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Conservation agriculture and carbon sequestration: Between myth and farmer reality

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1. Introduction

1.1. Conservation agriculture

Human efforts to produce ever-greater amounts of food leave their mark on the environment. Persistent use of conventional farming practices based on extensive tillage, especially when combined with removal or in situ burning of crop residue, have magnified soil erosion losses and the soil resource base has been steadily degraded. Another direct consequence of farmers' persistent use of traditional production practices is rapidly increasing production costs; the costs of inputs such as improved varieties and fertilizers continue to increase and farmers make inefficient use of them. Despite the availability of improved varieties with increased yield potential, the potential increase in production is not achieved because of poor crop management systems. Nowadays, people have come to understand that agriculture should not only be high yielding, but also sustainable. Conservation agriculture (CA) has been proposed as a widely adapted set of management principles that can assure more sustainable agricultural production. Conservation agriculture is a broader concept than conservation tillage, a system where at least 30% of the soil surface is covered with crop residues after seeding of the next crop. In CA, the emphasis not only lies on tillage components but on the combination of the following three principles:

1. Reduction in tillage: The objective is to achieve zero tillage (i.e., no tillage at all); however, the system may involve controlled tillage seeding systems that do not disturb more than 20–25% of the soil surface.
2. Retention of adequate levels of crop residues and soil surface cover: The objective is the retention of sufficient residue on the soil to:
   - protect the soil from water and wind erosion;
   - reduce water run-off and evaporation;
   - improve water productivity; and
   - enhance soil physical, chemical, and biological properties associated with long-term sustainable productivity.
3. Use of crop rotations: The objective is to employ diversified crop rotations to:
   - help moderate/mitigate possible weed, disease and pest problems;
   - utilize the beneficial effects of some crops on soil conditions and on the productivity of the next crop; and
   - provide farmers with economically viable options that minimize risk.

These CA principles are applicable to a wide range of crop production systems from low-yielding, dry, rain-fed conditions to high-yielding, irrigated conditions. However, applying the principles of CA will be very different in different situations. Specific and compatible management components such as pest and weed control tactics, nutrient management strategies, rotation crops, etc. will need to be identified through adaptive research with active farmer involvement.

Conservation agriculture has been promoted as an agricultural practice that increases agricultural sustainability and is associated with the potential to lessen greenhouse gas emissions. There are, however, contrasting reports on the potential of CA practices for C sequestration (i.e., the process of removing carbon dioxide, CO_2, from the atmosphere and depositing it in the soil).

2. Carbon and nitrogen cycling

2.1. The global carbon and nitrogen cycle

The global carbon cycle consists of a short-term biochemical cycle, superimposed on a long-term geochemical cycle. Annually, human activities distort both cycles by emitting 8.6 Pg C (petagram, 10^{15} grams, or 1 trillion kg). Of this emitted C, 3.3 Pg C is absorbed by the atmosphere and 2.2 Pg C is absorbed by the ocean (Figure 1a). In the last 150 years, CO_2 emissions to the atmosphere have increased by 31%. The soil C pool comprises two components:

(1) The soil organic carbon (SOC) pool

(2) The soil inorganic carbon (SIC) pool

Agricultural activities mainly affect the SOC pool. In addition, soil C degradation leads to important soil quality losses and poses a threat to both agricultural production systems and food security. Ensuring net removal of carbon dioxide from the atmosphere into the soil (*soil carbon sequestration*) increases the sustainability of farming systems.

The N on earth consists mainly of a pool of nitrogen gas in the atmosphere and a pool of N that cycles among biota and soil in the form of nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+) (Figure 1b). Human activity has doubled the N transfer from the atmosphere to biologically available pools (mainly through industrial N fixation) with associated increased emission, transport, reaction and deposition of trace nitrogen gases such as nitrous oxide (N_2O), nitric oxide (NO) and ammonia (NH_3).

The global C and N cycles are connected. Decomposition of soil organic matter releases CO_2 into the atmosphere and ammonium (NH_4^+) into the soil, and when ammonium is not taken up by micro-organisms it is oxidized under aerobic conditions to nitrate (NO_3^-) (Figure 1b). This process, called *nitrification,* consists of two steps. Ammonium, when not taken up by micro-organisms, reacts with oxygen to form nitrite (NO_2^-), which is followed by the oxidation of these nitrites into nitrates (NO_3^-).

When the oxygen status of the soil changes, nitrification is inhibited and the *denitrification* process reduces nitrate (NO_3^-) to nitrite (NO_2^-), nitric oxide (NO), nitrous oxide (N_2O), and dinitrogen (N_2). In soils, nitrification and denitrification can occur at the same time, and there are even micro-organisms that can oxidize NH_4^+/NO_2^-, and reduce NO_2^-/NO_3^- at the same time. N_2O is a gas contributing to greenhouse gas emissions. The contribution to global warming of the most important biological greenhouse gasses are 70%, 23%, and 7% for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), respectively.

2.2. Carbon and nitrogen cycling in agricultural systems

2.2.1. Carbon

Carbon uptake in crops occurs through photosynthesis and enters the soil as a residue of above- or below-ground biomass. The dead organic material is colonized by a variety of soil organisms, which derive energy for growth from the oxidative decomposition of complex organic molecules. During decomposition, about half of the C is mineralized and released as CO_2. There are four sources of CO_2 emissions in agricultural systems:

- Plant respiration
- Oxidation of organic carbon in soils and crop residues

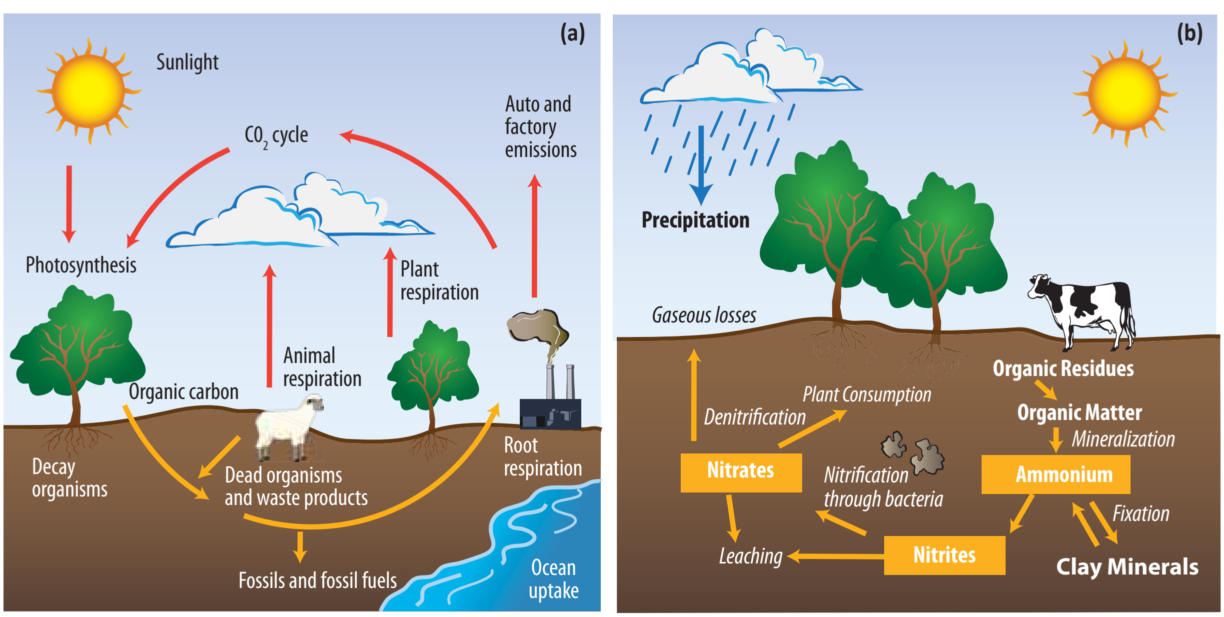

Figure 1. (a) The carbon cycle. Human and animal activity release CO_2, which is absorbed by the ocean, the atmosphere and other sinks. C extraction for use as fossil fuels such as coal, gas, and oil, has led to an increase in CO_2 emission. (b) The nitrogen cycle. The main pool of N in the soil is in the form of nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+) *(adapted from www.windows2universe.org).*

- Use of fossil fuels for agricultural machinery such as tractors and irrigation equipment
- Use of fossil fuels in the production of agricultural inputs such as fertilizers and pesticides.

Soils can also be producers of CH_4, e.g., wetlands or rice cultivation.

Carbon levels in soil are determined by the balance of inputs, as crop residues, and C losses through organic matter decomposition. Management to build up SOC requires increasing the C input, decreasing decomposition, or both.

The C input may be increased by:

- Intensifying crop rotations
- Reducing tillage and retaining crop residues
- Optimizing agronomic inputs such as fertilizers, irrigation, pesticides, and liming.

The decomposition of C may be decreased by:

- Altering tillage practices
- Including crops with slowly decomposing residue in the rotation.

Following an improvement in agricultural management practices, soil organic carbon will gradually approach a new steady state. Estimates of the time required to reach the new steady state range from 20 to 40 years to 50 to 100 years.

2.2.2. Nitrogen

The C and N cycle are linked through the reservoirs in crop and soil organic matter. Nitrogen can enter the soil from the atmosphere through dry and wet N deposition, fertilizers/manures and N fixation. The N content in the soil can be reduced by processes like ammonia (NH_3) volatilization and emission of denitrification products (N_2, N_2O, NO). Mineral N in the soil can also be used through the N uptake of the crop. The crop residues will add to the organic N pool. This organic N from decaying plant and animal residues is converted into inorganic mineral forms, leading first to the formation of ammonium (NH_4^+), in a process called *mineralization*. The opposite happens when ammonium is taken up by micro-organisms and reprocessed to organic N (*immobilization*). These two processes are continuously changing the mineral N reserves in the soil. In instances of excessive wetting, mineral N (particularly NO_3^-) may leach beyond the reach of the crop's roots (*leaching*, Figure 1b).

Nitrogen dynamics in agricultural systems are very much influenced by the large quantities added as N fertilizers. Nitrogen supply to soils increases productivity and biomass accumulation in the short-term. Therefore, increased N input levels have been perceived as a strategy to favor soil C sequestration. However, N application as fertilizers implies CO_2 emission costs, due to production, packaging, transport and application of the fertilizers. Additionally, increases in soil organic matter may accelerate N dynamics and thus emission of N_2O, a greenhouse gas. In summary, N affects the net greenhouse gas balance in four ways:

1. CO_2 is released from the energy and fossil fuels required for intensive production of N fertilizer
2. Crop yield changes as a function of the N application rate
3. Increased use of N fertilizer can cause a decline in soil pH. This calls for the use of agricultural lime, production of which is also energy-intensive and CO_2 yielding
4. N_2O emissions vary with tillage practice and as a function of the N application rate.

3. Managing soil carbon: Conventional versus conservation agriculture

3.1. Microbial carbon decomposition and immobilization

The increase in soil organic carbon in cropping systems depends on the input and characteristics of organic material added to the soil and its decomposition by micro-organisms. Organic matter is the principle C substrate for soil micro-organisms. Upon mineralization, some of the C in the organic material is used for growth and maintenance, while the remainder is respired as CO_2 and returns to the atmosphere. Factors regulating decomposition are:

(1) Climate
(2) Chemical constraints related to soil biota resources
(3) Physical properties of the soil
(4) Biological regulation through interactions between macro- and micro-organisms.

Research has shown that plant material decomposes most rapidly in soils with a relatively large volume of pores with neck diameters of 15–60 μm. As decomposition proceeds, resource quality changes: the substrates which assimilate readily are rapidly metabolized whereas resistant compounds such as lignin substances tend to accumulate.

Nutrient element deficiency at any stage of decomposition may limit microbial activity and thereby block nutrient release. The nutrient lacking is most often N.

3.1.1 The influence of soil macrofauna on aggregation

Soil macrofaunal activity has been found to contribute to both macro- and microaggregate formation. In particular, earthworms, ants, and termites ('ecosystems engineers') ingest a mixture of organic matter and mineral soil favoring residue incorporation into the soil and thus contribute to aggregation levels. Earthworms' casting promotes the creation of stable organic-mineral complexes with reduced decomposition rates and favors soil stability if allowed to dry or age. Soil macrofauna also play an important role in microaggregate formation. During gut transit, organic materials are intimately mixed and become encrusted with mucus to create nuclei for microaggregate inception.

In conventional systems, there is a direct impact (physical abrasion by tillage and absence of residue cover) and indirect impact (habitat destruction by tillage) on soil macrofauna leading to absent or very low populations. This explains why soil macrofauna populations are generally greater under CA compared to conventional systems. The greater biological complexity under CA implies that macrofauna partly regulate decomposition by microbial biomass, and favor biogenic aggregate formations.

3.1.2. Macroaggregates and microaggregates-within-macroaggregates

Macroaggregates are gradually bound together by temporary (i.e., fungal hyphae and roots) and transient binding agents. These temporary binding agents (i.e., microbial- and plant-derived polysaccharides) gradually decompose into fragments (particulate organic matter or POM) which, when coated with bacteria and fungi mucilages, become encrusted with clays. This process results in the creation of microaggregates-within-macroaggregates (Figure 2). It is occluded intra-aggregate particulate organic carbon (iPOM C) in soil microaggregates which constitute the main mechanisms for long-term soil C sequestration in agricultural soils.

Microaggregates-within-macroaggregates constitute relatively stable and secluded habitats for micro-organisms. Macroaggregate turnover under low level disturbance conditions in CA is slow enough to allow fine iPOM C to be predominantly stabilized in free and intra-microaggregates. Conventional systems alter this process.

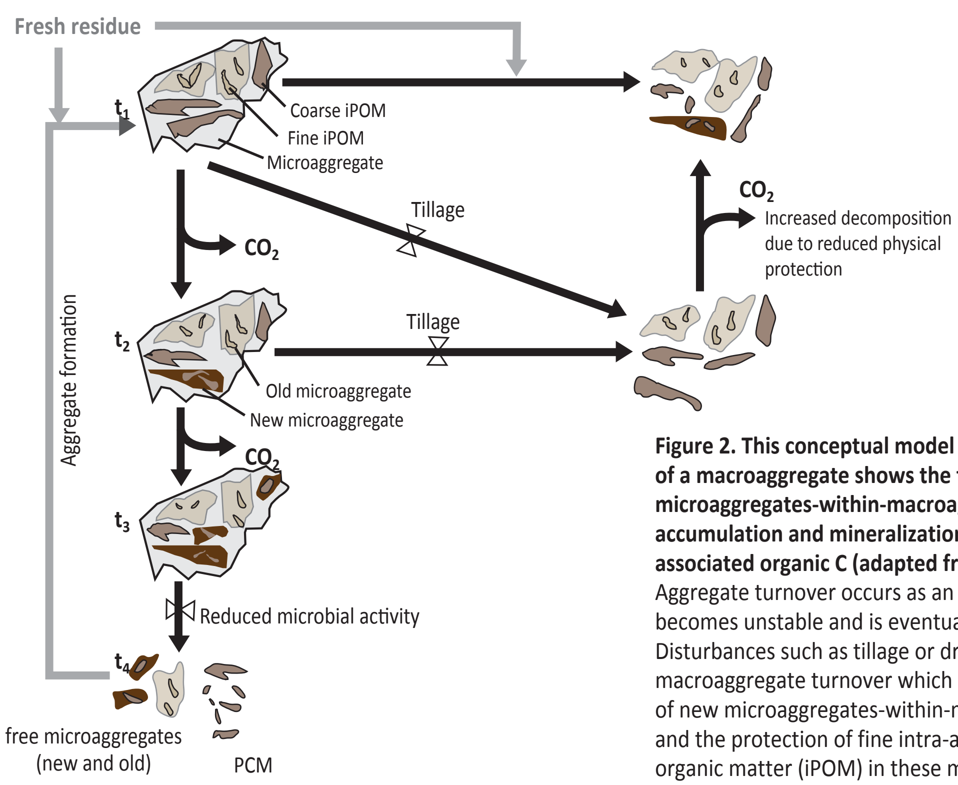

Figure 2. This conceptual model of the 'life cycle' of a macroaggregate shows the formation of new microaggregates-within-macroaggregates and the accumulation and mineralization of aggregate-associated organic C (adapted from Six et al., 2000). Aggregate turnover occurs as an aggregate is formed, becomes unstable and is eventually disrupted. Disturbances such as tillage or dry–wet cycles enhance macroaggregate turnover which prevents the formation of new microaggregates-within-macroaggregates and the protection of fine intra-aggregate particulate organic matter (iPOM) in these microaggregates.

Tillage disrupts macroaggregates exposing coarse iPOM C to microbial attack and preventing its incorporation into microaggregates as fine iPOM C. Soil organic carbon differences found between CA and conventional systems are mostly explained by iPOM C protected in microaggregates due to drastic differences caused by tillage disturbance (Figure 3).

The slower turnover of microaggregates-within-macroaggregates in zero tillage allows greater protection of coarse POM and greater stabilization of mineral-bound C decomposition products in the microaggregates-within-macroaggregates.

3.2. The importance of full carbon cycle analysis

C sequestration in soil, C storage in crop residue and CO_2 emissions from farming activities should be considered together to evaluate the mitigation capacity of different farming activities to atmospheric CO_2. To include farming activities, estimates must be made of energy use and CO_2 emissions for primary fuels, electricity, fertilizers, lime, pesticides, irrigation, seed production, and farm machinery. The largest contribution CA makes to reducing CO_2 emissions associated with farming activities is through the reduction of tillage operations. However, while enhanced C sequestration will continue for a finite time, the reduction in net CO_2 flux to the atmosphere, caused by reduced fossil fuel use, can

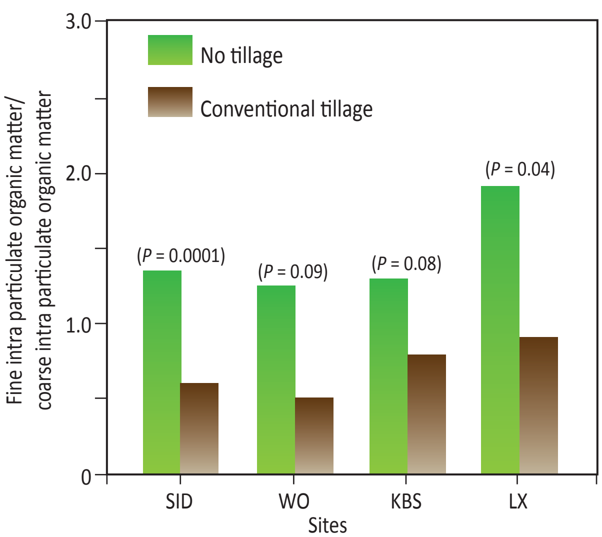

Figure 3. Differences in the ratio of fine intra particulate organic matter/coarse intra particulate organic matter between conservation agriculture (no tillage) and conventional systems (adapted from Six et al., 2004).

continue indefinitely, as long as the alternative practice is continued and could more than offset the amount of C sequestered in the soil in the long-term.

Conservation agriculture can also reduce CO_2 emissions by saving irrigation water. Irrigation contributes to CO_2 emissions because energy is used to pump irrigation water and, when dissolved, calcium (Ca) precipitates in the soil, forming $CaCO_3$ and releasing CO_2 to the atmosphere. The use of residue in zero tillage systems elevates the soil moisture content, potentially saving irrigation water.

3.3. The influence of conservation agriculture on soil organic carbon stocks

Soil organic carbon stocks can be measured directly with soil samples or can be inferred via soil CO_2 emissions. When measuring SOC in soil samples, the following factors have to be taken into account:

(1) Bulk density

(2) Depth of sampling.

Bulk density can be affected by tillage practice. Higher values for bulk density have been reported under zero tillage. Therefore, if we sample at the same depth for CA and for conventional tillage, a greater mass of soil will be taken from the zero tillage soil. This could increase the mass of SOC in the zero tillage soil and could exaggerate the difference in SOC between the two systems. An equivalent soil mass should be taken, when the entire topsoil is not sampled and there are significant amounts of SOC situated beneath the lowest sampling depth.

Tillage practice can also influence the distribution of SOC in the profile with higher soil organic matter (SOM) content in the surface layers with zero tillage than with conventional tillage, but a higher content of SOC in the deeper layers where residue is incorporated through tillage. Therefore, it could be necessary to adjust the *depth of sampling*. To account for possible differences in root distribution and rhizodeposition between management practices, the entire soil profile should be sampled.

Changes in soil C can, in principle, be inferred from continuous measurements of net ecosystem CO_2 exchange between the land surface and the atmosphere, provided other C additions or losses (e.g., harvested grain) are properly taken into account. Measurements of CO_2 emissions have been confined mainly to the period after tillage events. However, at a seasonal level, the CO_2 fluxes are also slightly greater for conventional tillage compared to CA.

To better understand the influence of the different components comprising CA (reduced tillage, crop residue retention, and crop rotation) on SOC stocks, we will discuss the effects of each of these components.

3.3.1 The influence of tillage practice on soil organic carbon stocks

The influence of reduced tillage on SOC stocks still seems unknown. Results are often conflicting. In many studies, SOC levels under zero tillage were significantly different from SOC levels under conventional and reduced tillage, whereas SOC levels under conventional and reduced tillage were not significantly different. The mechanisms that govern the balance between increased or no sequestration after conversion to zero tillage are not clear. Although more research is needed, some important factors can be distinguished:

(1) Differences in root development and rhizodeposits:

Crop root-derived C may be very important for C storage in soil. Zero tillage can produce greater horizontal distribution of roots and greater root density near the surface.

(2) Baseline C content:

The effectiveness of C storage in zero tillage is reduced and can be negative when the baseline SOC content increases. It can be speculated that old depleted soils have more potential to sequester carbon compared to young soils rich in carbon. Soils that have lost SOC through soil erosion have a high potential to gain SOC when converted from conventional tillage to zero tillage.

(3) Soil bulk density and porosity:

Physical properties appear to determine whether or not the use of zero tillage practices will enhance C storage by increasing physical protection of SOC. Pores with a neck diameter between 15 and 60 µm seem to result in rapid decomposition of the C within.

(4) Climate:

Management impacts are sensitive to climate in the following order from largest to smallest changes in SOC: tropical moist > tropical dry > temperate moist > temperate dry. Hence, the effects of tillage on soil carbon tend to be smaller or negative in cold-temperate soils. Climatic conditions that influence the plant and soil processes driving soil organic matter dynamics influence the impacts of agricultural management on SOC storage. The processes involved are:

1. The breakdown of SOM following cultivation
2. The formation of aggregates in soils after a change in tillage practice
3. The increased productivity and C input with the implementation of a new cropping practice

(5) Landscape position and erosion/deposition history:

Most of the available studies on C sequestration in different management systems have been conducted on small research plots. In general, these are situated on small, level portions of agricultural fields to minimize confounding effects. However, this does not allow the study of the interaction of other factors on changes in SOC. Landscape position and erosion/deposition history play a significant role. Landscape positions that had a low SOC stock in the past due to past erosion generally show gains in SOC. Positions with large SOC stocks due to deposition show losses after 15 years of zero tillage.

(6) Suboptimal conditions at the farm level:

Research is mostly undertaken on plots that are managed in ideal conditions. This is not always the case in farmers' fields. Agricultural production and farmers' decisions are affected by multiple constraints and natural resource management is tackled at the farming system level, in many cases leading to sub-optimal plot management, particularly when production resources are scarce. These suboptimal conditions could lead to a delay of 2–5 years in the SOC build-up period.

3.3.2. The influence of crop rotation on soil organic carbon stocks

An increase in moisture conservation related to CA practices can result in the possibility of growing an extra cover crop right after the harvest of the main crop. Cover crops enhance soil protection, soil fertility, groundwater quality, pest management, SOC concentration, soil structure and water stable aggregates. Cover crops promote SOC sequestration by increasing the input of plant residue and providing a vegetal cover during critical periods. The inclusion of a N_2-fixing green-manure crop is, however, only feasible in regions without a prolonged dry season (Figure 4).

CA can increase the possibility for crop intensification due to a faster turnaround time between harvest and planting. Crops can be planted earlier and in a more appropriate planting time. Moreover, new crops can be introduced since the actual growing period can be increased or yet another crop can be planted right after harvest of the main crop. The increased input of C as a result of the greater productivity due to crop intensification can result in increased C sequestration. The effect of crop rotation on C sequestration can be due to increased biomass C input, because of the intensified production, or due to the changed quality of the residue input. Crop rotation is more effective than monoculture systems in retaining C and N in the soil.

3.3.3. The influence of residue retention on soil organic carbon stocks

Crop residues are precursors of the SOM pool. The decomposition of plant material to simple C compounds and assimilation and repeated cycling of C through microbial biomass with formation of new cells are the primary stages in the humus formation process. Returning more crop residue is associated with an increase in SOC concentration.

The rate of decomposition depends not only on the amount of crop residues retained, but also on soil characteristics and the composition of residues (i.e., the soluble fraction, lignin, hemic cellulose and polyphenol content).

3.3.4. Conservation agriculture: The combined effect of minimum tillage, residue retention and crop rotation on soil organic carbon stocks

Conservation agriculture is not a one-component technology but the product of the cumulative effect of all three components from which it is comprised. However, applying these three components is not always easy. In more arid areas, competition for residue is extremely high and farmers struggle to keep sufficient residue on the soil. Reducing tillage without sufficient residue retention can lead to tremendous soil degradation.

The crop intensification component will result in an added effect on C storage in zero tillage systems. But, to obtain an accumulation of SOM there must not only be a C input from crop residues but a net external input of N, e.g., including a N-fixing green-manure crop in the crop rotation. Conventional tillage can diminish the effect of a N-fixing green-manure crop either because the N-input can be reduced by soil mineral N release or the N can be lost by leaching (NO_3^-) or in gaseous forms (via NH_3, volatilization or denitrification) due to SOM mineralization stimulated by disc plowing. Hence, intensification of cropping practices, by the elimination of the fallow and moving toward continuous cropping is the first step towards increased C sequestration. Reducing tillage intensity, by the adoption of zero tillage, enhances the cropping intensity effect.

Fig. 4: A field of alfalfa, a typical N_2-fixing green-manure crop.

4. Conservation agriculture in relation to other trace gasses

In studies of greenhouse gasses in CA, CO_2 is the most studied gas. However, we should consider the net result of fluxes for all three major biogenic greenhouse gasses (CO_2, N_2O, and CH_4) on radiative forcing, which is essential for understanding agriculture's impact on the net global warming potential. Increases in SOM, can increase N cycling in soil which leads to larger emissions of N_2O, as nitrification is stimulated. As a result, more NO_3- will be formed in the soil, but when anaerobic micro-sites are formed, reduction of N_2O or N_2 will be reduced which will increase the N_2O/N_2 ratio. However, zero tillage with residue retention improves soil structure compared to conventional tillage, so fewer anaerobic micro-sites will be formed. More research is needed to determine how the emissions of N_2O and NO are really affected.

Better aeration of the soil as a result of increased soil organic matter content and the resultant increased aggregation stability will inhibit denitrification and stimulate oxidation of CH_4. Converting natural soils to agricultural soils reduces their capacity to serve as a sink for CH_4. However, soil as a sink for CH_4 is far less important than as a source for N_20.

5. Farmers managing soil carbon

5.1. The economic potential of conservation agriculture for carbon sequestration

The technical potential of CA for C sequestration has been established in the previous sections. In the following section, we will discuss the economic potential of CA for C sequestration considering the profitability and the cost of C sequestration, and the prospects for widespread adoption. Generally, the off-site public benefits of CA exceed the on-farm private benefits. It should be noted that the profitability of CA varies widely, depending on the characteristics of farming systems, local markets and institutions, and relevant agri-environmental policies. The cost of production and labor use may increase under CA, at least initially, but the gross margins and returns to labor are larger than under conventional tillage. For example, the reduction of field operational costs and the higher returns in yield mean that CA practices have a higher relative profitability compared with conventional tillage, in diverse farming systems, climates, and regions.

There are relatively few studies on the cost of C sequestration. However, it seems that C sequestration through improved crop system management is competitive with non-agricultural C sequestration (with C prices between USD $10–25 per ton).

Carbon markets offer the potential of additional income for farmers including, under certain conditions, smallholders in developing countries. The Clean Development Mechanism (CDM) of the Kyoto Protocol provided both the framework and the stimulus for carbon trading (Figure 5). The CDM allows industrialized countries to invest in emission reductions wherever it is cheapest globally. Although the price is low, this offers another potential source of income for farmers, and may provide added incentive for the adoption of C sequestration technology. By reducing their CO_2 emissions, farmers would not only work more sustainably, but also receive additional income in return.

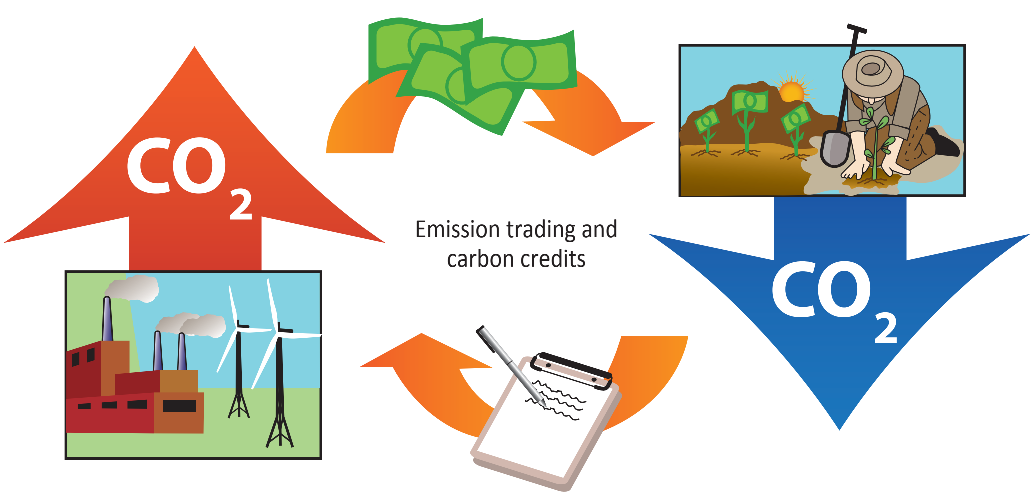

Figure 5: Schematic visualization of the Clean Development Mechanism (CDM). Industrialized countries can invest in emission reductions wherever it is cheapest globally. This provides farmers with an opportunity for additional income.

5.2. Farmers managing soil carbon: beyond direct incentives

Management of the majority of soil C lies in the hands of the farmers, pastoralists, and forest managers whose decisions are determined by multiple goals. The major potential for CA as a climate mitigation strategy is based on its related agronomic and economic productivity gains. As described earlier, the additional private benefits from adoption of CA are generally substantial, even without market or subsidy payments from C sequestration. Conservation agriculture has the win-win combination of being a soil and water conservation technology that can also increase productivity in most cases. For instance, higher yields are the result of better soil quality, especially in the topsoil. Increased aggregation and soil organic matter at the soil surface lead to increased water and nutrient use efficiency, as well as reduced soil erosion. The increased production profitability can be the major driving factor for farmers to implement CA and the soil carbon sequestration strategy, and thus, go beyond ineffective and expensive direct incentives.

5.3. Constraints and pathways for adoption

Conservation agriculture appears to generate attractive private and social benefits, as well as improve yield stability and the productivity of inputs. As it is clear that there are many benefits linked to the adoption of CA, we could wonder why the adoption rates are not faster. There are a few reasons that deserve discussion:

(1) Competitive demands on resources at the farm level, such as crop residues, can constitute serious bottlenecks to CA implementation, especially in semi-arid rainfed agriculture areas where there is a high demand to use crop residues for purposes other than leaving them in the field (e.g., for animal feed).

(2) The smallholders are very diverse, with a variety of characteristics. This slows down the adoption of new productivity-enhancing technologies.

(3) Many poor smallholders are risk averse and avoid introducing new practices with the perceived additional risk to household food security.

(4) Smallholders have little access to financial capital for new equipment or the purchase of inputs such as herbicides.

(5) When farmers rely on family or shared labor, often the workers lack the understanding of CA even if the farmer does have a good appreciation of its principles and practices.

(6) Sometimes the farmers themselves lack education and thus are excluded from some of the knowledge streams which provide information about CA.

(7) Small scale itself can be a constraint for the efficient utilization of much CA farm equipment.

It is unlikely that complex, multi-component technologies such as CA can be successfully scaled up through traditional linear models of research and extension. Instead they require the development of innovative systems to adapt technologies to local conditions. For this purpose, decentralized learning hubs within different farming systems and agro-ecological zones are being developed. In these hubs, intense contact and exchange of information is organized between the different partners in the research and extension process. Through research and training, regional CA networks are established to facilitate and stimulate research and the extension of innovation systems and technologies. The hubs are directly linked to the strategic science platforms operated by the international centers and national research institutes to permit the synthesis and global understanding of CA, and its adaptability to different environments, cropping systems and farmers' circumstances.

5.4. The consequences of rotating tillage practices for carbon sequestration

Because SOC responds dynamically to management, a policy to promote C sequestration presupposes the maintenance of the practices, which promote the accumulation of organic matter. Once the switch to zero tillage is made, it is best not to return to conventional tilling. However, tillage systems are rotated for various reasons, including optimizing yields and managing pest and disease problems. It has not been tested in the field, but simulation models show that changing the management from zero tillage to conventional tillage within monoculture systems reduces soil C content. The tillage events result in loss of soil C, with an increased CO_2 emission after tillage. In the longer term, the effect of a single tillage operation on SOC content in fields that have been under zero tillage for an extended period seems to differ between soils with different properties.

6. Conclusions and future perspectives

Currently, the global area of land under cultivation has been strongly degraded. Crops require ever-increasing inputs to maintain yields. Conservation agriculture is a cropping system characterized by both short-term maximization of crop production as well as by potential long-term sustainability. Important gaps still need to be addressed if CA is to be used as a strategy for C sequestration. For the developing world and the more tropical and subtropical areas, information is lacking on the influence of tillage and crop rotation on C storage. Most studies have been conducted at the plot level, and more holistic research at the farm level, including agro-ecosystem constraints, is needed, as well as total C sequestration budgets at the regional and global levels.

Although C sequestration is questionable in some areas and in some cropping systems, CA remains an important technology that improves soil processes, controls soil erosion, and reduces tillage-related production costs. Global food security, global environmental preservation, as well as farmer-level increased livelihood, should be the main goals of a sustainable farming system.

Further reading:

Govaerts, B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K. D., Dixon, J., Dendooven, L., 2009 Conservation agriculture and soil carbon sequestration: Between myth and farmer reality. Critical Reviews in Plant Sciences, 28:3, 97–122.

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