Modelling soil carbon in agricultural systems: a way to widen the experimental space

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Abstract. Mechanistic and explanatory simulation models provide robust and objective methods to extrapolate likely responses of crops and soils to climate change over different landscapes and time periods. Central to such simulation models are the supply of mineralised nutrients, in particular nitrogen, to crops through linked crop and nutrient sub-models that is achieved through modelling soil carbon dynamics. Attention to soil processes is therefore an essential part of building robust and sustainable production systems and understanding the potential impacts of climate change. To the farmer, focus must be on the productive capacity of the land and its rejuvenation to sustain production. In the broader context of reducing atmospheric CO_2 concentration through soil C sequestration, understanding soil processes and the immediate environment likewise require attention to productivity issues. This is because without maintaining productivity a better understanding of soil organic carbon (SOC) processes is unlikely to lead to increased SOC sequestration in Australia's farming land. Some gaps in knowledge of how to manage SOC are being addressed in a national research effort, including the scant measured data against which models can be tested. Nevertheless, continuing to apply models to push the boundaries well beyond what can be achieved in practice widens the experimental space, allowing new ideas to be tested where physical experiments are not possible. This raises optimism that new ways may be discovered to explain change in SOC and increase SOC where it is possible in a beneficial way.

1. Introduction

Modelling is widely applied to explore practicable and theoretical options in various scientific disciplines. The very early modelling attempts of engineers to model the flow of mass and/or energy [e.g. 1]) meant that nowadays the engineering disciplines like civil engineering, aerospace and mathematics have modelling as an integral part of any serious research enquiry [e.g. 2]. There are


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other disciplines that are still catching up and there are others such as soil science, where there are many advanced models describing numerous components, that will allow their application well beyond what is presently seen.

Simulation models can provide robust and objective methods to extrapolate likely responses of crops and soils to climate change over different landscapes and time periods [e.g. 3]). Whilst simulation modelling can be easily confused with statistical descriptive modelling its distinguishing feature is its propensity for extrapolation beyond the original data. Central to such crop simulation models is the supply of mineralised nutrients to crops, in particular nitrogen, through linked crop and nutrient sub-models that is achieved through modelling soil carbon dynamics [e.g. 4, 5, 6, 7]). Carbon in the soil is primarily linked to carbon in the atmosphere through vegetation and animals. Free Air CO_2 Enrichment (FACE) experiments have shown that crop yields are increased at elevated atmospheric CO_2 concentrations [8], whilst crop nutrient levels (e.g. grain nitrogen concentration) are usually decreased [9, 10]. Such increase in crop growth is likely to result in an increase in soil organic carbon (SOC) storage without water stress but less likely under water stress [11]. Because of the critical nature of mineral nitrogen supplies for crops to maintain high productivity and the effects of immobilisation and mineralisation under altered SOC conditions a focus is required not only on the soil but also the vegetation management. Such a focus has been made in forest systems that have shown no evidence of a progressive nitrogen limitation (PNL) under a prolonged elevated CO_2 environment [12] although for broad acre production systems PNL may impact future N-supply to plants [13]. Therefore, attention to processes, rather than statistical associations, is an essential part of building robust production systems. To the land manager and farmer, focus must be on the productive capacity of the land and its rejuvenation to sustain production and ecosystems beyond the present. This is particularly the case for degraded soil if productivity is to be sustained.

In a broader context of reducing atmospheric CO_2 through soil C sequestration across large areas attention to productivity is considered crucial not only because if its direct link to increased biomass production but also because of the economics of production. The value of production and SOC and their biophysical relationship will therefore be important in our understanding and management of soil C sequestration in Australia's farming land. Modelling together the biophysical and economic constraints may also provide the opportunity to identify the best option to increase SOC within specific regions and agro-ecological zones. Some gaps in our knowledge of how to manage SOC are being addressed in a national research effort. A necessary part of this is the testing of models against the scant measured data that are available. But modelling offers more than testing our understanding of processes against measured data, it allows the exploration of management practices that may offer potential to increase SOC sequestration.

2. Measurements

The measurement of components of the soil involved in SOC dynamics is fundamental to any carbon modelling effort. Standards need to be set so that others can repeat the observations. Hence the national focus on standardised measurement is very helpful to advancing our knowledge and management of soil carbon.

A realistic representation of soils/treatments from soil sampling, often requires a composite sample, which is bulked from multiple sub-samples. It is clear that a large number of sub-samples provide a more realistic representation of the soils/treatment in the composite sample. Chan et al. [14] recommend at least 20 sub-sample cores for obtaining a representative composite sample for estimating the soil C at a particular site. In reality, due to the high costs of such field measurement, the number of samples to make a composite sample typically varies and often is much less than a recommended number, thus introducing more error particularly those relying on repeated measures. For example, in the same long term experiment, the number of sub-samples varied from four [15] to at least 10 [16, 17]. One of the problems in measured SOC data reported is its large variation that is attributed to many reasons including the lack of resource for conducting far more than the actual sub-samples taken. An example of this problem is taken from a well managed long term experiment

(Figure 1). Differences in SOC between two consecutive years can be up to several tonnes, the likely effect of inherent spatial variability, which can be over 30 times the mean rate of change (e.g. 250 kg/year) [18]. Such variation shows impossible mass balance between samplings times. Whilst increased sampling size and extending the sampling intervals by many years are recommended to preserve mass balance, modelling allows the exploration of hypotheses without such limitations.

Another problem in our experimental measurements of SOC to address soil carbon sequestration is the measurement and definition of the plant material that is returned to the soil. This is a key carbon input that drives the microbial processes for soil carbon turnover. Farmers need to understand the differences and ultimately the effectiveness of their SOC change from various sources of carbon input. Large differences exist between crop residues left over on the surface to those that are effectively incorporated into the soil by tillage or animals. Cropping residues are often estimated from a harvest index for running a simulation model, such as RothC. But this is only part of the carbon dynamics as plant material from above and below ground sources contribute. Although we can measure SOC with some degree of accuracy and defined uncertainty, the amount of plant root material is scarcely measured, instead estimating it from above ground production using an assumed root-shoot ratio [19, 20]. In addition we do not have the luxury of measuring what we would like because it is too costly. A well tested simulation model is clearly an efficient means of addressing many aspects beyond the possibility of experimental measurement and provides proof of concept for long-term management systems without being conflicted by cost and experimental error associated with repeated measures.

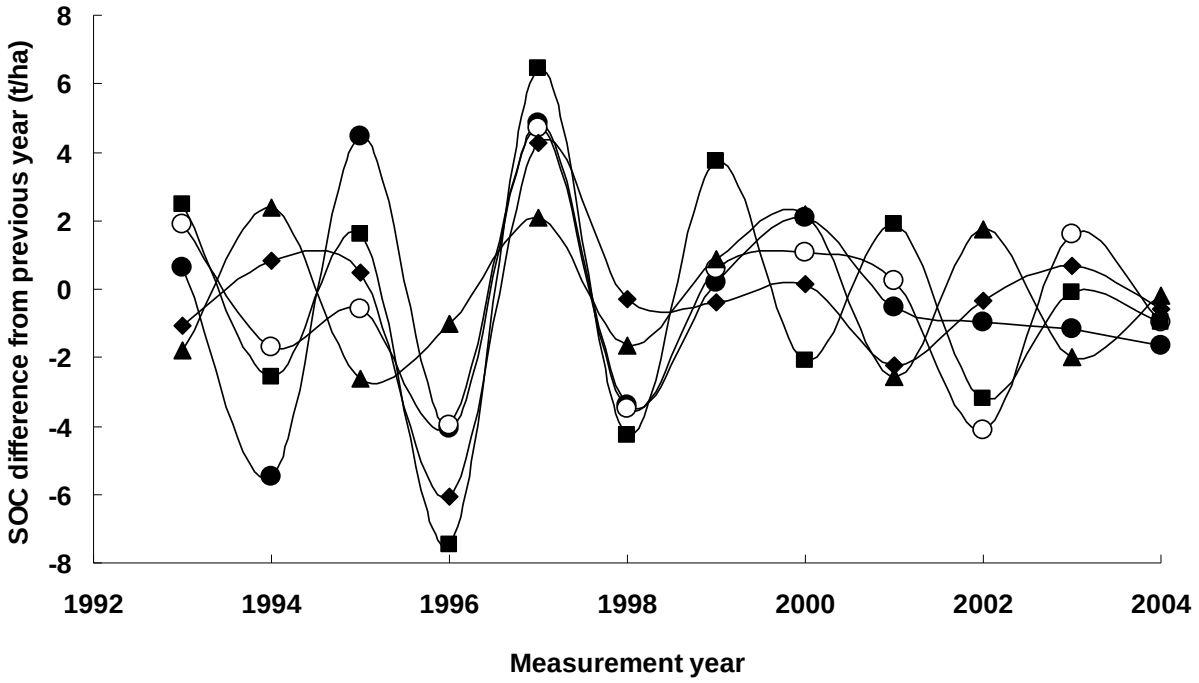

Figure 1: The difference in soil organic carbon (SOC) measured between two consecutive years from a long term cropping experiment (data reanalysed from Liu et al. [19]). No-tillage - stubble retained WL (●), Conventional cultivation - Stubble retained WL (○), No-tillage - Stubble burnt WL (▲), Conventional cultivation - Stubble burnt WL (■), Conventional cultivation - Stubble burnt WW (♦), WL: Wheat-lupin rotation, WW: Wheat-wheat rotation.

3. Modelling

Most soil carbon models are based on first-order decay of soil organic carbon with the role of microbes as decomposers controlling the decay rates [21]. Consequently, SOC is the result of the equilibrium balance of carbon inputs from plant-derived materials and outputs through decomposition affected by soil water and clay content and temperature. Many reports have demonstrated how various SOC models can simulate these processes against measured SOC [22, 23] or comparative modelling studies against measured SOC [e.g. 24, 25]). However, there are very few modelling studies that attempt to explore strategies that increase SOC or explain changes over time compared to those that rely on long term field experiments [e.g. 26]. Wang and Dalal [27] reported that only no-till stubble retention with N application over 33 years long term experiment could increase SOC in Queensland, Australia. Conant et al. [28] reviewed the effect of pasture management and showed that SOC can be increased by improved management practices such as fertilisation, improved grazing management, sowing of legumes and grasses, earthworm introduction and irrigation. Chan et al. [29] used paired-site approach to compare several farming practice systems in south-eastern Australia and found significantly higher SOC stocks occurred only as a result of pasture improvement using P application over unimproved pastures. The changes in SOC were clearly influenced not only by farming practices, but also by climate and soil, and their interactions [30, 31]. It is therefore a challenge for scientists to take disparate experimental results and help farmers develop reliable practices to boost SOC in their paddocks.

The modelling of such inputs and outputs of C varies among models, but some account of important components such as soil erosion is important. Modelling offers the ability to explore practices that have not been robustly tested. For example, SOC levels in a long term experiment have been observed to decrease where stubble was retained on the soil surface in a semi-arid environment [32]. However, subsequent simulation analyses showed that surface retention of the stubble is only equivalent to 26% incorporation of stubble into the soil [19]. With this level of stubble return, SOC would vary widely over a spatial scale because of climatic and soil differences (Figure 2). In this way, modelling opened up a new line of enquiry with respect to developing ways to increase SOC. More recent work from Liu et al. [33] shows that it appears possible to increase SOC in rainfed wheat cropping soils of south eastern Australia by incorporating some higher threshold amount of wheat stubble into the soil. Whilst the suggested incorporation thresholds appear quite large at 50-70% of harvested stubble, practical methods need to be developed and tested to see if this can be achieved in the field. Liu et al. [33] goes on to argue that if such levels of incorporation can be achieved in practice then large gains could be made that potentially could assist Australia meet its emission reduction targets.

That modelling study widened the experimental space and proposed an optimistic approach to soil carbon management. Most long term agronomic experiments were never specifically designed to increase SOC and so don't tend to have very high C input levels, which might help us better understand the mechanisms. Therefore, the reliance on historical experiments not specifically designed to increase SOC may be problematic because statistical associations, whilst evident, need further articulation of the mechanisms involved in boosting SOC. Modelling employing mechanistic and explanatory variables offers a way to break free of this limitation, particularly with their ability to easily examine practices that have not been experimentally tested.

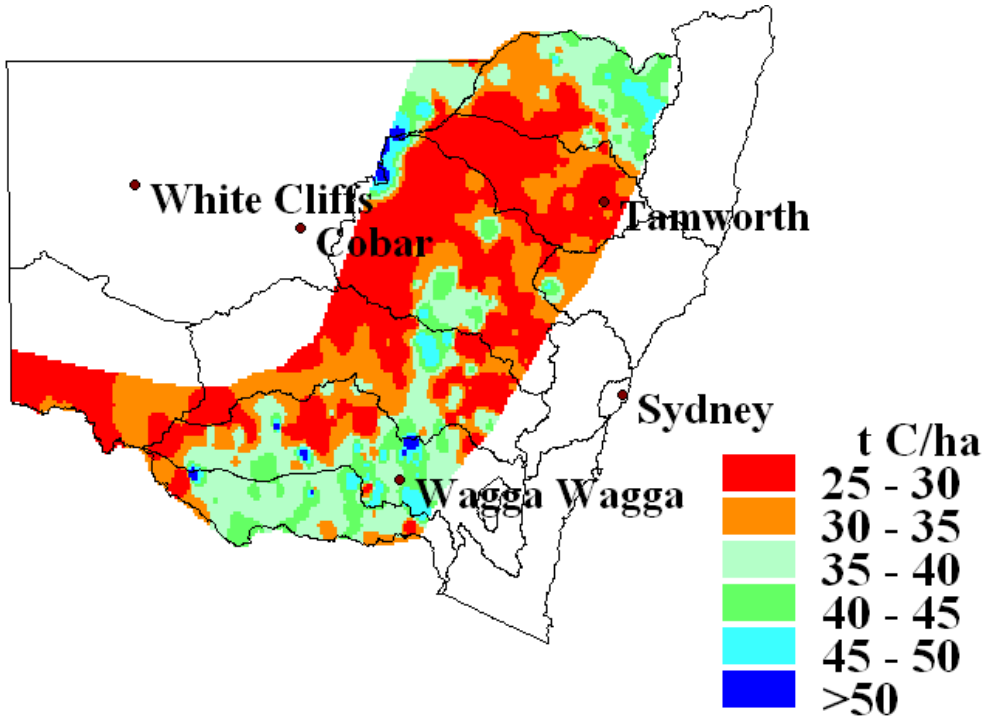

Figure 2: Simulated soil organic carbon (SOC 0-30 cm) equilibration level over New South Wales showing the large spatial variation in SOC from 25 to over 50 t/ha after 50 years under a present climate cropping regime with 26% residue incorporation (from Liu et al. [33]).

4. A way forward

Although modelling is a useful tool to widen the experimental space in soil science, we see that the performance of our contemporary models needs to be better documented. Typical measures of performance should include statistical measures of bias and relative and absolute accuracy such as root mean square error. Whilst the deficiencies in model design and sources of input data error will be apparent in many cases, the measured overall performance is an objective way to assess the extent that any particular model can be relied on and how much SOC change might be realistically achieved. If models are tested against measured data, then the accuracy of both model and data can be articulated and therefore advance soil carbon modelling. We suggest that long-term data sets involving SOC could be made more readily available in formats that could be rapidly applied to modelling studies.

There is a clear need in Australia to commence new long-term field experiments that attempt to increase SOC. Field experimentation examples that are pushing the boundaries are the work of Gill et al. [34, 35, 36] where organic material is placed into the soil with resultant large changes in soil properties and improved productivity. Farming systems that have high productivity in terms of the accumulation of biomass that can find its way into the soil are clearly ones that will feature more in future farming systems that raise SOC. Farming systems in the higher rainfall and cooler areas offer potential in this regard, and modelling such systems widen the experimental space for raising SOC levels in other parts of the Australian landscape. For degraded soils, there may be scope for increasing SOC, because they are starting from low levels and modelling can provide a way to explore options.

A wider experimental space will allow new untested ideas to be pursued where physical experiments are not possible. This raises optimism that new ways may be discovered to explain change in SOC and increase SOC where it is possible in a beneficial way.

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