanism from soil depends on the total pressure gradient and pore size and pore continuity. When the soil is consolidated with only small pores, gas exchange is primarily by diffusion. When the soil has large pores, gas exchange can also occur still by mass flow. Out in the field, both processes are occurring simultaneously.

The degree to which air pressure fluctuations and convective flow can exchange gas between soil and the atmosphere has long been debated among soil physicists. Most believe that diffusion, rather than convection, is the more important gas exchange mechanism. Recent evidence suggests that convection can, in certain circumstances following intensive tillage, contribute significantly to gas exchange and soil aeration, particularly at shallow depths and in soils with large pores.[10] The tillage-induced CO_2 loss recently identified demonstrates the role of mass flow as a cause of C loss from tilled soils. The magnitudes of CO_2 fluxes were too large to be accounted for by simple diffusion from the soil.[3] The tillage-induced change in soil air permeability showed that convection contributes significantly to gas exchange.[11]

While the effects of mass flow are intermittent and variable, they tend to be particularly significant immediately after a tillage event up to the time that the soil reconsolidates. External factors that cause soil reconsolidation may include secondary tillage, raindrop impact, or wheel track compaction. The real concern follows an intensive tillage operation, where the change in the soil physical properties increases soil air permeability and changes the gaseous loss from a diffusion-controlled process to a convectively controlled process. Methods for measuring change in soil air permeability on large scales have not been developed.

SOIL PRODUCTIVITY AND ENVIRONMENTAL BENEFITS

While moldboard plowing and other forms of intensive tillage have done much to increase U.S. crop production over the past 150 years, the increase in production has been accompanied by unseen costs of decreased soil quality from erosion and increased greenhouse gas emissions.[1,12] The organic matter of many of the prairie's soils has declined from that present under virgin conditions. The unseen, unmeasured costs that result from intensive tillage include loss in soil C due to enhanced oxidation and depletion of soil fertility reserves. The magnitude of these unseen costs depends primarily on the intensity of tillage, the quantity and quality of crop residue returned to the soil, and the crop rotation. Intensive tillage, primarily moldboard plowing, decreases soil C in virtually all crop production systems.

CONCLUSIONS

Concern for soil productivity and greenhouse gas emissions requires new knowledge to minimize agriculture's impact on the environment. Soil C is the foundation of a healthy environment and sustainable agriculture. This is highly dependent on management decisions that influence intensity of tillage and the amount and placement of residues. Conservation tillage or no-till systems have shown increases in soil organic matter within 10 to 12 years of consistent use. The increase in soil organic matter depends on a delicate balance between the residue inputs of the previous crops and the tillage intensity associated with establishing the next crop. Farmers are faced with serious decisions with respect to environmental consequences of maintaining sustainable production and managing this delicate balance.

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