Kirschbaum, M.U.F., Moinet, G.Y.K, Hedley, C.B., Beare, M.H. and McNally, S.R., 2018. Are soil carbon stocks controlled by a soil's capacity to protect carbon from decomposition?. In: *Farm environmental planning – Science, policy and practice*. (Eds L. D. Currie and C. L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 31. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 7 pages.

# ARE SOIL CARBON STOCKS CONTROLLED BY A SOIL'S CAPACITY TO PROTECT CARBON FROM DECOMPOSITION?

**Miko UF Kirschbaum[1], Gabriel YK Moinet[1], Carolyn B Hedley[1], Michael H Beare[2], Sam R McNally[2]**

*[1]Manaaki Whenua - Landcare Research, Private Bag 11052, Palmerston North 4442*
*[2]Plant and Food Research, Private Bag 4704, Christchurch 8140*
*Email: KirschbaumM@LandcareResearch.co.nz*

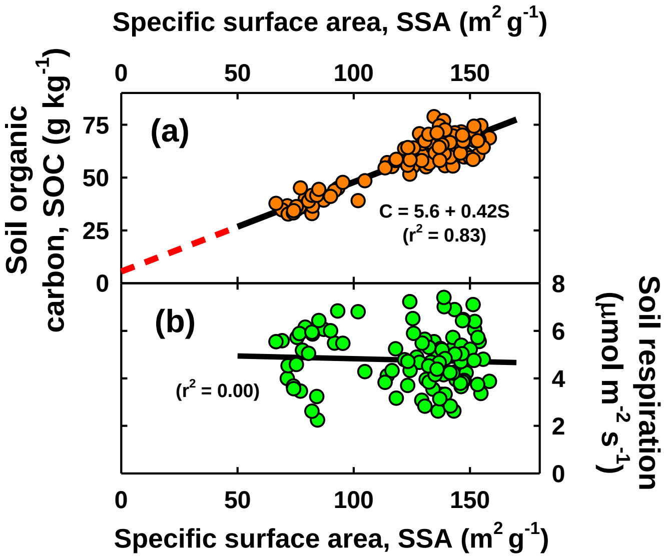
Net greenhouse gas emissions can be reduced by increasing soil organic carbon (SOC), but the factors controlling SOC must be understood so that management changes can be identified to increase SOC. It is known that soils differ in their ability to protect and stabilise SOC. But is SOC protection limited by a soil's maximum capacity to protect carbon, or do soil protection properties act to reduce SOC turn-over rates without defined upper limits? Here, we use observations from two specific New Zealand sites, and from a national soils data set to gain insights into the controls of SOC protection.

The first observation came from a site in the Waikato region. It consisted of observations from neighbouring paddocks on a single intensively managed dairy farm. Most relevant factors, such as climate, soil fertility, plant species and pasture management were therefore the same except specific surface area (SSA). Soil respiration was also unrelated to specific surface area (Fig. 1b), thus suggesting the carbon inputs into the soil were independent of specific surface area. Under those conditions, SOC was highly ($r^2 = 0.83$) linearly correlated with the soil's specific surface area (Fig 1a).

And extrapolation of the fitted relationship back to zero specific surface area had only a small intercept on the y-axis. Together, these observations mean that

1) The protection of soil organic carbon is tightly and linearly dependent on the amount of stabilising surfaces in the soil;
2) Specific surface area is a key property of the soil's carbon protection capacity;

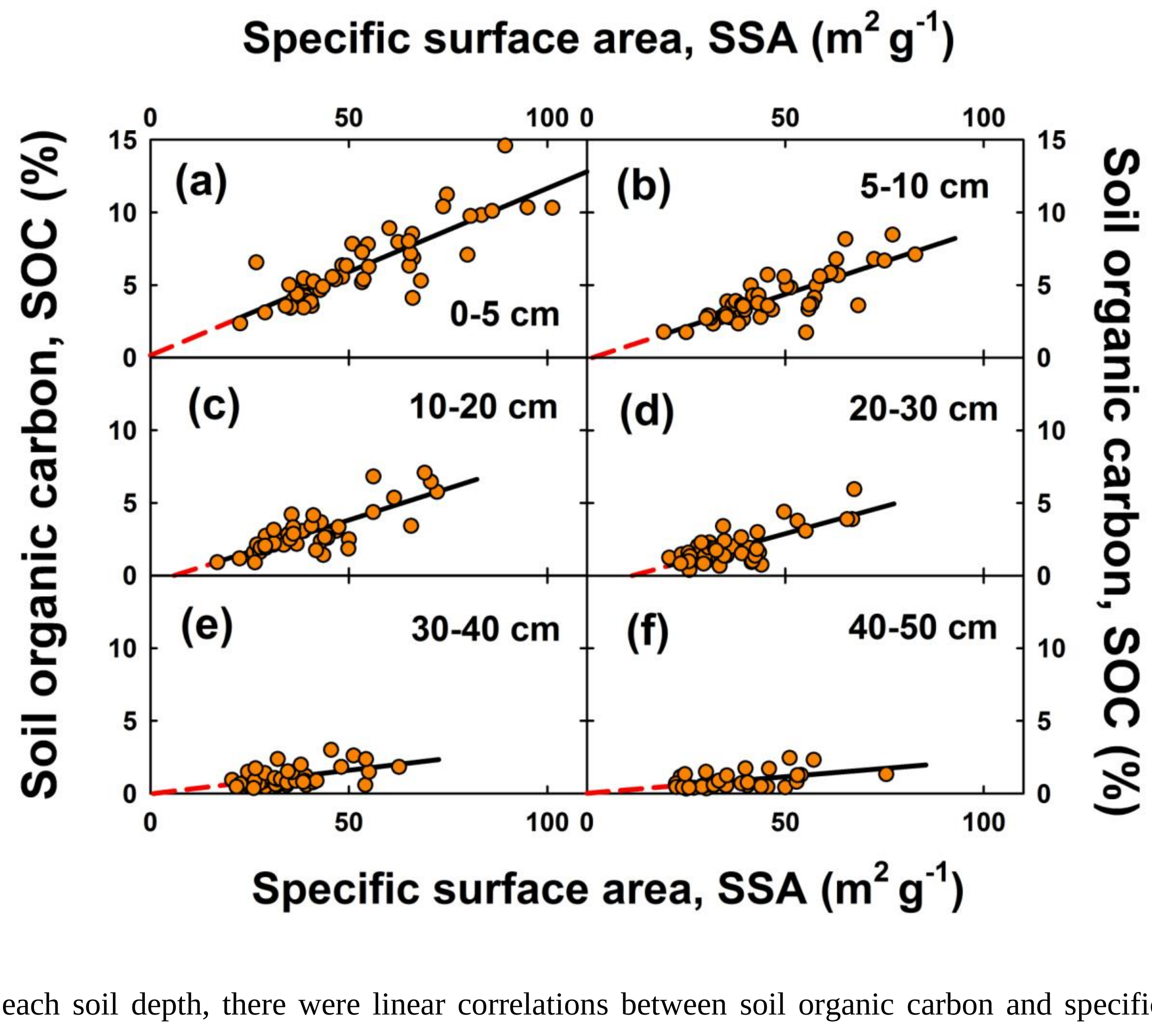
***Figure 1.*** *Soil organic carbon of the top 20 cm of a soil (a) and corresponding soil respiration rates (b) as a function of specific surface area. The solid black lines have been fitted to the data, with respective equations given in the figures. The dashed red line in (a) is an extrapolation of the fitted line to zero specific surface area.*



3) Extrapolation of the relationship to zero specific surface area results in an intercepts close to zero which indicates that there is little room for other protective mechanisms of soil organic carbon, such as biochemical protection. It implies that the most important mechanism of protection of carbon in the soil is by the mineral matrix in the soil.

A second set of key observations came from the Tuapaka site in the Manawatu region. It is an extensively managed sheep and beef farm located on a hill side over an altitude range of about 300 metres. There are thus some temperature and precipitation differences and differences in slope, aspect and other differences related to stock accessibility. There were also significant soil texture differences, again quantified through specific surface area. The range of values was quite marked and extended up to five-fold differences across the range of soils (Fig. 2).

***Figure 2**: Measurements of soil carbon at six different depths from 50 sample locations on a single sheep farm (Tuapaka) located in the Manawatu region. At each soil depth, a linear relationship was fitted to the data, and the dashed lines give the extrapolation of those linear relationships to zero specific surface area.*




At each soil depth, there were linear correlations between soil organic carbon and specific surface area, with the slopes of the relationships decreasing with depth. If one assumes that the differences between soil layers corresponded to differences in carbon input rates then one can further conclude that soil carbon concentration depended linearly on specific surface area and increased (in a non-quantified way) with carbon input rate.

The linear relationships had intercepts at zero SSA that were close to zero. That implied, consistent with the Waikato observations, that SOC was protected by the soil matrix rather than biochemically, that mineral surface area was the functionally relevant measure of protective capacity, and that the linear dependence on specific surface area was equally evident at different carbon input rates.

We then tested three conceptual models, which we called RATE, MAX and COMBINED models to assess which of these was most consistent with the observations. The RATE and MAX models are briefly described below, and the COMBINED model simply combines the key attributes of the first two models. In all three models, the equilibrium amount of protected carbon is found when carbon inflow into protective sites matches carbon outflow, but the models use different formulations to describe these respective inflows and outflows.

The MAX model describes protection by only considering an effect of the maximum number of sites available for protection (with no modification of decomposition rates). Hence:

$$P_{in} = C_{in}\{1 - e^{[k_1(C_{max}-P)]}\} \tag{1a}$$

$$P_{out} = P\ k_2 \tag{1b}$$

where $P$ is the size of the pool of protected carbon, $P_{in}$ and $P_{out}$ are the rates of carbon inflow and outflow from the protected carbon pool, $C_{in}$ is the total carbon input rate, $k_1$ and $k_2$ are constants, and $C_{max}$ is a maximum amount of protected carbon, calculated as:

$$C_{max} = S\ k_3 \tag{2}$$

where $S$ is specific surface area and $k_3$ is another constant.

This model essentially assumes that the inflow of material into protected sites can be large when sites do not yet hold much carbon, but as more and more available protective sites are occupied, additional uptake of protected carbon becomes more and more limited, following a negative exponential relationship.

***RATE model***

The RATE model describes protection by assuming that protection acts by linearly reducing the specific decomposition rate. It considers no upper limits to that effect.

$$P_{in} = k_4\ C_{in} \tag{3a}$$

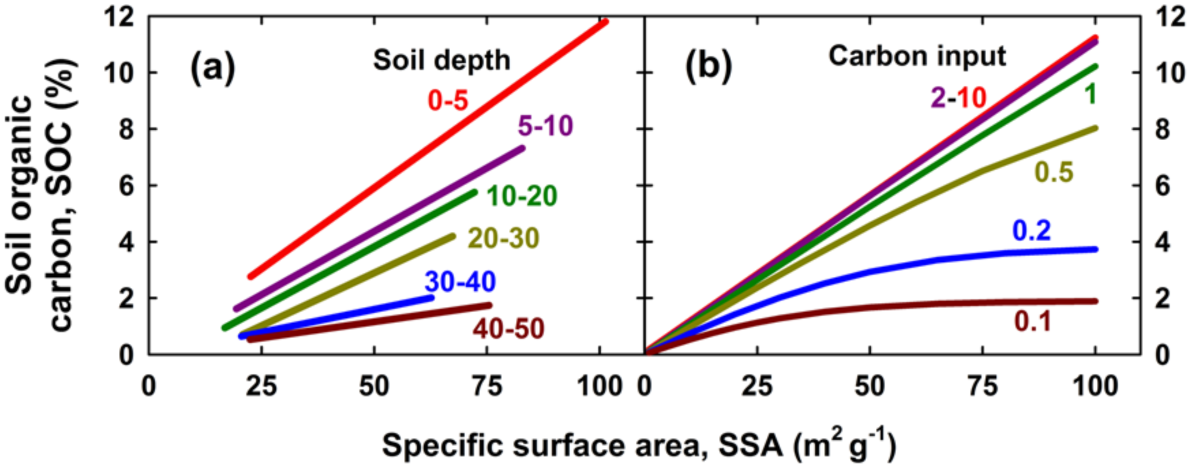
$$P_{out} = {}^{P\ k_5}/_{S} \tag{3b}$$

where $S$ is specific surface area, $C_{in}$ is the carbon input rate (as before), and $k_4$ and $k_5$ are additional constant for a given set of environmental conditions. It essentially gives the rate of turn-over of protected organic carbon and incorporates the effects of environmental factors, such as temperature or moisture availability, on specific decomposition rates. This model has the properties that the amount of protected carbon is proportional to both the rate of carbon input and to the stabilisation properties of specific surface area and inversely proportional to the specific rate of carbon turn-over.

*COMBINED model*

The COMBINED model simply combines the attributes of the other two models by using Eq. 1a for the flux into protected sites and Eq. 3b for the flux out of protected sites.

***Figure 3****: Soil carbon as a function of specific surface area at different carbon input rates. Shown are observations (a) and modelled (b) responses using the MAX model. The observations show the fitted linear relations from Figure 2 from six different depths as shown in the figure. The modelled relationships use different carbon input rates (in tC ha$^{-1}$ yr$^{-1}$ per soil layer) as shown in the figure to emulate the effect of soil depth.*



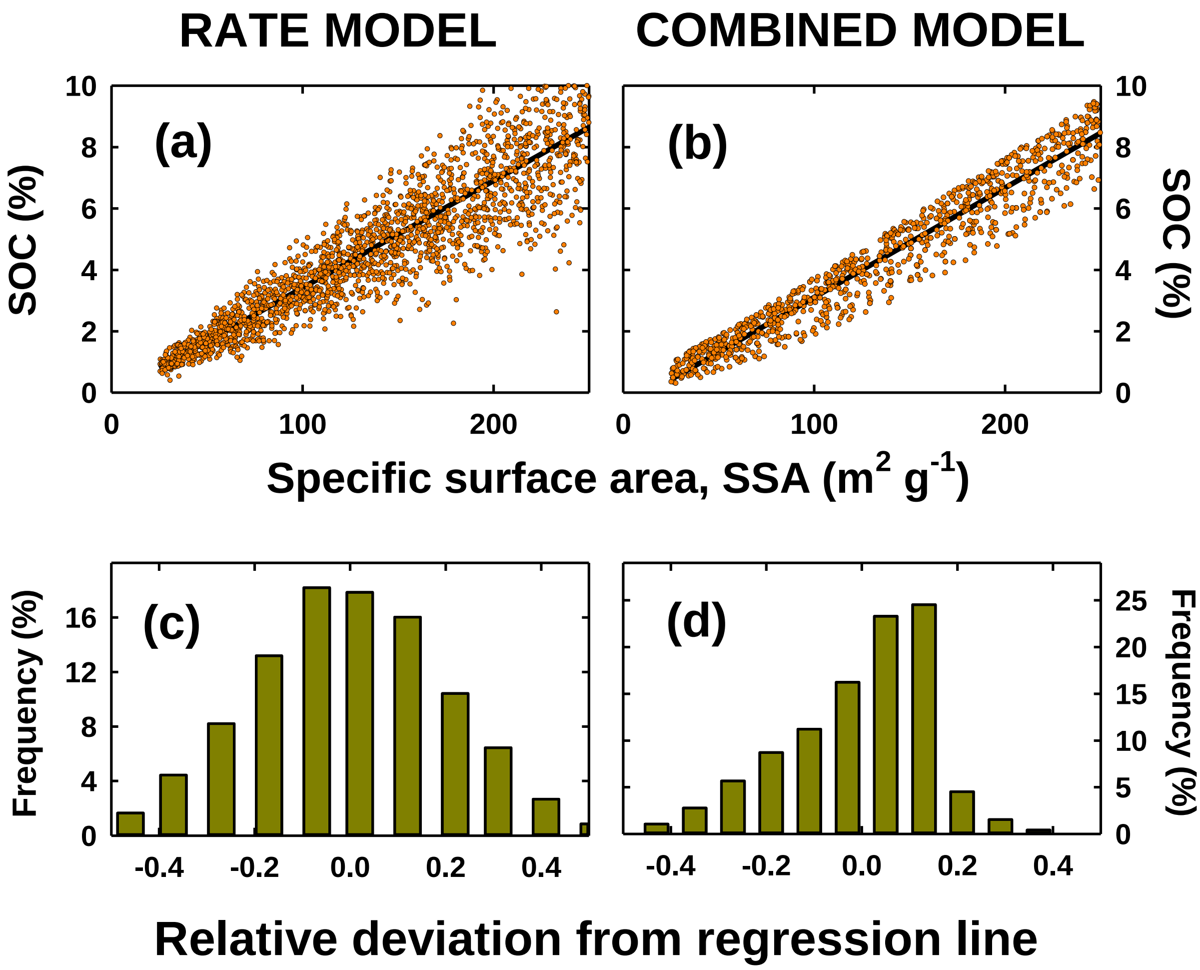

The comparison between Figure 3a and 3b indicates that the MAX model is not consistent with the observed patterns. The observations are characterised by linear relationship that emanate from the origin (Fig. 3a). Differences in slope are evident across the range of specific surface areas, and there is no apparent non-linearity in the relationships. Differences in slope are also clearly evident between the highest and the second highest soils layer. This is a pattern typically found in soils, in which soil carbon concentrations tend to be highest right at the soil surface and decrease most strongly over the first few centimetres.

The MAX model, on the other hand, showed clear non-linearity in the relationship, with all curves emanating from the origin, but showing little difference at lowest specific surface area despite very wide differences in carbon input rates (Fig. 3b). At low carbon input rates, curves then change into asymptotic relationships, with the proportional differences between carbon input rates widening at higher specific surface areas. Changes between carbon input rates also start to emerge only for larger differences in input rates, but there is very little difference for carbon input rates from 2-10 tC ha$^{-1}$ yr$^{-1}$ per soil layer. This would imply that very carbon-rich soils should have uniform carbon concentrations with depth over some reasonable range of depths before differences start to emerge lower down in the profile of such soils. This is not typically observed.

We, therefore, concluded that the MAX model was not consistent with observations and excluded it from further consideration. The RATE and COMBINED models, however, were consistent with the observed patterns in Figure 3a. We therefore looked for different diagnostic patterns to distinguish between those two remaining models.

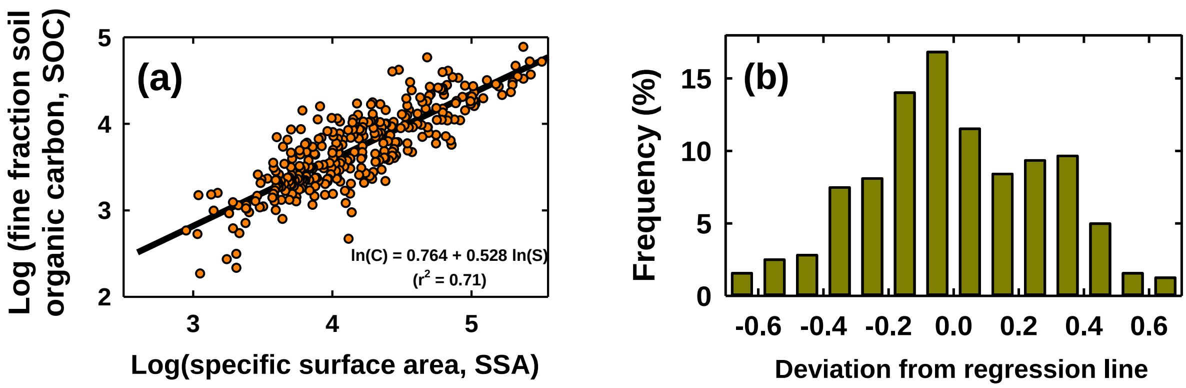
For that, we turned to the national soils data base for additional evidence to distinguish between the competing models. Using the RATE model, SOC could, in principle, increase to any value driven purely by C input rates and an existing protective capacity that reduced turn-over rates. A probability distribution of SOC in any number of soils that all share similar specific surface areas should, therefore, reflect any probability distribution in carbon input rates. Running a number of simulations over a range of specific surface areas, and with carbon input rates following a normal distribution, we found that resultant SOC also followed a normal distribution to reflect the statistical distribution of input values (Figs. 4a, c).

***Figure 4****: Modelled soil carbon as a function of specific surface area at different carbon input rates, modelled with the RATE (a, c) and COMBINED (b, d) models. Each data point represents a separate simulation, with a randomly chosen specific surface area over the range of values shown in the figure, and a carbon input rate based on a normal distribution around mean values. Individual model data points are shown in a and c, and their frequency distribution in c and d.*




For simulations with the COMBINED model (or the MAX model – data not shown), on the other hand, the resultant patterns look different. At any given SSA, if SOC were limited by a maximum protective capacity in the soil, it would have to result in a skewed distribution of SOC around mean values. Some points could be much lower than the maximum protective capacity if carbon input rates were very low, but points could not exceed the maximum protective capacity even with exceptionally high carbon input rates. When we ran the COMBINED model, it resulted in the expected skewed distribution of SOC around mean values (Fig. 4b, d). The distinct differences in the frequency distributions between the two models (Fig. 4c, 4d) provided a diagnostic test to distinguish between the models. It then allowed us to look at New Zealand's national soils data set (Fig. 5a) to assess which observed distribution would be more consistent with the modelled data.

***Figure 5****: Observed soil carbon concentration as a function of specific surface area in the national soils data base (both on log scales) in (a), and the frequency distribution of all data points from the line of best fit (in b).*




A comparison of the frequency distribution in the observations (Fig. 5b) showed a reasonably normal distribution of points around mean values. The skew apparent in model simulations using the COMBINED model (Fig. 4d) was not evident in the observations. Instead, the observed frequency distribution (Fig. 5b) was more consistent with that simulated with the RATE model (Fig. 4c).

Based on this available evidence and the simulations based on three different conceptual models, we concluded that:

1. The strong linear correlation between soil carbon concentrations and specific surface area indicated that specific surface area either is the key property of soils that determines a soil's capacity for protecting carbon, or must itself be highly correlated with that property.
2. The extrapolation of linear relationships to zero specific surface area left little room for biochemical protection of organic matter in the soil. If protection had included a large component of biochemical protection, it should have been unrelated to soil properties or resulted in a linear relationship of SOC with specific surface area but a significant positive offset.
3. The evidence did not support the presence of a maximum protective capacity in soils.
4. The evidence did not even support a joint control between turnover-rate modification by specific surface area and maximum protective capacity in soils.
5. Instead, our analysis suggests that SOC, $C$, can be described with the simple RATE model as:
   $C = C_{in} S/t$, where $C_{in}$ is the carbon input rate, $S$ is specific surface area, and $t$ a specific SOC turn-over rate.

The work reported here presents new insights into the protective mechanisms of carbon in the soil. It has important implications for an understanding of the controls of soil carbon so that mitigation efforts can be directed towards those aspects that can be manipulated while respecting the control by those aspects that cannot be changed. In particular, these findings reaffirm the usefulness of adding additional amounts of carbon to soils as a means of increasing SOC.

**Acknowledgement**: We acknowledge funding support for this work by the Global Partnership in Livestock Emissions Research (GPLER).