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Soil organic carbon stock changes under grazed grasslands in New Zealand

Louis A Schipper[1,2], Paul L Mudge[3,2], Miko U F Kirschbaum[4,2], Carolyn B Hedley[4,2], Nancy E Golubiewski[4,5], Simeon J Smaill[6], Francis M Kelliher[7,8,2], David Whitehead[8,2] *

[1]University of Waikato, Hamilton, New Zealand, louis.schipper@waikato.ac.nz

[2] New Zealand Agricultural Greenhouse Gas Research Centre

[3]Landcare Research, Hamilton, New Zealand

[4]Landcare Research, Palmerston North, New Zealand,

[5]Auckland Council, Auckland, New Zealand

[6]Scion, Christchurch, New Zealand

[7]AgResearch, Lincoln, New Zealand

[8]Lincoln University, Lincoln, New Zealand

[9]Landcare Research, Lincoln, New Zealand, whiteheadd@landcareresearch.co.nz

Abstract
We reviewed New Zealand studies of changes in soil carbon following conversion from woody vegetation to grassland, and under long-term grazed grasslands. Soil carbon increased by 13.7 MgC ha^{-1} following initial conversion from forests to grassland. In the last 3-4 decades, resampling of soils under grassland on flat land showed that soil carbon had declined for Allophanic, Gley and Organic soils by 0.54, 0.32 and 2.9 MgC ha^{-1} y^{-1}, respectively. For the same period, soil carbon had increased in grassland soils on stable mid-slope hill country by 0.6 MgC ha^{-1} y^{-1}. We do not know if these changes are ongoing, except for the Organic soils where losses will continue if they remain drained. Addition of phosphorus fertiliser did not result in changes in carbon stocks. Irrigation resulted in decreasing soil carbon by 7 MgC ha^{-1}. Carbon losses during grassland renewal ranged between 0.8-4.1 MgC ha^{-1}. Soil carbon increased in tussock grasslands with addition of fertiliser when not overgrazed. Estimates at the national scale suggest show no change or a gain in soil carbon but uncertainties are large. We advocate for improved sampling and investigation of the causes for changes in soil carbon.

Keywords: carbon inventory, carbon stocks, grassland, land use change, land management

Introduction
Globally, there is twice as much carbon in the soil than that in terrestrial vegetation and the atmosphere combined, and retaining or increasing soil carbon is important for both climate stability and for maintaining and improving soil services. To a large degree, the opportunity to increase soil carbon depends on land use and management of productive land. In New Zealand, the predominant productive land use is grassland grazed by dairy cows and drystock such as sheep and beef animals. In 2012, there were about 5.8 Mha of high producing grassland (22% of New Zealand's total land area), 7.5 Mha of low producing grassland (28%) and 1.4 Mha of grassland with woody biomass (5%). Originally, New Zealand was largely covered by forest that was converted to grassland following human arrival. Following this conversion to grasslands for grazing, production increased over time due to a number of management strategies such as applications of fertiliser and lime together with the optimisation of grazing regimes.

Although land use has been intensifying in New Zealand grazing systems for decades (MacLeod & Moller 2006), few data exist to understand its consequences for soil quality, including changes in soil carbon. Changes in soil carbon stocks are the net effect of plant inputs originating from plant photosynthesis and heterotrophic respiration. Knowing whether different management strategies increase or decrease carbon stocks is problematic because many of the factors that are manipulated alter rates of both carbon inputs and losses.

Changes in soil organic carbon are determined by the complex interplay between (1) changes in net primary production; (2) the carbon fraction taken off-site through grazing; (3) carbon allocation within the system between labile and stabilised soil carbon and (4) changes in soil carbon decomposition rates. There is a particularly important trade-off between carbon removed by grazing or remaining on site and available for soil carbon formation (Kirschbaum et al. 2017). Changes in soil carbon cannot be understood fully unless all four factors are considered together in an overall assessment.

Objective

To improve our understanding of soil carbon dynamic in New Zealand, we reviewed all available published information on the influence of land use and management on soil carbon in New Zealand's grazed grassland systems. We synthesised values as reported in the various studies, assuming the authors used the best approach to estimate annual soil carbon stock changes to a specified depth.

Land use change to and from grassland

The effects of land use change were modelled by McNeill et al. (2014) including the conversions between native forest, low producing grassland, tussock grassland, exotic forest and high producing grasslands (Table 1). In general, soil carbon was higher in the mineral soils for high producing grasslands compared with those for other land uses. Soil carbon stocks were lower in forests but this estimate did not include above-ground biomass which would have been higher in forests. While this conclusion was derived using a statistical model, we also found that the difference between forest and grassland soils was well supported by comparative stock measurements made on adjacent grassland and forest sites.

Changes within grasslands for different soil orders

While much of New Zealand has been under grassland for many decades, over the last few decades, several studies have identified additional changes in soil carbon within the category of high producing grasslands. Schipper et al. (2014) demonstrated that, for flat land, Allophanic and Gley soils had lost soil carbon at an average statistically significant rate of 0.54 and 0.32 MgC ha^{-1} y^{-1} respectively, with no other detectable significant changes for other soil orders except Organic soils. In contrast, Parfitt et al (2014) reported no statistically significant changes in soil carbon under drystock and dairy farming. As these studies were undertaken over different periods of time and samples taken from different depths, the discrepancies warrant further investigation. Both these studies showed that soil carbon on the stable mid-slopes of hill country increased significantly. Whether these changes are ongoing remains an important question to address.

In agreement with international studies, drainage of Organic soils resulted in large losses of carbon. These losses are expected to continue as long as the peat is drained (Campbell et al. 2015, Pronger et al 2014, Schipper & McLeod 2002). For their small area in New Zealand, these carbon losses represent a disproportionate contribution to changes in the national soil carbon inventory. Further, in New Zealand currently we do not have land management solutions targeted at reducing these losses.

Table 1: Soil organic carbon (SOC) changes attributable to land use change. Land use effects are expressed relative to the value of SOC for low producing grassland taken from the intercept in the model described by McNeill et al. (2014).

Model intercept	SOC (MgC ha^{-1})	Standard error
Low producing grassland	106.0	3.9
Land use category	Change in SOC from land use effect (MgC ha^{-1})	Standard error
Pre-1990 natural forests	-13.7	3.7
Pre-1990 planted forests	-13.5	5.8
Post-1989 planted forests	-14.1	4.9
Grassland with woody biomass	-7.8	3.7
High-producing grassland	-0.6	3.1
Perennial cropland	-17.5	6.4
Annual cropland	-16.2	4.5
Vegetated wetland	30.1	8.5

Effects of grassland management on soil carbon stocks

In New Zealand, various management practices aim to increase grassland productivity, including addition of fertiliser with phosphorus, nitrogen and other nutrients, irrigation, and grassland renewal. From the few studies where changes in soil carbon have been measured under different management practices our findings are:

- Drawing from four long-term trials on both flat land and hill country, there was no evidence that phosphorus fertiliser application influenced soil carbon stocks despite, in some cases, a doubling of grassland productivity.
- Building on findings from on a long-term flood irrigation trial (Schipper et al. 2013), Mudge et al. (2017) added a national scale sampling at 24 adjacent sprinkler-irrigated and non-irrigated sites and showed that soil carbon stocks (0-0.3 m depth) were about 7 Mg ha^{-1} lower at irrigated sites compared with those at dryland sites, despite much higher productivity.
- Occasional grassland renewal and the associated cultivation led to carbon losses of about 0.8 to 4 MgC ha^{-1} during the renewal process but these are unlikely to greatly affect long-term soil carbon stocks if renewal is infrequent (Rutledge et al. 2017). This contrasts with general losses of soil carbon due to frequent and repeated cultivation.
- The effect of different animal stock types or numbers of grazing animals on soil carbon stocks is poorly understood (Barnett et al. 2014).
- There is some evidence that fertiliser inputs to tussock grasslands result in increased soil carbon stocks (McIntosh et al. 1994) particularly when grazing is also well managed.

Overall data coverage in New Zealand is still weak or absent for some management practices. For example, there have been no long-term studies of the effect of nitrogen fertiliser application on soil carbon stocks. Multi-factor studies are needed to understand the complex and variable responses of soil carbon, which are affected not only by land use and management, but also soil type, topography, climate, and land cover/ land use history.

Extrapolating data from soils sampled repeatedly beneath grazed grassland to a depth of 0.3 m at the national scale resulted in estimated carbon stock changes of –1.6 to 1.1 MtC y^{-1} (95% confidence limits) according to the Schipper et al. (2014) compilation, and 0.8 to 5.1 MtC y^{-1} according to the Parfitt et al. (2014) compilation. Limitations of the available data warrant further consideration. For example, there have been no systematic measurements of changes in soil carbon following land use conversion to grazed grassland, or for different management practices. Instead, the estimates available to date have relied on a compilation of soil carbon data from field trials that were established for different purposes. A major constraint of this approach is that these trials are not likely to be representative spatially or temporally. This can affect the estimates and their uncertainty, and a better understanding of their representativeness is needed.

Conclusions

Our analysis revealed large and important gaps in our understanding of both the magnitude and the associated uncertainties of change in soil carbon for New Zealand grasslands. The representativeness of existing soil sampling data is also uncertain. These gaps may best be addressed by establishing a national framework and methodology for sampling soils through time along with site-specific leveraging on previous studies. Establishment of a national measurement system would reduce uncertainty in changes in carbon stock while resampling of existing sample sites or additional sampling at paired land use sites would allow more rapid, but spatially constrained, estimates of changes in soil carbon stocks.

This abstract is based on the recent paper by Schipper et al. (2017). A review of soil carbon change in grazed New Zealand pastures. New Zealand Journal of Agricultural Research (in press). http://dx.doi.org/10.1080/00288233.2017.1284134

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