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The trade-offs between milk production and soil organic carbon storage in dairy systems under different management and environmental factors

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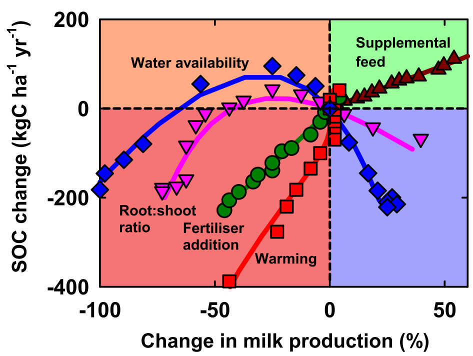
HIGHLIGHTS

- We modelled the response of soil C and milk production to various drivers.
- The model was tested against eddy-covariance data with excellent agreement.
- Outcomes depended on C gain, grazing loss, soil C stability and decomposition rates.
- There were trade-offs between C use for grazing and SOC formation.
- Increasing soil C is difficult because both soil C and milk production need C.

GRAPHICAL ABSTRACT



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ABSTRACT

A possible agricultural climate change mitigation option is to increase the amount of soil organic carbon (SOC). Conversely, some factors might lead to inadvertent losses of SOC. Here, we explore the effect of various management options and environmental changes on SOC storage and milk production of dairy pastures in New Zealand. We used CenW 4.1, a process-based ecophysiological model, to run a range of scenarios to assess the effects of changes in management options, plant properties and environmental factors on SOC and milk production. We tested the model by using 2 years of observations of the exchanges of water and CO_2 measured with an eddy covariance system on a dairy farm in New Zealand's Waikato region. We obtained excellent agreement between the model and observations, especially for evapotranspiration and net photosynthesis.

For the scenario analysis, we found that SOC could be increased through supplying supplemental feed, increasing fertiliser application, or increasing water availability through irrigation on very dry sites, but SOC decreased again for larger increases in water availability. Soil warming strongly reduced SOC. For other changes in key properties, such as changes in soil water-holding capacity and plant root:shoot ratios, SOC changes were often negatively correlated with changes in milk production.

The work showed that changes in SOC were 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 SOC; and (4) changes in SOC decomposition rates. There is a particularly important trade-off between carbon either being removed by grazing or remaining on site and available for SOC

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formation. Changes in SOC cannot be fully understood unless all four factors are considered together in an overall assessment.

1. Introduction

Cattle-based dairy farming is New Zealand's largest export-earning primary-industry sector (DairyNZ, 2014) as price trends over recent decades made dairying generally more profitable than sheep and beef farming or commercial forestry. There are now almost 5 million dairy cows in New Zealand, grazing on approximately 1.7 Mha of mainly flat, high-quality land. Yields have increased steadily, with average farms now producing about 1000 kg of milksolids (fat and protein) per hectare per year (kgMS ha^{-1} yr^{-1}).

However, dairy farming is also the biggest contributor to New Zealand's net greenhouse gas emissions, primarily due to emissions of nitrous oxide and methane (Kirschbaum et al., 2012; MfE, 2014). Concern also relates to potential losses of soil organic carbon (SOC), and Schipper et al. (2007) analysed archived soil samples and reported a significant SOC loss of 21 ± 18 (95% confidence intervals) tC ha^{-1} to 1 m depth from flat dairy pastures in New Zealand over the preceding 2–3 decades. At the same time, limited sampling of grazed pastures in hill country indicates that they may have gained similar amounts of SOC as those lost on flat dairy land (Schipper et al., 2010).

In a further, more refined analysis, Schipper et al. (2014) found that significant SOC losses on flat land were confined to gley and allophanic soils, with no significant differences between dairy and drystock. These findings, however, conflict with those of the study by Parfitt et al. (2014), who analysed data from a soil-quality sampling programme (Sparling et al., 2004). Sampling depth in that study extended to only 10 cm and data had not been collected for recording changes in SOC and covered a more recent period of observations. In contrast to the SOC losses observed by Schipper et al. (2014), Parfitt et al. (2014) observed no significant change in SOC under flat dairy or drystock pastures.

To date, no readily apparent, and well-substantiated, causes for either of those patterns, or the differences between the studies, have been identified. In principle, the differences between the data sets could relate to differences in sampling methodologies, or they could indicate that the downward trend observed by Schipper et al. (2014) based on sampling over an earlier period has ceased, or even been reversed, over more recent years.

In any case, both New Zealand studies and an earlier European study (Bellamy et al., 2005) indicate that SOC is not inherently constant, but can be changed through changes in pasture management or environmental factors. Environmental conditions are changing globally, with rising temperatures and CO^2 concentrations (Hartmann et al., 2013). Various empirical approaches have shown that temperature is a key determinant of SOC turn-over (e.g. Kirschbaum, 2000) that has led to concerns about SOC losses with ongoing temperature increases that could become a positive feedback to force further climate change (e.g. Sitch et al., 2008). Conversely, increasing CO^2 concentration has been shown to increase plant growth (e.g. Ainsworth and Long, 2005; Hickler et al., 2015; Kirschbaum and Lambie, 2015), which is likely to bring more carbon (C) into any system, with possible positive effects on productivity and SOC.

Dairy-farming has also been using increasing amounts of fertilisers (Parfitt et al., 2012), leading to higher pasture productivity and, together with inclusion of increasing amounts of supplemental feed, have allowed higher stocking rates (MacLeod and Moller, 2006; DairyNZ, 2014). Higher nitrogen inputs, however, have led to increasing nitrate leaching into water ways, which is a serious environmental side effect of dairy farming (Saggar et al., 2008; Ausseil et al., 2013). Supplemental cattle feed may come from hay or maize silage grown by farmers themselves, or purchased from specialist producers. In 2014, New Zealand also imported about 2 Mt of palm kernel expeller (or extract; PKE), a by-product of the palm-oil industry in Indonesia and Malaysia.

Increasing areas of pasture are also being irrigated, especially on the drier east coasts of New Zealand's main islands. The greatest expansion of dairying over recent years has occurred in Canterbury on the east coast of the South Island (e.g. Dymond et al., 2013). There is evidence that irrigation may have reduced SOC (Schipper et al., 2013; Condron et al., 2014; Mudge et al., 2016) even though in natural grasslands, SOC stocks tend to increase with precipitation (e.g. Harradine and Jenny, 1958).

There is interest in understanding how any of these external factors may change SOC (e.g. Parsons et al., 2013; Rumpel et al., 2015), and whether management can be purposefully modified to increase SOC and thereby assist in the task of reducing net C emissions to the atmosphere (e.g. Smith et al., 2008). However, while it is generally desirable to increase SOC levels, dairy farms are commercial enterprises, where milk production is the primary focus and profitability a key determinant of management decisions. The challenge lies in understanding the complex array of interacting factors that together determine SOC levels (Fig. 1). External drivers may change:

1) Net C inputs for SOC formation, principally through net primary production (NPP), which may be supplemented through imported feed;
2) The fraction of C inputs that is grazed or harvested and taken off site versus the fraction retained on site and available for SOC formation. Carbon taken off site includes animal respiration, methane emissions and produce export. Produce export also affects nitrogen stocks with indirect effects on subsequent carbon inputs;
3) The fraction of C allocated to labile versus more resistant pools. Root-deposited C, in particular, is more readily incorporated into stable SOC than surface-deposited C that is more easily respired;

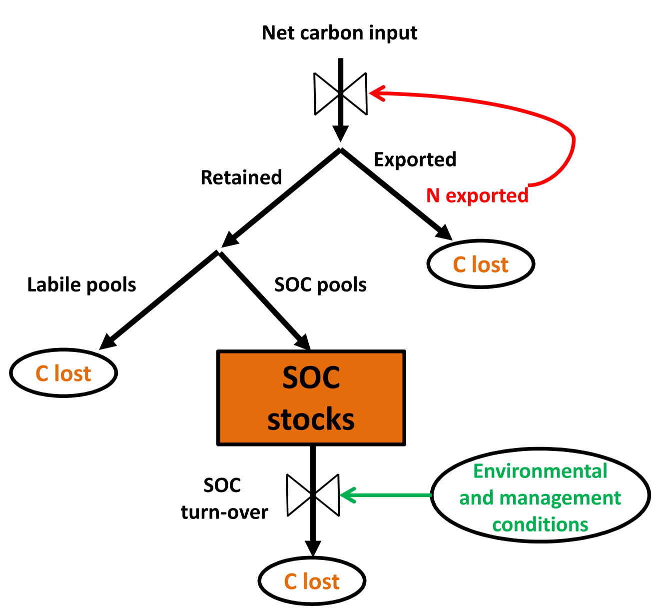

Fig. 1. Interactions between different processes in grazing systems that together determine their soil C stocks. Net carbon input consists of net primary production (NPP) plus supplemental feed.