



Management of Grazed Landscapes to Increase Soil Carbon Stocks in Temperate, Dryland Grasslands

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Management of the temperate, grazed grasslands in New Zealand for more than a century has led to swards dominated by ryegrass/clover, which, with inputs of inorganic fertilizers, are highly productive for grazing animals. In the last 20 years the widespread introduction of irrigation to dryland areas on flat land has increased productivity further. However, these intensive practices decrease soil carbon stocks. In contrast, there is limited evidence that improved management of dryland, grazed, hill country grasslands can lead to increases in soil carbon stocks. To address global needs for food security and climate change mitigation, priority actions to increase soil carbon stocks need to focus on improved management practices to increase carbon inputs and retention in soils identified as having high potential for increasing carbon storage. While there are limited data from New Zealand studies, international observations suggest that soil carbon stocks can be increased by enhancing below-ground carbon inputs from plants with deep roots, using swards with diverse species, and moderate grazing rather than harvesting biomass. However, there is less certainty about the processes regulating the formation and decomposition of soil organic matter and their dependence on soil physical properties and microbial access. Scaling findings from plot studies to forecast long-term changes in soil carbon stocks at the landscape scale can be done using models but new approaches are required to integrate the impacts of multiple concurrent practices associated with grazing management.

Keywords: diverse swards, grasslands, grazing management, microbial processes, soil carbon

OPEN ACCESS

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Specialty section:

This article was submitted to
Agroecology and Ecosystem Services,
a section of the journal
Frontiers in Sustainable Food Systems

Received: 21 July 2020

Accepted: 24 September 2020

Published: 28 October 2020

Citation:

Whitehead D (2020) Management of
Grazed Landscapes to Increase Soil
Carbon Stocks in Temperate, Dryland
Grasslands.
Front. Sustain. Food Syst. 4:585913.
doi: 10.3389/fsufs.2020.585913

INTRODUCTION

Grasslands occupy 26% of the global land area (Conant et al., 2017) and their use for grazing livestock across 34 million km² provides a critical contribution to food security to meet the demands of an increasing global population (Soussana et al., 2010). Because of the extensive area of grasslands, the carbon stored as soil organic matter (SOM) amounts to 20% of global carbon stocks to a depth of 1 m (Stockmann et al., 2013). Improved management of grasslands to increase carbon stocks (McSherry and Ritchie, 2013; Conant et al., 2017) could help mitigate agricultural greenhouse gas emissions (Smith et al., 2016), improve soil fertility (Lal, 2004), and enhance the resilience of agricultural systems to extreme weather events (Pan et al., 2009). Zomer et al. (2017) estimated that global cropland soils could sequester 26–53% of the target carbon storage of the 4 per 1,000 Initiative (Soussana et al., 2017). However, predicting the impacts of management on grassland soil stocks is problematic because of the complex interactions among climate and soil

types (Conant et al., 2017), and management practices including grazing intensity, frequency, and duration (Zhou et al., 2017), irrigation, fertilizer addition, and plant species mixes. Grazing animals decouple the stoichiometric linkages between carbon and nitrogen cycling in soils by the removal of biomass and return of carbon in dung and high concentrations of nitrogen in urine patches (Soussana and Lemaire, 2014).

The focus of this perspective is on temperate grasslands in New Zealand, where 55% of the land area is managed for sheep, beef and dairy cattle, but agricultural production also contributes 50% of national greenhouse gas emissions (Whitehead et al., 2018). Average soil carbon stocks are moderately high (Tate et al., 2005), and maintaining these stocks is important because further increases are likely to be difficult to achieve (Minasny et al., 2017). Much of the focus on changes in carbon stocks in New Zealand has been on flat, highly productive sites used for dairy farming (Schipper et al., 2017; Whitehead et al., 2018), where there is increasing concern that mean soil carbon stocks at sites irrigated for 3–90 years were 6.99 tC ha⁻¹ lower than those at adjacent non-irrigated sites (Mudge et al., 2016).

In contrast, there is evidence from two studies that carbon stocks (0.3 m depth) increased on managed, non-irrigated hill country with a slope of about 30% at about 1.3 tC ha⁻¹ y⁻¹ over 5 years (Parfitt et al., 2014) and about 0.6 tC ha⁻¹ y⁻¹ over 30 years (Schipper et al., 2014). These findings are highly uncertain because of possible sampling anomalies, but may be attributable, in part, to the re-formation of topsoil following the historical removal of trees and increased nitrogen availability from fixation by leguminous clover species (Parfitt et al., 2013). This suggests that introducing forage legumes into New Zealand's extensive hill country grasslands (Monk et al., 2016) could increase carbon stocks at low cost (Vermeulen et al., 2019), with additional environmental and social benefits (Smith et al., 2016).

PROCESSES REGULATING CHANGES IN SOIL CARBON STOCKS

There is an underlying assumption that increased photosynthesis and above-ground biomass will increase carbon inputs and retention as SOM. However, increases in primary production often result in increased removal of biomass by grazing or cutting (Mackay et al., 2018). Further, biomass removal, plant composition of swards, compensatory growth, biomass decomposition, and carbon return in animal excreta all affect SOM formation and decomposition. So, increased carbon inputs may lead to small changes, no changes, or even losses in carbon stocks.

To investigate the effects of interacting management practices on soil carbon, Kirschbaum et al. (2017) identified four key points of constraint that regulate the transfer of carbon inputs into stabilized SOM: (1) carbon inputs, (2) biomass export by grazing or cutting, the effects of changes in the amounts and chemical nature of carbon inputs on (3) retention into different pools for

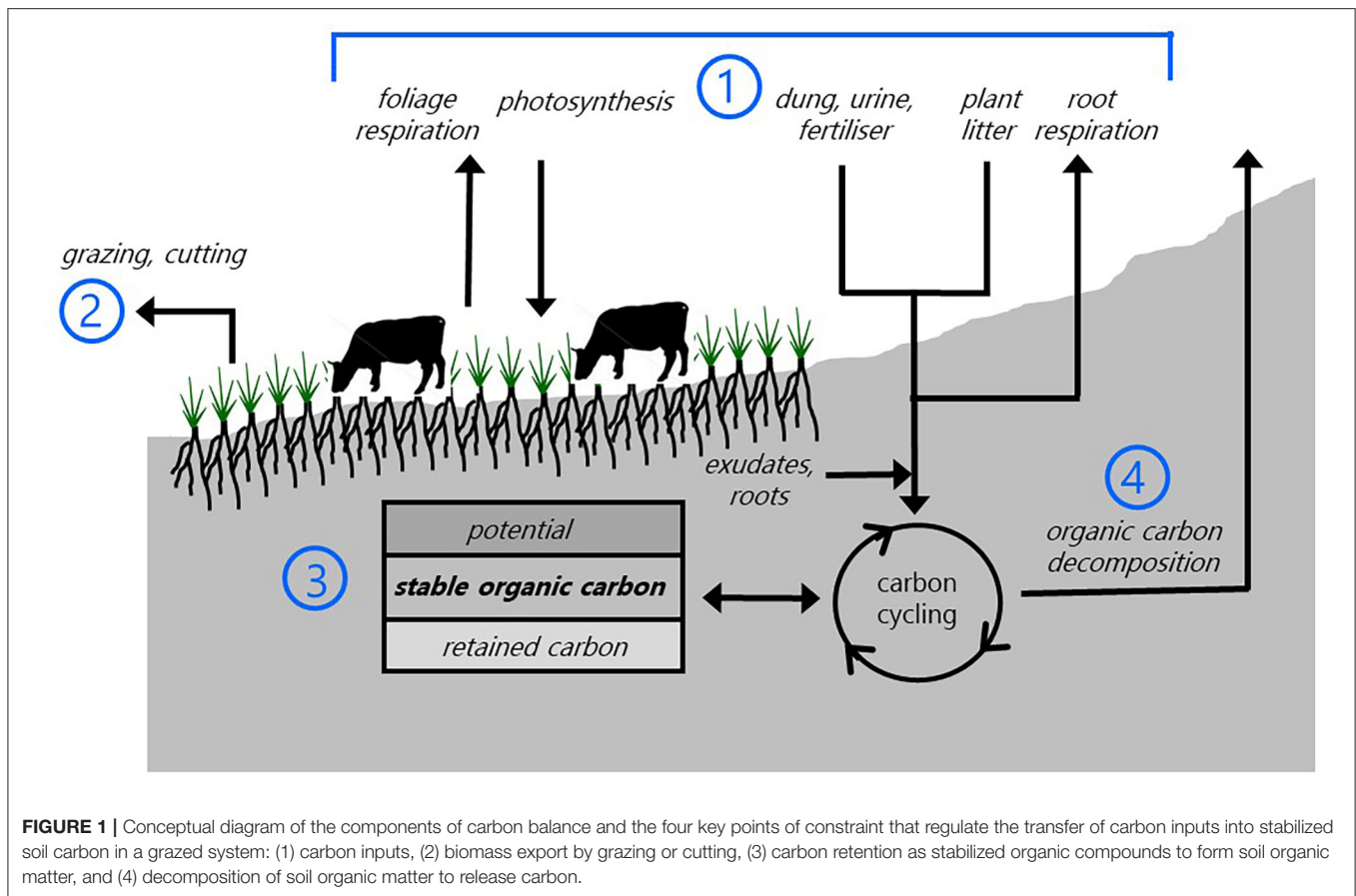
SOM formation, and (4) carbon loss from SOM decomposition (Figure 1).

The allocation of carbon below-ground depends on vegetation type and growing conditions but, from a review of 128 studies, Pausch and Kuzyakov (2018) estimated that grasses allocated 33% of carbon fixed by photosynthesis below ground, of which 16% was stored in roots, 12% lost as root respiration, and 5% deposited as root exudates in the rhizosphere (constraint 1). Using a ¹⁴C tracer over 35 days, Saggar et al. (1997) showed that the proportion of carbon allocated to roots was 10% higher for a low-fertility grassland than that for a high-fertility grassland, but the total amount of carbon allocated was higher for the high-fertility grassland. Carbon inputs from plant material as litterfall and from root death are also variable. However, inputs from above-ground biomass can be reduced by 60% when biomass is removed by grazing or cutting (constraint 2) (Soussana et al., 2010). Of the biomass intake by cattle, 25–40% as non-digestible carbon is returned to the soil in dung (Soussana et al., 2010), resulting in decoupling of the carbon and nitrogen cycles (Soussana and Lemaire, 2014). Processing by soil fauna and microbes partitions carbon inputs into pools that can be labile and lost, or into more stable carbon compounds that are retained to form SOM (constraint 3), or are decomposed (constraint 4).

INCREASING PLANT CARBON INPUTS TO SOIL

Swards of perennial ryegrass (*Lolium perenne* L.) with nitrogen-fixing white clover (*Trifolium repens* L.) are dominant in New Zealand grassland systems because they are productive and managed easily for rotational grazing (Crush et al., 2005). However, intensive breeding programmes have favored above-ground biomass production at the expense of carbon allocation below-ground (Lee et al., 2012). Plants with deep roots and high root biomass may increase soil carbon inputs (constraint 1), but this may be tempered by a trade-off with reduced carbon allocation above-ground and differences in root longevity. However, swards with high species diversity comprising grasses, legumes and broadleaved forbes (Kell, 2011; Mueller et al., 2013) can be more productive, more resilient to periods of drought, and lead to increased SOM storage (Nobilly et al., 2013; Lange et al., 2015). This is attributed to the combination of plant traits (Wright et al., 2004) that enhance the use of resources to avoid inter-species competition (Mason et al., 2016). McNally et al. (2015) estimated that increased root mass and rooting depth for a sward with seven species compared with conventional ryegrass/clover could increase soil carbon inputs to a depth of 0.3 m by up to 1.2 tC ha⁻¹. Rutledge et al. (2017a) estimated net carbon balance at the same site for 3 years following conversion to both the mixed and conventional swards. Accounting for differences between the two sites prior to conversion, net carbon gain by the mixed sward occurred more rapidly and was 2.5 tC ha⁻¹ higher over 3 years than that for the conventional sward.

Renewal of grassland swards by re-seeding with new cultivars is common practice to enhance productivity, although this is usually confined to flat land with high-intensity grazing (Kerr



et al., 2015). Liáng et al. (2020) used a model to show that renewal every 25 years could result in annual carbon losses of $0.16 \text{ tC ha}^{-1} \text{ y}^{-1}$, but the magnitude depended on plant age effects on the balance of photosynthesis to respiration. Rutledge et al. (2017b) estimated changes in carbon stocks with sward renewal using minimal tillage and showed that losses of soil carbon of $1.6\text{--}2 \text{ tC ha}^{-1} \text{ y}^{-1}$ could be minimized by reducing the length of the fallow period, sowing in conditions favorable for rapid establishment, and adding supplementary carbon inputs. Paddock-scale measurements over 10 years with variable weather conditions in Switzerland also highlighted the need to minimize fallow periods following sward renewal to avoid carbon losses (Ammann et al., 2020).

In a meta-analysis of global data from 192 studies, Conant et al. (2017) showed that fertilizer addition, increased species diversity (including legumes), irrigation, and reduced cultivation increase soil carbon stocks of between 0.1 and $1.0 \text{ tC ha}^{-1} \text{ y}^{-1}$, but the positive effects were specific for climate, soil type, and vegetation characteristics. Large increases in productivity resulting from variable-rate applications of fertilizers in New Zealand hill country depend on soil type and slope (White et al., 2017). However, the effects on carbon stocks are not clear because there are, surprisingly, few field measurements of the effects of nutrient availability on production, the allocation of carbon below-ground, and carbon stocks (Whitehead et al., 2018).

Schipper et al. (2017) concluded that application of phosphorus to four flat and hill country sites over 24–60 years showed no changes in carbon stocks. Application of lime to hill country is a common practice to increase soil pH and improve productivity. Findings from long-term studies of grasslands in France suggest that adding lime increases rates of SOM decomposition, but the magnitude depends on the effects of nitrogen management on the soil microbial community (Lochon et al., 2018). Measurements over 129 years from the Park Grass experiment in the UK also showed that adding lime increased SOM decomposition rates, but this was offset by increased incorporation of carbon inputs into stabilized carbon pools (Fornara et al., 2010).

IMPACTS OF GRAZING MANAGEMENT PRACTICES

The frequency and intensity of biomass removal by cutting or grazing and the return of carbon and nitrogen as dung and urine (constraint 2) regulate soil carbon inputs (Soussana et al., 2010). Although foliage removal by grazing reduces photosynthesis (Giltrap et al., 2020) and possibly carbon inputs to soil (McSherry and Ritchie, 2013), post-grazing plant growth can be stimulated. Further, this may increase the proportions of unpalatable broad-leaved species relative to grasses (Abdalla

et al., 2018), which could also increase carbon inputs. Analysis of changes in grassland soil carbon stocks in relation to climate zones revealed strong interactive effects of grazing intensity, temperature, and precipitation (Abdalla et al., 2018).

Findings from paired comparisons of grazing treatments show conflicting results. In northern China, intensive grazing resulted in a decrease in carbon stocks that was reversed by animal exclusion over 30 years (Wang et al., 2011). Chen et al. (2015) showed that carbon stocks at low and high grazing intensities were lower than those at moderate grazing intensity in the Steppe region in China. In New Zealand there were no differences in carbon stocks for grassland grazed at different intensities by sheep on hill country (Hoogendoorn et al., 2016). After removing the interactive effects of climate, Sanderman et al. (2015) attributed 22% of the variability in carbon stocks to differences in grazing management in southern Australia but they were unable to detect significant differences between continuous and rotational grazing practices. Bork et al. (2020) showed that the variability in soil carbon stocks across 32 sites in a Canadian prairie was explained more by livestock numbers than rainfall. Orgill et al. (2018) compared carbon stocks in ungrazed, continuous grazing with bi-annual rest periods and intensive grazing with frequent rest periods after 5 years, all well-supplied with nutrients, in southern Australia. Carbon stocks were 28% higher in the intensive grazing treatment compared with the ungrazed treatment, suggesting that increasing grazing intensity may lead to short-term increases in carbon stocks. The effects were attributed to differences in carbon allocation to roots and shoots, root growth rates and turnover, shading effects, and nutrient availability. Franzluebbers et al. (2019) were not able to detect differences in carbon stocks after 8 years of continuous and rotational grazing in tallgrass prairie in North America.

In European grasslands, both grazing and mowing are common management practices (Soussana et al., 2010). At adjacent grassland sites in central France, net carbon uptake from photosynthesis was higher when paddocks were mowed than grazed (Puche et al., 2019). However, accounting for biomass harvest reduced net carbon gain for the mowed sites. Koncz et al. (2017) showed that soil respiration for a dryland grassland in Hungary over a 3-year period was 20% higher for mowing compared with grazing and attributed this to differences in above-ground biomass with minor effects from seasonal changes in soil water content and temperature. Oates and Jackson (2014) concluded that the dominant components determining annual carbon balance in grazed grassland in northern central USA were cool-season carbon inputs from photosynthesis and losses from soil respiration.

RETENTION AND STABILIZATION OF SOIL CARBON

The processes regulating carbon retention and the formation (constraint 3) and decomposition of stabilized SOM (constraint 4) depend on interactions among the composition of carbon inputs, soil texture, and microbial communities. The protection of carbon as relatively simple organic products

from microbial decomposition is associated with organo-mineral complexes (Basile-Doelsch et al., 2020; Lavallee et al., 2020). Management can disrupt these processes, but the complexities are not well-understood (Dignac et al., 2017).

The concept of carbon saturation for individual soils is contentious (Chenu et al., 2018), but the capacity of soils to store carbon is strongly related to the availability of stabilization surfaces in the mineral matrix. This can be estimated from the specific surface area of the soil particles (Beare et al., 2014; McNally et al., 2017), calculated from the adsorbed water content after air drying in controlled conditions (Kirschbaum et al., 2020a). In a conceptual model, Kirschbaum et al. (2020b) showed that the amount of protected SOM is strongly related to the rate of carbon input, the soil specific surface area, and the rate of SOM turnover regulated by climate, soil texture, and environmental variables. The model showed that there is no upper limit to the protected SOM.

Using ^{13}C labeling with ryegrass and clover growing in mesocosms, Carmona et al. (2020) showed that irrigation increased above-ground biomass and the amount of carbon partitioned into above-ground biomass by 16%, but decreased the proportion partitioned to roots by 35% compared with non-irrigated plants. However, irrigation did not increase the quantity of net carbon inputs to the soil. The findings suggest that soil carbon losses with irrigation could be explained by increased turnover of root-derived carbon rather than reduced carbon inputs and/or by the effects of changes in the composition of carbon inputs on decomposition. Crème et al. (2017) reported that changes in the chemical composition of litter and root tissue when nitrogen-fixing lucerne was introduced into grassland increased SOM decomposition more than SOM stabilization.

The effects of fertilizer application, sward diversity, grazing, and dung deposition on carbon transfer, stabilization, and decomposition are regulated by microbial processes. Findings from the addition of lime to grassland by Fornara et al. (2010) and Lochon et al. (2018) were consistent with the increase in pH resulting in a change in microbial community composition and increased microbial activity leading to increased SOM decomposition. The long-term Jena Experiment showed that greater soil carbon storage with higher plant diversity was attributable to increases in rhizosphere carbon inputs to the microbial community with small effects on SOM decomposition (Lange et al., 2015). Zhao et al. (2017) used meta-analysis to show that light and moderate grazing intensity had no effect on microbial communities. In contrast, heavy grazing resulted in losses of bacterial and fungal communities, but an increase in the ratio of fungal to bacterial communities that may have decreased rates of nutrient turnover. In comparison with an unmanaged control, Gavrichkova et al. (2008) showed that the combined effects of mowing and grazing enhanced rhizodeposition and the availability of carbon substrates for microbes, but decreased rates of SOM mineralisation, suggesting that the microbial community became more energy efficient.

CONCLUSIONS

Several knowledge gaps persist as barriers to identify management practices to increase soil carbon stocks. They include a lack of data from field measurements of the interacting effects of climate, soil, and management practices on microbial communities and below-ground processes, slow rates of change and high spatial variability in soil carbon stocks in field conditions (Whitehead et al., 2018). Increases in uncertainty in measuring changes in stocks with increasing spatial scale (Maillard et al., 2017) and the consequences for other ecosystem services deter adoption of practices by farmers and policy makers (Bradford et al., 2019).

Three approaches are needed to reveal insights into increasing carbon stocks: (1) increased field measurements to reduce uncertainty in the effects of management, including management history, on soil carbon stocks, (2) meta-analysis of long-term (decades) field observations, and (3) detailed short-term (months), often small-scale, experimental observations in laboratory conditions. A fourth approach, modeling to integrate concepts and observations across spatial and temporal scales, will provide the capability to forecast the impacts of interacting management practices on soil carbon stocks (Wang et al., 2020). For dairy farming, Kirschbaum et al. (2017) used a model to demonstrate that the complexity of multiple drivers can lead to feedback responses resulting in trade-off effects on outcomes other than carbon stocks, specifically meat and milk production. A similar analysis is yet to be done for extensive grazing regimes on dryland hill country.

From the processes regulating the points of constraint on carbon flows identified in **Figure 1**, the major effort has been to identify management interventions to increase soil carbon inputs. Moderate grazing, dung returns, introducing legumes (Soussana et al., 2010; Monk et al., 2016), increasing sward

diversity (Lange et al., 2015), rotational grazing (Oates and Jackson, 2014) and lower grazing or cutting intensity (Koncz et al., 2017) can minimize carbon losses, maintain carbon stocks and mitigate greenhouse gas emissions. However, further research (Whitehead et al., 2018) is needed to determine the impacts of management practices on the below-ground processes that influence the formation and decomposition of SOM and carbon stocks, independent of carbon inputs.

Integrating the findings from plot studies, usually limited to investigating a few variables, to include complex interactions from multiple simultaneous management practices and scaling to landscapes including hill country, are problematic, but initial attempts using models are promising (Wang et al., 2020). Identifying management practices that increase carbon inputs, retention and SOM formation, and reduced decomposition, especially on soils with a high potential to store carbon (McNally et al., 2017; Kirschbaum et al., 2020a), could provide a useful framework for managers to increase carbon stocks at landscape scales.

AUTHOR CONTRIBUTIONS

DW developed the ideas and wrote the manuscript.

FUNDING

This work was supported by Manaaki Whenua—Landcare Research's Strategic Science Investment Fund from the Ministry of Business, Innovation and Employment, New Zealand.

ACKNOWLEDGMENTS

The author is grateful for helpful comments to improve clarity from Miko U F Kirschbaum and the reviewers.

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Conflict of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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