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Review

Management practices to reduce losses or increase soil carbon stocks in temperate grazed grasslands: New Zealand as a case study

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ABSTRACT

Even small increases in the large pool of soil organic carbon could result in large reductions in atmospheric CO_2 concentrations sufficient to limit global warming below the threshold of 2 °C required for climate stability. Globally, grasslands occupy 70% of the world's agricultural area, so interventions to farm management practices to reduce losses or increase soil carbon stocks in grassland are highly relevant. Here, we review the literature with particular emphasis on New Zealand and report on the effects of management practices on changes in soil carbon stocks for temperate grazed grasslands. We include findings from models that explore the trade-offs between multiple desirable outcomes, such as increasing soil carbon stocks and milk production.

Farm management practices can affect soil carbon stocks through changes in net primary production, the proportions of biomass removed, the degree of stabilisation of carbon in the soil and changes to the rate of soil carbon decomposition. The carbon saturation deficit defines the potential for a soil to stabilise additional carbon. Earlier reviews have concluded that, while labile carbon is the dominant substrate for soil carbon decomposition, a fraction of soil carbon stocks is stabilised and protected from decomposition by the formation of organo-mineral complexes. Recent evidence shows that the rate of organic carbon decomposition is determined primarily by the extent of soil organic carbon protection and, therefore, the availability of substrates to microbial activity.

New Zealand grassland systems have moderate to high soil carbon stocks in the surface layers (i.e., upper 0.15 m) where most roots are located, so the carbon saturation deficit is relatively low and the scope to increase soil carbon stocks by carbon inputs from primary production may be limited. International studies have shown that the addition of fertilisers, feed imports, and applications of manure and effluent can increase soil carbon stocks, especially for degraded soils, but the responses in New Zealand soils are uncertain because of the limited number of studies. However, recent evidence shows that irrigation can reduce soil carbon stocks in New Zealand, but neither the processes nor the long-term trends are known. Studies of sward renewal have shown that short-term losses of carbon losses resulting from the disturbance can be mitigated using rapid replacement of the new sward, minimum tillage and avoidance of times when the soil water content is high. Swards comprising multiple species have also shown that soil carbon stocks may be increased after periods of several years. Model simulations have shown that the goal of increasing both soil carbon and milk production could be achieved best by increasing carbon inputs from supplementary animal feed. However, losses of carbon at feed export sites need to be minimised to achieve overall net gains in soil carbon. Grazing intensity can have a big influence on soil carbon stocks but the magnitude and direction of the effects are not consistent between studies.

Biochar addition could possibly increase soil carbon stocks but it is not yet an economical option for large-

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scale application in New Zealand. There is some evidence that the introduction of earthworms and dung beetles could potentially increase soil carbon stabilisation, but the greenhouse gas benefits are confounded by possible increases in nitrous oxide emissions. The new practice of full inversion tillage during grassland renewal has the potential to increase soil carbon stocks under suitable conditions but full life-cycle analysis including the effects of the disruptive operations has yet to be completed.

We conclude with a list of criteria that determine the success and suitability of management options to increase soil carbon stocks and identify priority research questions that need to be addressed using experimental and modelling approaches to optimise management options to increase soil carbon stocks.

1. Introduction

The upper 1 m of the world's soils contains about three times as much carbon (1417 Pg, where 1 Petagram = 10^{15} g or 10^{9} t) as the world's vegetation and almost twice as much as the atmosphere (Batjes, 2014). Even fractionally small changes in the amount of soil carbon could have large effects on the carbon dioxide (CO_2) concentration in the atmosphere with resultant impacts on the rate of climate change (Smith, 2008). In 2000, grasslands occupied approximately 33 million km^2, equivalent to 26% of the Earth's land area and 70% of the world's agricultural area (Conant et al., 2011). These grassland soils contain 303 Pg of carbon to a depth of 1 m, and this is about 20% of the world's total soil carbon stock (Stockmann et al., 2013). Since agriculture is responsible for 24% of total global greenhouse gas emissions (Smith et al., 2014), improved grassland management is critically important for mitigating emissions so, in this review, we focus on grasslands managed for grazing.

In addition to offsetting greenhouse gas emissions, it is widely accepted that increasing soil carbon levels also improves soil properties (including soil structure and water-holding capacity) that promote plant production and sustainable crop yield, although evidence is restricted largely to intensive cropping systems or the restoration of degraded soils (Lal, 2004; Pan et al., 2009). The importance of maintaining soil carbon stocks both for mitigating greenhouse gas emissions and providing food security is recognised in the Sustainable Development Goals set by the United Nations, particularly for zero hunger (SGD 2), climate action (SDG 13), and life on land (SDG 15) by 2030 (FAO, 2018).

There is now a major international focus on improving 'land carbon management' through increasing soil carbon stocks (Soussana et al., 2017), termed the '4 per 1000 Initiative: Soils for Food Security and Climate' (4 per 1000, 2018). This initiative sets the aspirational goal to increase global soil carbon stocks by 4‰ per year for all land uses. While it is uncertain how far this aspirational goal can be achieved realistically, there is recognition that many agricultural practices can be modified cost effectively across large spatial scales with gains in soil carbon stocks and additional environmental and social benefits (Smith et al., 2016).

For grazed grasslands, soil carbon stocks depend on four key factors (Kirschbaum et al., 2017): (i) total carbon inputs, mainly through net primary production but also including supplemental carbon inputs such as imported animal feed; (ii) the partitioning of carbon inputs between the fraction that is harvested and taken off site and the fraction that is retained on site and remains available for soil carbon formation; (iii) the partitioning of carbon between labile carbon that is readily mineralised and carbon that is retained and stabilised into more resistant pools; and (iv) the biophysical drivers of the specific rate of soil carbon decomposition. In grazing systems, climatic and management effects can alter the size and relative contributions that these factors make to affecting changes in soil carbon stocks. Soussana and Lemaire (2014) also recognised the distinction between the primary effects of biomass inputs and removal and the secondary effects of the return of carbon in dung and urine and from animal treading, and the coupling of carbon and nitrogen cycling.

Several studies have attempted to summarise the effects of agricultural practices on soil carbon stocks including a meta-analysis (Conant et al., 2017), and a review of international field observations (Dignac et al., 2017) and those for New Zealand by Schipper et al. (2017). In this review, we first assess the role of carbon inputs, carbon stabilisation and the vulnerability of carbon loss. We then identify practices with the greatest potential to increase soil carbon stocks. We organise the concepts in the framework described in Fig. 1 that shows the processes regulating carbon uptake, losses and stabilisation that result in changes in soil carbon stock. We group the management practices that modify the processes into interventions that consider (i) external supplementary inputs either directly as animal feed, organic amendments or through promoting plant growth, (ii) sward management practices to increase sward productivity and carbon inputs to the soil, and (iii) farm operations outside usual practices to manage soils for maximising carbon storage.

We focus on New Zealand as a case study because managed grassland for sheep, beef, and dairy cattle is the dominant agricultural land use. For the total land area of 26.8 × 10^4 Mha, 55% is in grasslands at present, comprising 5.8, 7.5 and 1.3 Mha of high- and low-producing, grassland (including tussock) and grassland with woody vegetation, respectively (Ministry for the Environment, Statistics New Zealand, 2015). Management of these grasslands is important because, in 2015, 77% of New Zealand's export earnings were from the primary sector and 39% from dairy products (Ministry for Primary Industries, 2015). This also resulted in 50% of total greenhouse gas emissions in 2015 being associated with agricultural activities (Ministry for the Environment, 2016).

Attributable to historical land use with substantial forest clearance and conversion to managed grasslands for grazing in the 19^{th} century, mean soil carbon concentration to a depth of 0.3 m in New Zealand's grasslands is estimated to be moderately high at 3.5%, with national carbon stocks of approximately 1480 ± 58 Tg (Tate et al., 2005; 1 Teragram = 10^{12} g or 10^{6} t). In this review, we restrict ourselves to options that would allow ongoing grazing management, and thus exclude discussion of the sequestration potential of establishing new forests on grasslands.

2. Determining changes in soil carbon stocks

Detection of small proportional changes in carbon stocks is needed for the purpose of greenhouse gas inventories (Sparling et al., 2004). This is leading to increasing emphasis on improving sampling methodology and experimental design to reduce uncertainties in estimating changes in carbon stock from direct, repeated measurements of carbon concentration in soil cores. These methods are well described by Minasny et al. (2013) and their application in New Zealand by Schipper et al. (2017). An alternative approach to direct measurements of soil carbon is to estimate changes in net carbon balance from measurements of the cumulative rates of carbon inputs and losses (Chapin et al., 2006; Mudge et al., 2011). Carbon inputs are principally from photosynthesis but also include those from dung and urine returned to the soil, additions of fertiliser and animal effluent and supplementary feed. Carbon losses are from respiration, biomass removed by grazing, dissolved carbon in leaching and erosion (assumed to be negligible for managed grassland on flat land).