Ameliorating the Effects of Climate Change with Soil Carbon:
Increasing Soil Carbon, Crop Productivity and Farm Profitability

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Abstract
This paper explains how atmospheric carbon is introduced into the soil and how it stored in stable forms. It identifies the farming techniques that are responsible for the decline in soil carbon and gives alternative organic farming practices that do not damage carbon. Increasing soil carbon can reduce the 25% of Australia's greenhouse gases created by agriculture and assist in ameliorating the effects of climate change. Increasing soil carbon will ensure good production outcomes and farm profitability. Soil carbon, particularly the stable forms such as humus and glomalin increase farm profitability by increasing yields, soil fertility, soil moisture retention, aeration, nitrogen fixation, mineral availability, disease suppression, soil tilth and general structure. They build soil structures that are highly resistant to erosion and have minimal loss of water-soluble nutrients. This is of critical importance to all our aquatic systems, especially the Great Barrier Reef.

Introduction

Climate change is one of the major issues affecting all of us on our planet. Experts expect that it will have a negative effect on our food supply due to more frequent adverse weather events leading to increasing crop failures. The security of our food supply concerns all of us.

It is possible to have farming systems that sequester more atmospheric greenhouse gases than they emit and help reverse the cause of climate change. These farming systems are also more resilient in the weather extremes of floods and droughts that are predicted as part of global warming.

Scientific studies show that by increasing soil carbon, farming systems can have significantly less nutrient and pesticide runoff. This is particularly important where our agricultural activities are affecting the water quality in sensitive area such as the Great Barrier Reef.

The latest report from the Great Barrier Reef Marine Park Authority states: “Water quality in the Great Barrier Reef is principally affected by land-based activities in its adjacent catchments, including vegetation modification, grazing, agriculture, urban development, industrial development and aquaculture. Nutrients, sediments and pesticides are the pollutants of most concern for the health of the Great Barrier Reef.” *(Prange J et al, 2007)*

This paper gives examples of research into farming systems that can ensure good water quality, negative greenhouse gas emissions and high yield. The studies are from long term comparison trials of organic agriculture with current conventional farming systems. Very importantly, the farming techniques can be used by all farmers. It is not necessary to become an organic farmer to adopt the methods on conventional farming systems.

One of the central tenets of organic farming is to improve soil health and productivity by increasing organic matter (carbon) levels, particularly humus.

Published studies show that these best practice organic farming systems are more resilient to the predicted weather extremes. The studies showed that organic systems have higher yields than conventional farming systems in weather extremes such as floods and droughts. (*Drinkwater, L. E., Wagoner, P. & Sarrantonio, M. 1998, Welsh R. 1999),*

Systems Use Water More Efficiently

Research shows that organic systems use water more efficiently due to better soil structure and higher levels of humus. *(Lotter 2003, Pimentel 2005) 'Soil water held in the crop root zone was measured and shown to be consistently higher by a statistically significant margin in the organic plots than the conventional plots, due to the higher organic matter content in the organic treated soils' (Lotter 2003).*

The open structure allows rain water to quickly penetrate the soil, resulting in less water loss from run off. *'The exceptional water capture capability of the organic treatments stood out during the torrential downpours during hurricane Floyd in September of 1999. The organic systems captured about twice as much water as the CNV* [conventional] *treatment during that two day event' (Lotter 2003).*

Humus stores 20 times it weight in water so that rain and irrigation water is not lost through leaching or evaporation *(Handrek 1990, Stevenson 1998, Handrek and Black 2002).* It is stored in the soil for later use by the plants *(Drinkwater 1998, Zimmer 2000, Mader 2002).* One consistent piece of information coming from many studies is that organic agriculture performs better than conventional agriculture in adverse weather events, such as droughts *(Drinkwater, L. E., Wagoner, P. & Sarrantonio, M. 1998, Welsh R. 1999, Lotter 2003, Pimentel 2005).*

Erosion and Soil Loss

Soil loss and erosion from farming systems is a major concern around the world *(MA Report 2005,* Prange J et al, 2007*).* Comparison studies have shown that organic systems have less soil loss due to the better soil health *(Reganold et al. 1987, Reganold et al. 2001, Mader et al. 2002, Pimentel 2005).*

'We compare the long-term effects (since 1948) of organic and conventional farming on selected properties of the same soil. The organically-farmed soil had significantly higher organic matter content, thicker topsoil depth, higher polysaccharide content, lower modulus of rupture and less soil erosion than the conventionally-farmed soil. This study indicates that, in the long term, the organic farming system was more effective than the conventional farming system in reducing soil erosion and, therefore, in maintaining soil productivity' (Reganold et al. 1987).

Nitrogen Loss

The use of synthetic nitrogen fertilisers is responsible for one of the major greenhouse gases (nitrous oxide) and for the leaching of water-soluble forms of nitrogen causing pollution in aquatic systems. There is a growing body of data showing that organic systems are far more efficient in using nitrogen, resulting in much lower levels of greenhouse gases and soluble leachates. This is due to the soil carbon, particularly the humus fraction binding onto the nitrogen molecules and ions. *(Mader et al 2002)*

Building Resilient Farming Systems

A scientific review by Cornell University of a 22 year-long comparison field trial of organic and conventional farming systems, publish in the journal *Bioscience (Pimentel 2005),* found that:

- the improved soil allowed the organic land to generate yields equal to or greater than the conventional crops after 5 years;
- the yield of conventional crops declined substantially during drought years;
- the organic crops fluctuated only slightly during drought years, due to greater water holding potential in the enriched soil.

Greenhouse Gas Abatement

Very importantly organic agriculture can help reverse climate change. Published peer review scientific studies in North America and Europe show that best practice organic agriculture emits less greenhouse gases than conventional agriculture and the carbon sequestration from increasing soil organic matter leads to a net reduction in greenhouse gases. (*Drinkwater, L. E., Wagoner, P. & Sarrantonio, M. 1998, Mader P et al, 2002, Pimentel D 2005, Reganold, J. P., et al, 2001)*

Organic agriculture helps to reduce greenhouse gases by converting atmospheric carbon dioxide (CO_2) into soil organic matter. Some forms of conventional agriculture have caused a massive decline in soil organic matter, due to oxidizing organic carbon by incorrect tillage, the overuse of nitrogen fertilizers and from topsoil loss through wind and water erosion.

According to Dr Christine Jones, one of Australia's leading experts on carbon sequestration: *'Every tonne of carbon lost from soil adds 3.67 tonnes of carbon dioxide (CO_2) gas to the atmosphere. Conversely, every 1 t/ha increase in soil organic carbon represents 3.67 tonnes of CO_2 sequestered from the atmosphere and removed from the greenhouse gas equation.'*

'For example, a 1% increase in organic carbon in the top 20 cm of soil with a bulk density of 1.2 g/cm^3 represents a 24 t/ha increase in soil OC which equates to 88 t/ha of CO_2 sequestered." (Jones 2006)

Data from the Rodale Institute's long-running comparison of organic and conventional cropping systems confirms that organic methods are far more effective at removing carbon dioxide from the atmosphere and fixing it as beneficial organic matter in the soil.

According to the Rodale Institute *"U.S. agriculture as currently practiced emits a total of 1.5 trillion pounds of* CO_2 *annually into the atmosphere. Converting all U.S. cropland to organic would not only wipe out agriculture's massive emission problem. By eliminating energy-costly chemical fertilizers, it would actually give us a net increase in soil carbon of 734 billion pounds."* (*Rodale 2003).*

The critical thing about this data is that it is based what has been achieved in controlled scientific trials. It can be readily achieved by farmers around the world.

How do Farming Systems Increase Soil Carbon?

The correct farming techniques can sequester carbon into the soil and reverse the 25% of Australia's greenhouse gases created by Agriculture. The processes to increase soil carbon can be divided into three steps

1. Use plants to grow soil carbon
2. Use microorganisms to convert soil carbon into stable forms
3. Avoid farming techniques that destroy soil carbon

Why is Carbon Important to Productive Farming?

Soil carbon is one of the most neglected yet most important factors in soil fertility, disease control, water efficiency and farm productivity. Humus and its related acids are significantly important forms of carbon. Below is a summary of the benefits of humus

Humus Improves Nutrient availability:

- Stores 90 to 95% of the nitrogen in the soil, 15 to 80% of phosphorus and 50 to 20% of sulphur in the soil
- Has many sites that hold minerals and consequently dramatically increases the soils TEC (The amount of plant available nutrients that the soil can store)
- Stores cations, such as calcium, magnesium, potassium and all trace elements
- Prevents nutrient leaching by holding them
- Organic acids (humic, fulvic. ulmic and others) help make minerals available by dissolving locked up minerals

- Prevents mineral ions from being locked up
- Encourages a range of microbes that make locked up minerals available to plants.
- Helps to neutralise the pH
- Buffers the soil from strong changes in pH

Humus Improves Soil Structure:
- Promotes good soil structure which creates soil spaces for air and water
- Assists with good/strong ped formation
- Encourages macro organisms (ie earthworms and beetles etc) that form pores in the soil.

Humus Directly Assists Plants:
- The spaces allow microorganisms to turn the nitrogen in the air into nitrate and ammonia
- Soil carbon dioxide contained in these air spaces increases plant growth
- Helps plant and microbial growth through growth stimulating compounds
- Helps root growth, by making it easy for roots to travel through the soil

Humus Improves Soil Water Relationships:
- The open structure increases rain absorption
- Decreases water loss from run off
- Humus molecules soak up to 20 times their weight in water
- It is stored in the soil for later use by the plants.
- Improved ped formation helps the soil stay well drained

(Handrek 1990, Zimmer 2000)

1. Use plants to grow soil carbon

The most economical and effective way to increase soil carbon is to grow it.

Plants get between 95 and 98% of their minerals from the air and water. If we look at the chemical composition of an average plant, Carbon, Hydrogen and Oxygen account for over 95% of the minerals. The remaining 5% or less comes from the soil.

These minerals are combined using the energy of the sun via photosynthesis to produce the carbon based compounds that plants need to grow and reproduce.

The Carbon Gift - How Plants Increase Soil Carbon

It is estimated that between 30-60% of the atmospheric carbon dioxide (CO_2) absorbed by plants is deposited into the soil as organic matter in the form of bud sheaths that protect the delicate root tips and as a range of other root excretions.

These complex carbon compounds contain the complete range of minerals used by plants and are one of the ways that minerals are distributed throughout the topsoil. They feed billions of microbes – actinomycetes, bacteria and fungi that are beneficial to plants. Research shows that the greatest concentrations of microorganisms are found close to the roots of plants. This important area is called the Rhizosphere. These organisms perform a wide range of functions from helping to make soil minerals bio available to protecting plants from disease.

Research has shown that plant roots put many tonnes of complex carbon molecules and bio available minerals per hectare into the soil every year and are a very important part of the process of forming topsoils and good soil structure.

This means that well managed plants can put more bio available nutrients into the soil than they remove from it. Also the nutrients they put into the soil are some of the most important to the crop, to beneficial organisms and to the structure and fertility of the soil.

Managing Weeds to Increase Soil Carbon

If we look at weeds from this perspective, we can see that if we prevent the weeds from choking our crop, especially from getting the important sunlight, they can be increasing the fertility and health of the soil and actually helping our crop, rather than hindering it.

If the weeds are managed properly, and their residues are allowed to return to the soil, their nutrient removal from the soil is zero. In fact, as they are adding between 30% to 60% of the organic compounds they create through photosynthesis into the soil they are increasing soil fertility.

Studies of weed fallows and the microorganisms that they feed, show that they help with increasing the bioavailability of the minerals that are locked into the soil. Soil tests show an increase in soil fertility after weed fallows and when plants are grown as green manures.

It is one of the reasons why ground cover fallows restore soil health. They return tonnes of carbon into the soil, feed the microorganisms that make nutrients bio available and reduce soil pathogens.

The important thing is to ensure that the soil has adequate levels of all the minerals and moisture necessary for growth and that the weed management practices allow the crop to be the dominant plants.

Techniques where weeds are cut down, pulled or grazed and so that their residues will return to the soil will feed the crop. Cutting and grazing plants will result in significant percentages of roots being shed off so that the weed or cover crop plants can re-establish an equilibrium between their leaf and root areas.

These cast off roots not only add carbon and feed the soil microorganisms, they release nutrients to the crop and significantly lower nutrient and water competition. This addition of nutrients encourages the crop roots to grow deeper in the soil, below the weed roots resulting in larger crop root systems and better access to water and soil nutrients.

With these techniques, we are actually increasing the efficiency of the farm surface area capturing sunlight and using photosynthesis to make the carbon based molecules that eventually result in the fertile soils that feed our plants.

It is the nutrients that we lose off farm, either through selling the crop, through soil leaching or erosion that need to be replaced every year. Good fertilisation should always ensure that our soil has the optimum level of all the necessary minerals. If we do not replace the minerals that we remove from our soil when we sell our crop, we are mining our soil and running it down.

One of the reasons why good organic farmers notice that weeds do not become a problem in their systems is because they ensure they have excellent soil nutrition and health by using weed management techniques that build up the soil. **The process becomes one of effective weed management rather than weed eradication.**

One of the problems with herbicides is that by killing the ground cover plants, they stop the food supply that feeds these beneficials thereby lowering the count of beneficial species. Consequently soil borne pathogens like *Phytophthora* and *Fusarium* can take over, as the species that kept them under control are significantly reduced.

2. Use microorganisms to convert soil carbon into stable forms

The stable forms of soil carbon such as humus and glomalin are manufactured by microorganisms. (*Ingham 2003)* They convert the carbon compounds that are readily oxidised into CO_2 into stable polymers that can last thousands of years in the soil. (*Handrek 1990)*

Some of the current conventional farming techniques result in the soil carbon deposited by plant roots being oxidised and converted back into in carbon dioxide. This is the reason why soil organic matter (carbon) levels continue to decline in these farming systems.

The other significant depositories of carbon are the soil organisms. Research shows that they form a considerable percentage of soil carbon. It is essential to manage the soil to maintain high levels of soil organisms.

Also it is essential that farming techniques stimulate the species of soil microorganisms that create stable carbons, rather than stimulating the species that consume carbon and convert it into CO_2.

Creating stable carbon
The process of making composts uses microbes to build humus and other stable carbons. The microorganisms that create compost continue working in the soil after compost applications, converting the carbon gifted by plants roots into stable forms. Regular applications of compost and/or compost teas will inoculate the soil with beneficial organisms that build humus and other long lasting carbon polymers. Over time these species will predominate over the species that chew up carbon into CO_2

Regular applications of composts and/or compost tea also increase the number and diversity of species living in the soil biomass. This ensures that a significant proportion of soil carbon is stored in living species that will make minerals plant available and protect the health of the plants.

Composts bring a significant number of other benefits
Research shows that good quality compost is one of the most important ways to improve soil. It is very important to understand that compost is a lot more than a fertilizer. Compost contains humus, humic acids and most importantly a large number of beneficial microorganisms, that have a major role in the process of building healthy soils.

Compost provides the following benefits:
Humus
- Adds humus and organic matter to the soil
- Inoculates soil with humus building microorganisms.
- Improves soil structure to allow better infiltration of air and water.
- Humus stores 20 times it weight in water and significantly increases the capacity of soil to store water

Nutrients
- Mineral Nutrients
- Organic based nutrients
- Contains a complete range of nutrients
- Slow release
- Does not leach into aquatic environment

Beneficial micro-organisms
- Supplies a large range of beneficial fungi, bacteria and other useful species
- Suppresses soil pathogens
- Fixes nitrogen
- Increases soil carbon
- Release of locked up soil minerals
- Detoxifies poisons
- Feeds plants and soil life
- Builds soil structure

3. Avoid Farming Techniques that Destroy Soil Carbon

The continuous application of carbon as composts, manures, mulches and via plant growth will not increase soil carbon levels if farming practices destroy soil carbon. The following are some of the practices that result in a decline in carbon and alternatives that prevent this loss.

Reduce Nitrogen Applications

Synthetic nitrogen fertilisers are one of the major causes of the decline of soil carbon. This is because it stimulates a range of bacteria that feed on nitrogen and carbon to form amino acids for their growth and reproduction. These bacteria have a Carbon to Nitrogen ratio of around 30 to 1. In other words every ton of nitrogen applied results in the bacteria consuming 30 tons of carbon. The quick addition of these nitrogen fertilisers causes the nitrogen feeding bacteria to rapidly multiply, consuming the soil carbon to build their cells.

This process results in the stable forms being consumed causing a decline in the soil carbon levels. The best analogy is money in a bank. The addition of the large doses of nitrogen fertiliser is the equivalent of a large withdrawal.

Freshly deposited carbon compounds tend to readily oxidise into CO_2 unless they are converted into more stable forms. Stable forms of carbon take time to form. In many cases it requires years to rebuild the bank of stable carbon back to the previous levels.

Ensuring that a carbon source is included with nitrogen fertilisers protects the soil carbon bank, as the microbes will use the added carbon, rather than degrading the stable soil carbon. Composts, animal manures, green manures and legumes are good examples of carbon based nitrogen sources

Where possible plant available nitrogen should be obtained through rhizobium bacteria in legumes and free living nitrogen fixing microorganisms. These microorganisms work at a stable rate fixing the nitrogen in the soil air into plant available forms. They can utilise the steady stream of newly deposited carbon from plant roots to create amino acids, rather than destroying humus and other stable carbon polymers.

Carbon Eaters Rather than Carbon Builders

The use of synthetic nitrogen fertilisers changes the soil biota to favour microorganisms that consume carbon, rather than the species that build humus and other stable forms of carbon. By stimulating high levels of species that consume soil carbon, the carbon never gets to increase and usually continues to slowly decline.

The use of composts with microorganisms that build stable carbons will see soil carbon levels increase if the farm avoids practices that destroy soil carbon.

Reduce Herbicides, Pesticides and Fungicides

Research shows that the use of biocides (Herbicides, Pesticides and Fungicides) causes a decline in beneficial microorganisms. As early as 1962, Rachel Carson quoted research about the detrimental effect of biocides on soil microorganisms in her ground breaking book ‘Silent Spring’. *(Carson 1962)* Since then there have been regular studies confirming the damage agricultural chemicals are causing to our soil biota. *(Cox 2002)*

Recently the work of one of the worlds leading microbiologist, Dr Elaine Ingham has shown that these chemicals cause a significant decline in the beneficial microorganisms that build humus, suppress diseases and make nutrients available to plants. Many of the herbicides and fungicides have been shown to kill off beneficial soil fungi. (*Ingham 2003*) These types of fungi have been shown to suppress diseases, increase nutrient uptake (particularly phosphorus) and form glomalin.

Glomalin is a stable carbon polymer that forms long strings that work like reinforcing rods in the soil. Research is showing that they form a significant role in building a good soil structure that is resistant to erosion and compaction. The structure facilitates good aeration and water infiltration.

Avoiding the use of toxic chemicals is an important part of the process of developing healthy soils that are teeming with the beneficial species that will build the stable forms of carbon.

Use Correct Tillage Methods
Tillage is one of the oldest and most effective methods to prepare planting beds and to control weeds. Unfortunately it is also one of the most abused methods resulting in soil loss, damage to the soil structure and carbon loss through oxidation when used incorrectly.

It is important that tillage does not destroy soil structure by pulverising or smearing the soil peds. Farmers should be aware of the concept of good soil ‘tilth’. This is soil that is friable with a crumbly structure. Not a fine powder or large clumps. Both of these are indicators of poor structure and soil health. These conditions will increase the oxidation of organic matter turning it into CO_2.

Tillage should be done only when the soil has the correct moisture. Too wet and it smears and compresses. Too dry and it turns to dust and powder. Both of these effects result in long term soil damage that will reduce yields, increase susceptibility to pests and diseases, increase water and wind erosion and increase production costs.

Tillage should be done at the correct speeds so that the soil cracks and separates around the peds leaving them in tack, rather than smashing or smearing the peds by travelling too fast. Good ped structure ensures that the soil is less prone to erosion.

Deep tillage using rippers or chisel ploughs that result in minimal surface disturbance while opening up the subsoils to allow better aeration and water infiltration, are the preferred options. This will allow plant roots to grow deeper into the soil ensuring better nutrient and water uptake and greater carbon deposition.

Minimal surface disturbance ensures that the soil is less prone to erosion and oxidation thereby reducing or preventing carbon loss.

Control Weeds without Soil Damage
A large range of tillage methods can be used to control weeds in crops without damaging the soil and losing carbon.

Various spring tynes, some types of harrows, star weeders, knives and brushes can be used to pull out young weeds with only minimal soil disturbance.

Rotary hoes are very effective however this should be kept shallow at around 25mm to avoid destroying the soil structure. The fine 25mm layer of soil on the top acts as a mulch to suppress weed seeds when they germinate and conserves the deeper soil moisture and carbon. This ensures that carbon isn’t lost through oxidation in the bulk of the topsoil.

The same principles of very shallow cultivation should also apply with cutter bars, knives etc when weeding.

There are several cultivators with guidance systems, including GPS systems that ensure precision accuracy for controlling weeds. These can be set up with a wide range of implements and can be purchased in sizes suitable for small horticultural to large broadacre farms.

Organic farmers in the USA, Europe, NZ and Australia are using these to get excellent control over weeds in their crops.

Avoid Erosion

Erosion is one significant ways that soil carbon is lost. The top few centimetres of soil is the area richest in carbon. When this thin layer of soil is lost due to rain or wind, the carbon is lost as well.

Avoid Burning Stubble

Practices such as burning stubble should be avoided. Burning creates greenhouses gases as well as exposing the soil to damage from erosion and oxidation.

Encourage Vegetation Cover

Vegetation cover is the best way to prevent soil and carbon loss. As stated in the previous section *'Managing Weeds to Increase Soil Carbon'*, it is not always necessary to eradicate weeds. Effective management tools such as grazing or mowing can achieve better long term results.

Bare Soils Should be Avoided as much as Possible

Research shows that bare soils lose organic matter through oxidation, the killing of microorganisms and through wind and rain erosion. Cultivated soils should be planted with a cover crop as quickly as possible. The cover crop will protect the soil from damage and add carbon and other nutrients as it grows. The correct choice of species can increase soil nitrogen, conserve soil moisture through mulching and suppress weeds by out competing them.

Conclusion

Effective management of soil carbon not only reduces greenhouse gases by sequestrating carbon, the increase in soil carbon will increase the profitability of the farm by increasing soil fertility, increasing beneficial species, suppressing diseases, increasing water retention, improving drainage and aeration and increasing crop yields.

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