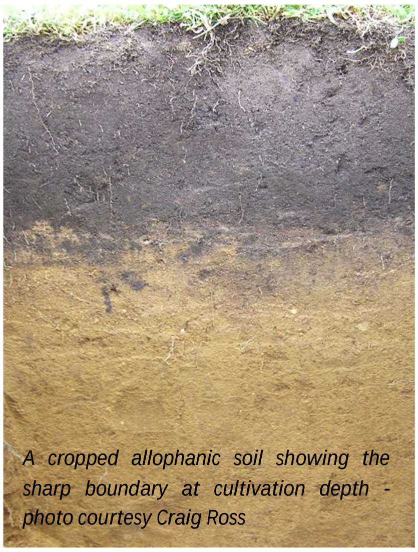
Modelling the benefits of soil carbon in cropping systems



A cropped allophanic soil showing the sharp boundary at cultivation depth - photo courtesy Craig Ross

Soil organic matter has been long-recognised as a valuable resource for many primary production systems. It plays an important role in nutrient cycling, soil water dynamics, soil physical integrity and contaminant attenuation (Fig. 1). Soil organic matter is not a static resource but is continually cycling, with portions of the resource turning over at different rates depending on the chemistry of the organic compounds that make it up. In the context of climate change, our ability to increase soil organic matter has emerged as an effective way of reducing the build-up of atmospheric carbon dioxide (CO_2) by storing soil carbon, which is about 45% of soil organic matter. Increasing the total stock of carbon in soil and/or increasing its longevity in soil are two important ways of storing the atmospheric CO_2 captured by plant photosynthesis, thus mitigating the global greenhouse gas (GHG) effect.

Key points from a study modelling a permanent increase in soil carbon under a dryland Canterbury wheat system with the APSIM model, over 40 years:

- Average crop yield and N_2O losses increased with greater soil carbon, likely a result of greater total soil N and N mineralisation rates. This effect was diminished at higher N fertiliser inputs.
- Other effects of greater soil carbon (reduced soil bulk density and greater water holding capacity) also affected crop yield and N_2O losses, but not in a consistent way.

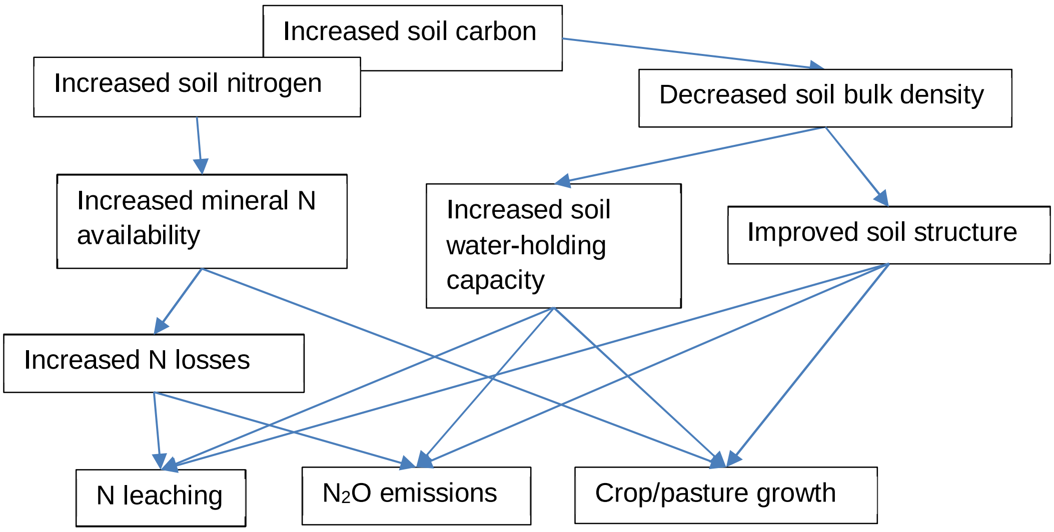


Figure 1: Some important effects of soil carbon on soil processes and crop system outcomes

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Agricultural soils have been globally recognised as having potential to sequester more soil carbon. In a number of countries there are incentive schemes in place for primary producers to modify their management in order to increase soil carbon stocks. Other countries (including New Zealand) are still considering whether to implement this approach in land management policy. A critical consideration is determining the potential for increasing soil carbon by altering soil management practise. This is because: a) all soils have a finite capacity for soil carbon sequestration, and b) international and national policy systems such as the Emissions Trading Scheme only recognise changes brought about by deliberate actions.

Field research has demonstrated that a number of agricultural management practises can increase soil carbon stocks. These include minimum tillage in cropping systems, adding pasture phases in crop rotations, and reducing the grazing intensity of pastures. Other practises such as increases in nitrogen fertiliser inputs and irrigation may increase soil carbon stocks through increases in plant production, but this effect is dependent upon harvest management. In a grazed pasture, if stocking rates are also increased this leads to greater carbon losses from the system via methane production, potentially offsetting the increased carbon inputs from greater plant production.

The need to understand the uncertainty in the soil carbon outcome resulting from changes in agricultural management leads us to develop and test models. Models can encapsulate our understanding of processes and relationships in soil-plant-animal systems and thus can be used to explore the consequences of planned management interventions for soil carbon storage. One such model that is widely used globally is the APSIM (Agricultural Production Systems sIMulator) model framework, which has been developed over decades by an international team led out of CSIRO in Australia (www.apsim.info). APSIM is a dynamic model that covers both cropping and pastoral systems with a wide range of crops and pasture types able to be simulated. It includes a wide array of management procedures that can be used to describe a variety of farming systems (cultivation, sowing, fertiliser, irrigation, harvesting, grazing, etc.). It has been well tested in New Zealand crop and pasture systems by comparing its outputs with experimental data, such as the Winchmore long-term pasture experiments.

The APSIM model is therefore an appropriate tool for investigating the benefits of increased soil carbon in cropping systems. In this study we have used the APSIM soil carbon and nitrogen module, combined with its wheat growth module, to simulate a simple wheat management regime on a specific soil profile. This was part of an international collaboration looking at similar systems in different soil and climate areas across seven countries. The approach we used was to hold soil carbon content at a range of fixed values (by resetting the values at the end of each growing season) and then look at the effect of those different soil carbon levels on valuable system outcomes, such as crop yield. We also included the effects of changes in soil carbon on the emissions of nitrous oxide (N_2O), as it is a much more potent greenhouse gas than CO_2, and it is important to be aware of potential trade-offs (commonly known as "emissions swapping").

We undertook this soil carbon adjustment exercise with the APSIM model for a dryland winter wheat cropping system on the Canterbury Plains. The cultivar simulated was Phoenix and the soil type was a Paparua Silt Loam. We assumed that soil carbon could be increased by one percentage point on this soil type (which has been observed in long-term studies of minimum tillage) and simulated two levels of soil carbon (1.6 and 2.6% in the top 300 mm, Fig. 2) under three different levels of nitrogen fertiliser input (0, 150 and 300 kgN/ha/y).

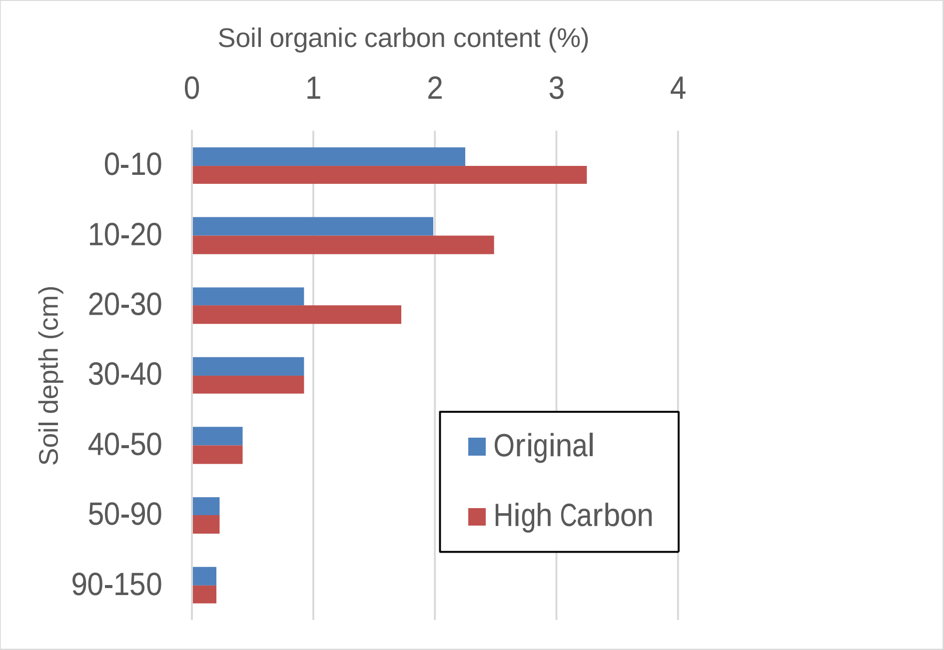

Figure 2: Simulated soil carbon profiles

This exercise has shown that, all else being equal, greater soil carbon leads to higher crop yield (Table 1). This increase in yield can readily be attributed to greater soil nitrogen mineralisation that arises from the increased soil N associated with soil carbon, and the consequently greater N and water uptake by the crop. However, as the fertiliser N input increases, this increase in yield attributable to soil organic matter is reduced – at 300 kg N fertiliser the yield difference is less than 2% compared to 52% without fertiliser. The increase in fertiliser N input masks the benefit of additional N cycling at a higher level of soil organic matter. In addition, both higher levels of soil carbon and greater fertiliser N input also lead to increases in N_2O emissions.

Table 1: The effect of two different levels of soil carbon on average annual wheat yield and annual nitrous oxide emissions over a 40-year simulation on a Paparua silt loam in the Canterbury plains. The results for three N fertiliser rates are shown.

Soil carbon level	Fertiliser input (kgN/ha/y)	Wheat yield (kgDM/ha/y)	Nitrous oxide emissions (kgN/ha/y)
1.6%	0	970	0.20
	150	4108	0.51
	300	5782	1.07
2.6%	0	1475	0.33
	150	4349	0.75
	300	5881	1.48

However, we know that changes in soil carbon content also influence soil properties other than nitrogen cycling (Fig. 1). In particular, increases in soil carbon will lead to a reduction in soil bulk density, an increase in field capacity and permanent wilting point, and an increase in saturated hydraulic conductivity. These soil physical characteristics will in turn have an influence on crop yield, soil water holding capacity, drainage and consequently on nitrogen leaching. However, until recently, the relationships between soil carbon and the soil physical properties were not considered in APSIM. Therefore the APSIM team have used large soil databases to develop a number of algorithms (called pedo-transfer functions) that relate soil carbon content to these additional physical properties and have implemented them in the model. Using these algorithms the dynamics of soil properties can be simulated by the model and influence those critical system outcomes. Figure 3 shows an example of such a pedo-transfer function, using data from the New Zealand national soils database to show that the field capacity of silty clay loams is higher at greater levels of soil carbon. For this soil type, with soil carbon between 0 and 6%, field capacity increases by 10% while permanent wilting point increases by 4%, indicating an overall increase in soil water holding capacity.

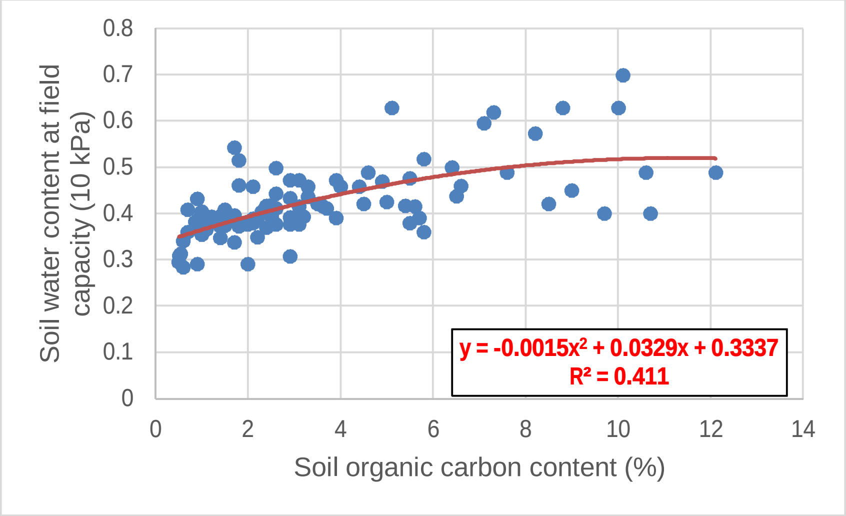

Figure 3: Relationship between soil organic carbon content and field capacity in 97 silty clay loam horizons in the New Zealand National Soils Database. The equation is the best fit polynomial, indicated by the red line, used to adjust soil properties in the model when simulating increased soil carbon.

When we included these soil carbon/soil physical property algorithms in the model simulations of two soil carbon contents and three fertiliser nitrogen levels on the Paparua soil, we found that the effect of greater soil carbon was considerably different to those values originally predicted when just considering the effects of N cycling alone (Table 2). At low levels of nitrogen fertiliser input, the “N-cycling + soil physical” model predicted lower increases in yield and N_2O emissions with greater soil carbon, compared to the “N-cycling alone” model. At high levels of nitrogen fertiliser input, the “N-cycling + soil physical” model predicted greater increases in yield but still lower N_2O emissions when soil carbon was increased, compared to the “N-cycling alone” model.

Table 2: The effect of an increase in soil carbon on wheat yield and annual nitrous oxide emissions, over a 40-year simulation on a Paparua silt loam at Lincoln, comparing simulations based on nitrogen cycling effects alone or based on nitrogen cycling and soil physical effects combined. The results for three N fertiliser rates are shown.

	Fertiliser input (kgN/ha/y)	**1.6% soil carbon**	**Difference at 2.6% soil carbon**	
			N-cycling effects	N-cycling and soil physical effects
Wheat yield (kgDM/ha/y)	0	970	+505	+402
	150	4108	+242	+283
	300	5783	+99	+253
Nitrous oxide emissions (kgN/ha/y)	0	0.20	+0.13	+0.09
	150	0.51	+0.24	+0.19
	300	1.07	+0.41	+0.29

A more detailed analysis of model dynamics suggests that the variation in wheat yield and N_20 loss outcomes for the “N-cycling + soil physical” modelling approach is the result of changes in both soil water and nitrogen conditions for the crop due to greater drainage. Thus, we conclude that simple nutrient cycling models can both overestimate and underestimate the benefits of greater soil carbon, depending on crop management. This emphasises the value of the systems modelling approach in considering the wider effects of altering an apparently simple crop-soil system that is actually quite complex.

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