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Research paper

The carbon balance of temperate grasslands part I: The impact of increased species diversity

S. Rutledge[a,b], A.M. Wall[a], P.L. Mudge[c], B. Troughton[d], D.I. Campbell[a], J. Pronger[a], C. Joshi[e], L.A. Schipper[a,*]

[a] School of Science and Environmental Research Institute, University of Waikato, Private Bag 3105, Hamilton 3240, New Zealand
[b] National Institute for Public Health and the Environment, Centre for Environmental Quality, PO Box 1, 3720 BA Bilthoven, The Netherlands
[c] Landcare Research, Private Bag 3127, Hamilton, New Zealand
[d] 103A Troughton Road, Waharoa, New Zealand
[e] Department of Mathematics and Statistics, University of Waikato, Private Bag 3105, Hamilton 3240, New Zealand

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ABSTRACT

Appropriate management of grasslands may aid the sequestration of carbon (C) in soil organic matter, thereby increasing soil quality and offsetting other CO_2 emissions to the atmosphere. In ungrazed grassland trials, higher species diversity has been found to enhance soil C sequestration due to increases in plant production and C inputs to the soil via roots. Little is known about the impact of increased species diversity on the change in soil C stocks in intensively grazed pastoral systems common in temperate regions. Here, we report the CO_2 and C balances of three blocks of an intensively managed dairy farm in temperate New Zealand. Two blocks underwent pasture renewal (PR): one block was renewed back to ryegrass-clover (NewRye), while the second was sown in a mix of higher species diversity including ryegrass, clover, timothy, prairie grass, lucerne, chicory and plantain (NewMix). A third block served as an undisturbed ryegrass-clover control (Control). We hypothesised that the block renewed to a more diverse pasture would have higher pasture production and C sink strength than either the unmodified pasture or the pasture renewed to ryegrass-clover. Net ecosystem production (NEP) was measured using eddy covariance, and other inputs and outputs of C (e.g. C in pasture removed by grazers and C deposited in dung) were calculated. NEP and the net ecosystem carbon balance (NECB) were determined for four years: one year before PR, and three years after. In the year before PR, we measured important differences in annual NEP (and thus NECB) which suggested unanticipated inherent site differences between blocks which affected C cycling: the NEP of the NewRye block was 116 to 160 $g\,C\,m^{-2}\,y^{-1}$ higher than that of the other blocks. These differences between blocks were accounted for when considering differences in NECBs as a result of the treatments in years following renewal. During the three years following PR, dry matter production was similar for the NewMix and NewRye blocks (15,033 and 14,708 $kg\,DM\,ha^{-1}\,y^{-1}$ respectively) and greater than the Control block (13,116 $kg\,DM\,ha^{-1}\,y^{-1}$). For 11 out of the 12 block-years the soil-pasture systems lost C as indicated by negative NECBs. Taking into consideration the pre-treatment differences between blocks, the NewMix pasture had a higher NECB (by 254 $g\,C\,m^{-2}$ over 3 years) than the NewRye pasture, indicating smaller C losses at the NewMix block. In contrast, there was no difference in NECB between NewMix and Control blocks. When PR is undertaken to increase pasture performance, renewal to a more diverse sward may decrease C losses compared to renewal to a ryegrass-clover sward. In contrast, there was no evidence that PR to a higher diversity sward decreased C losses compared to an unmodified ryegrass-clover sward. Many C balance studies based on eddy covariance techniques have not accounted for pre-existing differences between treatment blocks and we have demonstrated that this may be critically important for drawing conclusions about the true effect of imposed treatments on C balances.

* Corresponding author. Current address: School of Science University of Waikato, Private Bag 3105, Hamilton 3240, New Zealand.
E-mail address: louis.schipper@waikato.ac.nz (L.A. Schipper).

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1. Introduction

Soils form the largest terrestrial store of carbon (C) globally (Batjes, 1996; Janzen, 2004) and are therefore an important part of the global carbon cycle. Small changes in soil C content over large areas could substantially intensify or mitigate current increases in atmospheric CO_2 (Smith, 2008; Kell, 2012; Paustian et al., 2016). Moreover, soil C is important for soil health and biomass production because soil organic matter improves soil water holding capacity, nutrient cycling and soil structure (Milne et al., 2015). There is increased interest in identifying management practices that increase the photosynthetic input of C into soil or reduce the rate of loss of C to increase C sequestration in agricultural soils (Cole et al., 1997; Caldeira et al., 2004; Freibauer et al., 2004; Smith et al., 2008; Lal et al., 2011; Paustian et al., 2016).

Grazing lands are important stores of soil C due to their large spatial extent globally (~25% of the Earth's land area, Cole et al., 1997; Asner et al., 2004; Steinfeld et al., 2006) and their high C content compared to soils under different land uses (Conant et al., 2001; Tate et al., 2005). Despite this, there is evidence that many grassland soils are not C saturated (Beare et al., 2014), and have potential to sequester more atmospheric C provided suitable management practices are put in place.

A range of management practices have been proposed that may enhance soil C sequestration in grasslands, including: increasing primary productivity by alleviating nutrient or water deficiencies through fertilisation and irrigation (e.g. Conant et al., 2001; Finn et al., 2016; Smith et al., 2016), optimising grazing management (Allard et al., 2007; Klumpp et al., 2011), introducing earthworms (Schon et al., 2015), increasing the duration of grass leys or converting leys to permanent grasslands (Soussana et al., 2010), and finally, increasing plant species diversity and/or adding deep-rooting species – a topic which has received considerable research interest in the past decade (Fornara and Tilman, 2008; Steinbeiss et al., 2008; Kell, 2012; McNally et al., 2015).

Interest in using increased plant diversity to enhance soil C sequestration has largely arisen from results of two large (ungrazed) grassland experiments established on former arable land, where rates of C accumulation were significantly higher in plots with greater plant species diversity (Tilman et al., 2006; Fornara and Tilman, 2008; Steinbeiss et al., 2008; Lange et al., 2015). There are a number of mechanisms by which increased plant diversity could lead to greater soil C, but an increase in plant production (usually measured above ground) and increased C inputs to the soil via roots are the general mechanisms. The higher rates of C sequestration observed by Fornara and Tilman (2008) in more diverse grassland plots was largely attributed to higher C inputs, due to "the presence of highly complementary functional groups" (legumes and C4 grasses). They found a highly significant positive relationship between C accumulation and root biomass, suggesting that roots were important for soil C storage, which is consistent with a number of other studies (Rasse et al., 2005; Lu et al., 2011; Fornara and Tilman, 2012; Fornara et al., 2013). Increased C inputs via roots, which stimulated microbial activity and soil C stabilisation, were also concluded to be key mechanisms for the increase in C sequestration with increasing plant species diversity observed by Lange et al. (2015), Steinbeiss et al. (2008) and Cong et al. (2014).

Greater rooting depth may also play a role in the observed increase in C sequestration in more diverse grasslands. Higher diversity increases the chances of deeper rooted species being present, and further, at the same site as Fornara and Tilman (2008), Mueller et al. (2013) determined that interactions between species in more diverse plots meant that root depth distributions were twice as deep as expected compared to monocultures, due to phenotypic plasticity. Deeper roots could increase soil C by allowing plants access to more water and nutrients, thus enhancing production and C inputs to the soil. Probably of more importance, deeper roots would be a conduit for C to be incorporated into deeper soil horizons where C concentrations are lower and storage capacity higher (McNally et al., 2015).

Observed increases in plant productivity in ungrazed grasslands with higher diversity has led to interest in testing this approach in intensively grazed pastoral systems, such as those common in temperate regions such as New Zealand (NZ) (Pembleton et al., 2015; Mason et al., 2016). Currently, simple binary mixes comprised of perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) typically dominate NZ pastures grazed by dairy cattle. These pastures are easy to manage and are rotationally grazed year round, but have relatively shallow roots (Crush et al., 2005), which can lead to reduced production during dry conditions. Research in NZ has shown annual pasture production of more diverse swards to be higher, or the same as traditional ryegrass-clover pastures, with production during drier summer/autumn conditions consistently higher (RuzJerez et al., 1991; Nobilly et al., 2013; Woodward et al., 2013; Mason et al., 2016), likely due to increased root biomass – particularly lower in the soil profile (McNally et al., 2015), allowing greater access to soil water. While initial interest in more diverse pastures in NZ was largely driven by a quest to increase pasture production and/or quality, and thus milk and meat production (Totty et al., 2013; Pembleton et al., 2015), potential environmental benefits such as reduced nitrogen leaching losses and nitrous oxide emissions (Totty et al., 2013; Beukes et al., 2014), improved water use efficiency and soil C storage (McNally et al., 2015) are now gaining increased research attention.

In summary, studies in ungrazed grasslands have shown increased soil C sequestration in plots with greater diversity of plant species. These increases in soil C have largely been attributed to enhanced productivity leading to increased C inputs to the soil through more and/or deeper roots. In an intensively grazed New Zealand grassland, McNally et al. (2015) clearly demonstrated that more diverse pastures had higher root biomass (particularly at depth) than traditional ryegrass-clover pastures. Annual production from more diverse pastures in New Zealand has been reported to be higher, or the same as traditional ryegrass-clover pastures, with production during drier/warmer conditions being consistently higher in more diverse swards. Paddock scale measurements of CO_2 fluxes in New Zealand have revealed that predominantly ryegrass-clover pastures often switch from being net sinks of CO_2 in spring to net sources in summer-autumn if pastures become moisture stressed (Campbell et al., 2015; Rutledge et al., 2015; Hunt et al., 2016). Based on this combination of information, we hypothesised that a recently sown more diverse pasture would have higher C sink strength relative to either unmodified or resown ryegrass-clover pastures.

We tested this hypothesis by measuring the net ecosystem carbon balance (NECB) of a grazed New Zealand grassland renewed to a more diverse sward and comparing the NECB with that of a grassland renewed with a conventional ryegrass-clover pasture and with that of an existing untouched conventional ryegrass-clover pasture. Measurements of CO_2 fluxes were made using the eddy covariance technique for one year before and three years after pastures were renewed. Non CO_2-C fluxes such as supplementary feed imports and biomass removed by grazing cattle were also quantified.

An important consideration when evaluating the potential benefit of diverse swards is that at least short-term losses of C would be expected during the pasture renewal process due to killing the existing rye-clover pasture (Rutledge et al., 2014). This potential loss may offset any benefit from increased C storage from diverse pastures and needs to be factored into conclusions about