Importance of resilient pastures for New Zealand's agricultural soil carbon stocks

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Abstract
New Zealand's agricultural pastures contain significant soil carbon (C) stocks that are susceptible to change when impacted by management and natural processes (e.g., climate). Inputs of C to these pastoral soils is through photosynthetic uptake of atmospheric CO_2 either on-site or elsewhere. Changes in soil C stocks are in response to the management of the system that alters the input-output balance. Increasing the resilience of pastures to climatic events such as hot and dry summers or cool and wet winters can increase inputs of C to the soil while sustaining above-ground production and so provide an opportunity for C sequestration. Furthermore, increased pasture for grazing can reduce the need for management practices identified as detrimental for soil C stocks such as irrigation or the production of cropped supplemental feed. A reduction in the need for renewal and its associated soil C losses, and the establishment of a more diverse sward, especially if deeper-rooting species are included, has the potential for increasing soil C stocks provided the diversity can be maintained. From a soil C perspective, a resilient pasture maximises CO_2 uptake to ensure adequate above- and below-ground inputs to maintain or increase soil C stocks and minimise the need for management activities detrimental to soil C.

Keywords: agricultural management, greenhouse gases, photosynthesis, soil respiration

Introduction
Increasing soil carbon (C) stocks within pastoral systems is important for improving soil quality, increasing production, and providing a potential avenue for mitigating greenhouse gas (GHG) emissions (Paustian et al. 2019). Globally, soils are the largest terrestrial store of C, and while difficult to quantify accurately, stocks are estimated at between 1500 and 2400 Gt C (Friedlingstein et al. 2019). However, an estimated 133 Gt C has been lost from soils due to agricultural activities globally (Sanderman et al. 2017). If the C can be regained, these soils provide a significant opportunity to contribute towards offsetting anthropogenic GHG emissions as set out by the aspirational "4 per 1000 Initiative: Soils for Food Security and Climate" (4 per 1000 2020). Consequently, there is considerable incentive to understand the role agriculture plays in maintaining or increasing soil C stocks.

Grasslands typically have higher soil C contents than their arable cropland counterparts (Conant et al. 2017; Abdalla et al. 2018) but are not immune to losses of C. Indeed, the soil C stocks of agricultural grasslands respond to management of the land and can lead to gains or losses of C. Examples of agricultural grassland management processes that influence soil C stocks include harvesting or grazing of the pasture (Koncz et al. 2017), grazing intensity (Eyles et al. 2015), amendment applications (fertiliser, lime, effluent, manure, etc., Fornara et al. 2020), sward type (McSherry & Ritchie 2013) and irrigation (Hunt et al. 2016; Mudge et al. 2017), all of which have a different impact. Identifying the precise impact of any one process is difficult, and contrasting results have been observed where individual gains or losses of C may be the result of confounding management (Parsons et al. 2009). Furthermore, both climate and soil characteristics play a role, and any observed changes in soil C stocks are the integration of these factors and management. Central to these natural and anthropogenic processes within grasslands is the pasture sward itself. Pasture is critical to the grassland C cycle, and agricultural management is both a cause of and response to the behaviour of the pasture sward. One of the key determinants to maintaining soil C is having continuous plant cover providing regular inputs of C into the soil mainly through roots. While healthy pastures meet these criteria, pastures with increased gaps or lowered production might not.

Here, the role of pasture on the soil C stocks of New Zealand's agricultural grasslands is considered, addressing the question of how more resilient pastures can influence these stocks. In the context of this paper, we consider a major attribute of a resilient pasture to be the continuous supply of C into the soil where the inputs balance or exceed outputs and thus maintaining or growing soil C. First, we review the C stocks of New Zealand agricultural grassland soils, followed by pasture's role in converting atmospheric CO_2 to soil C before considering how pasture combined with management can maintain or increase soil C.

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Soil C stocks in New Zealand

Conversion of New Zealand's native forest to grassland is estimated to have increased soil C stocks by 13.7 t C/ha (Schipper et al. 2017), with New Zealand's grazed grasslands estimated to contain 1480 Mt C to 0.3 m depth (Tate et al. 2005), at a moderately high average soil C content of 3.5% (Whitehead et al. 2018). However, Schipper et al. (2007) identified that soils under pasture originally sampled in the 1970s and 1980s had lost C when resampled between 2003 and 2005. An expansion of this work (Schipper et al. 2010) suggested differences according to land use (losses under dairy; no change under dry-stock grazing). Later, Schipper et al. (2014) determined soil order to be of more importance than land use for flatland pastures, although Barnett et al. (2014) also found significantly lower C stocks in the A horizon of dairy farms compared to adjacent dry-stock farms. In a review of soil C change in New Zealand grasslands, Schipper et al. (2017) summarised that C had been lost from flat land soils of the Gley (–0.32 t C/ha/yr) and Allophanic (–0.54 t C/ha/yr) orders with the remaining mineral soil orders at steady state, although the ongoing nature of change is not known. However, there is clear evidence that organic soils are losing considerable C with measured annual losses ranging from –2.2 t C/ha/yr to –8.5 t C/ha/yr (Campbell et al. 2015, 2021). In contrast to flat land soils, pasture-based hill country soils were found to have gained C (0.6 t C/ha/yr), with insufficient data to determine any soil order effects. Schipper et al. (2017) concluded (with high uncertainty) that national C stocks for soils under pasture were either not changing or slightly gaining C.

McNally et al. (2017) estimated the additional capacity of the same New Zealand pasture soils to store more C. This concept referred to as the C saturation deficit (Beare et al. 2014), models the capacity of a soil to store C, then calculates the difference between this capacity and current stocks to provide a theoretical estimate of the sequestration potential of the soils. Allophanic soils were identified as having a greater C saturation deficit than non-allophanic soils, with the median C saturation deficit for pasture soils across all soil orders being 15.1 mg C/g soil. McNally et al. (2017) calculated a C sequestration potential of New Zealand's pasture soils of 124 Mt C (equivalent to an 8.3% gain). However, McNally et al. (2017) acknowledged that meeting this potential is likely unrealistic for reasons including the requirement for additional nutrients, and challenges in achieving the required C inputs. Nonetheless, it does suggest that there is some theoretical potential for increasing soil C stocks within New Zealand pastures. Perhaps of equal importance is ensuring existing stocks are maintained in the face of the increasing challenges that will be imposed by climate change and new management practices.

Role of pastures in soil C sequestration

The role of pasture in maintaining or increasing soil C stocks is complex and intertwined with management and climate. A simple view of these interactions is that both climate and management affect the ability of pasture to sequester C. However, it is also conceivable that pastures might influence management, whereby a high producing, long-life pasture can minimise the need for management processes with negative effects on soil C (e.g., pasture renewal, see below), and thus mitigate GHG emissions.

Pastures take up C through photosynthesis, with the total uptake of CO_2 referred to as gross primary production (GPP). Approximately half of the total GPP is then respired by the plants as autotrophic respiration, with the remainder stored in the vegetative tissue as above- and below-ground biomass (Janzen 2004). Heterotrophic respiration (C lost by organisms in the ecosystem other than from the plants, Kirschbaum et al. 2001) is typically of similar magnitude to autotrophic respiration (Janzen 2004; Lal 2008). The small difference between GPP and ecosystem respiration (ER; equals autotrophic + heterotrophic respiration) is the net CO_2 exchange (net ecosystem production; NEP), which is about an order of magnitude smaller than the constituent GPP and ER fluxes. Based on 37 site-years of CO_2 exchange data from Waikato and Canterbury, grazed pastures generally have a net uptake of CO_2 (positive NEP) ranging from around 0.5 to 4.5 t C/ha/yr (Figure 1). A portion of this CO_2 is stored as above-ground biomass, which is then utilised by grazing animals (whether grazed fresh or harvested and stored), and much is eventually returned to the atmosphere as CO_2 and methane during digestion by the grazing animals, or exported as product (milk/meat; Figure 2, Wall et al. 2019, 2020a). Of the C taken up by the pastures in grazed systems, only that allocated to roots, trampled and wasted pasture following grazing, and material digested and excreted by the grazers remains available for sequestration in the soil. In systems where the pasture is harvested and removed, excreta deposits and wastage are low, and the primary input of C to the soil is the C allocated to root growth thus reducing total C inputs. When all flows of C in pasture systems (Figure 2) are accounted for, the C balance (referred to as the net ecosystem C balance or NECB) for New Zealand agricultural grasslands suggests on average no change (Figure 1). However, there are years where individual sites might gain or lose C likely due to interactions of climate and management. Simply put, only when C inputs exceed C losses can soil C stocks increase (Paustian et al. 2019).

The key process for contributing C for potential storage in the soil of pasture systems is photosynthesis. That is, there needs to be a consistent uptake of atmospheric CO_2

to offset the respiratory losses. Maintaining adequate plant cover year-round to ensure continuous CO_2 uptake is essential. Of importance is the summer-early autumn period when hotter and drier conditions reduce plant growth, and CO_2 uptake (Figure 3). Observationally, this period is often characterised by a net release of CO_2 (i.e., a net loss of soil C) from pasture systems (Rutledge et al. 2015; Wall et al. 2019), with respiration losses exceeding photosynthetic uptake in the order of 1 to 2 t C/ha having been observed during drought conditions in Waikato (e.g., Wall et al. 2019). Despite the existence of plant cover, cold and wet winter conditions with lower light availability leading to reduced photosynthesis can also result in CO_2 uptake being limited (Figure 3). Furthermore, reduced plant cover due to treading damage (pugging) to the pasture (and soils) during wet periods also has negative impacts on soil C. Wall et al. (2020b) estimated a net C loss of around 0.3 t C/ha from a paddock that sustained pugging damage relative to a neighbouring paddock that was grazed at a similar time but managed to minimise damage. Pasture swards that are more resilient to climate, whether it be drought or wet conditions, can increase CO_2 uptake and therefore inputs of C to the soils, bolstering soil C stocks.

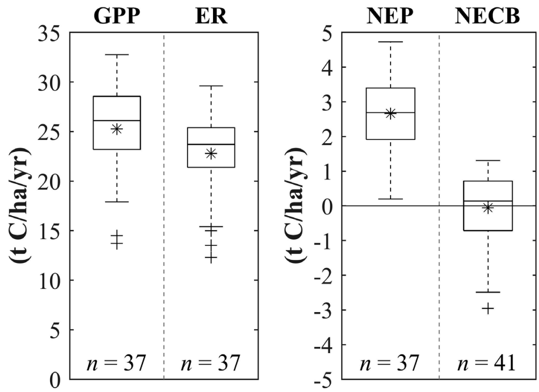

Figure 1 Distribution of measured annual carbon (C) fluxes from New Zealand agricultural grassland sites on mineral soils. GPP is gross primary production (total photosynthesis), ER is total ecosystem respiration, NEP is net ecosystem production (GPP – ER), and NECB is net ecosystem C balance and accounts for all other flows of C. The value of n is the number of site-years. The stars (*) represent the mean value. Note the difference in the y-axis scale between the GPP/ER and NEP/NECB plots. Data sources include University of Waikato unpublished data, Rutledge et al. (2015), Hunt et al. (2016), Laubach & Hunt (2018), Laubach et al. (2019) and Wall et al. (2019, 2020b).

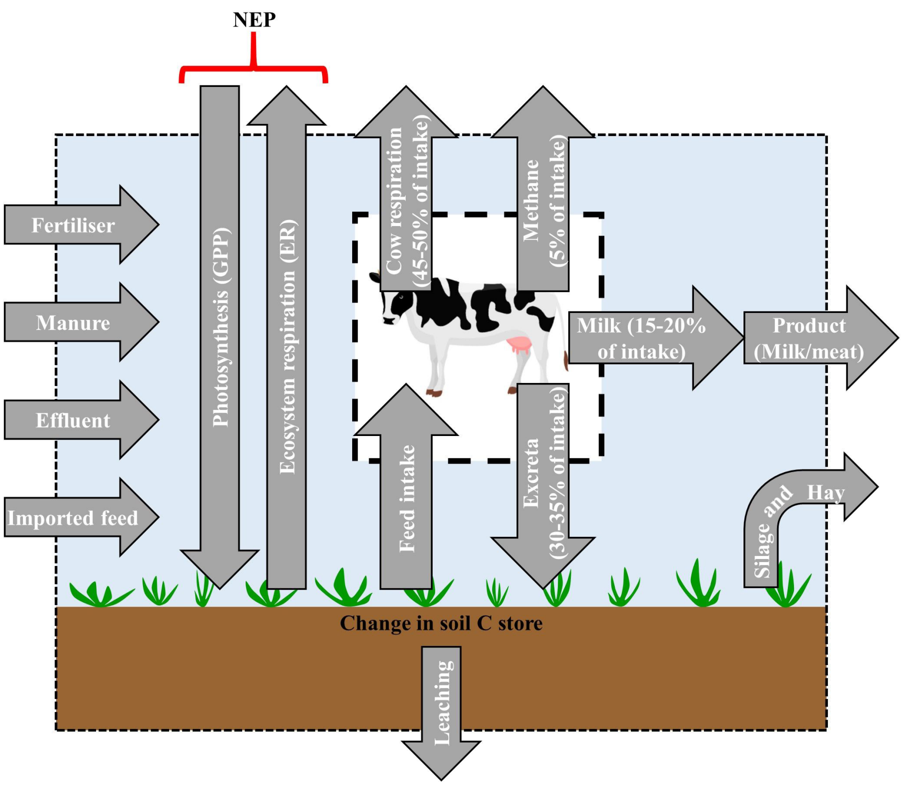

Figure 2 Flows of carbon (C) in a grazed dairy system, including the role of dairy cows. Arrows passing through the dashed lines indicate the direction of C flows into and out of the system e.g., paddock. The total of these flows is the net ecosystem C balance (NECB). GPP is gross primary productivity, and ER is ecosystem respiration.

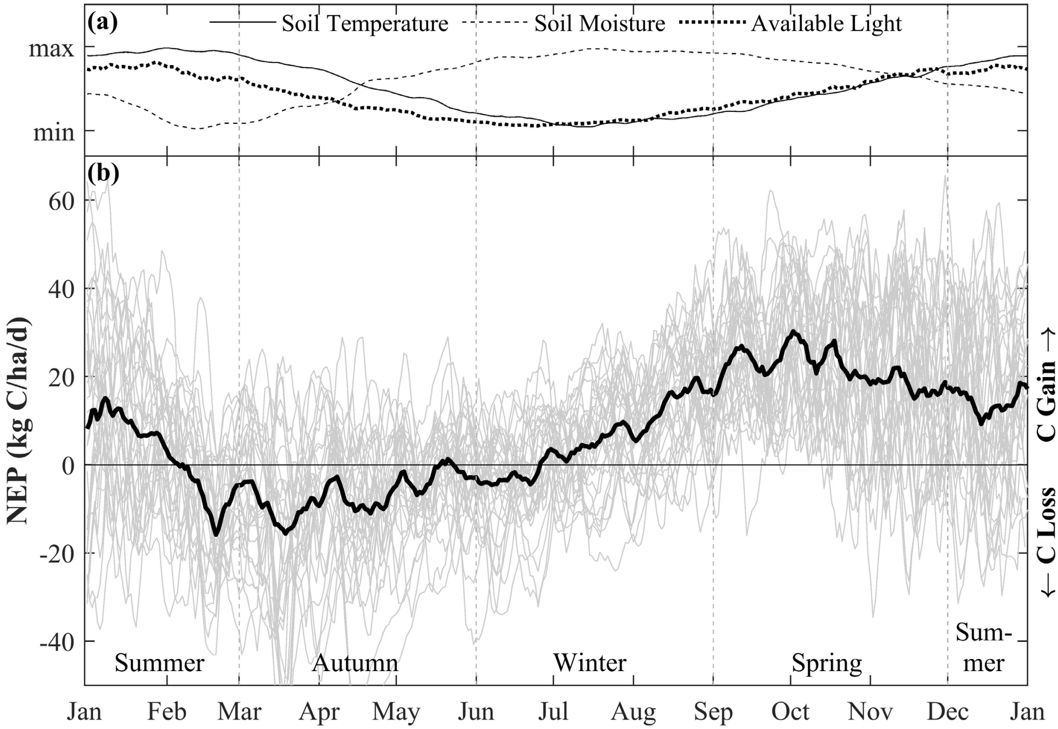

Figure 3 Measured annual patterns of net ecosystem production (NEP) and key environmental drivers of CO_2 exchange from five sites on two Waikato dairy farms between 2012 and 2020. Panel (a) displays generalised soil temperature, soil moisture and available light patterns; and panel (b) 7-day running means of daily CO_2 exchange for all sites and years (light grey lines), and overall mean NEP (thick black line). Note the direction of C gain and loss on the right vertical axis.

Roots play an essential role in the sequestration of C in soils via root turnover and rhizodeposition, with these below-ground inputs likely more important than above-ground litter inputs for C sequestration (Sainju et al. 2017). The allocation of C between below- and above-ground production differs between plant species, with examples of root:shoot ratios ranging from 0.13 for small-grained cereal crops to >2 for some perennial grasses (Bolinder et al. 2007; Sainju et al. 2017). Selection of, or development of plant species with traits that promote root growth such as greater root:shoot ratios provides an opportunity to allocate more C below-ground where it is likely more beneficial for C sequestration. However, in an agricultural system where maximising production of high-quality above-ground biomass is the priority, increasing below-ground biomass at the expense of above-ground biomass may not be desirable (Dodd et al. 2011). In such systems, only an increase in total CO_2 uptake coupled with an increased root:shoot ratio would be beneficial for the dual goal of maintaining (or increasing) production and increasing C inputs to the soil. Modelling work of dairy pasture systems suggests increasing the root:shoot ratio is only beneficial for soil C to a certain point, and any increase is detrimental to production (Kirschbaum et al. 2017) although total photosynthesis was held constant in all scenarios. Regardless, a key mechanism for increasing soil C stocks is through increasing C inputs from below-ground root biomass (McNally et al. 2015).

Pasture management practices affecting soil C

The following examples consider how the management of pastures can influence soil C stocks, and how these stocks could be maintained or increased by a more resilient pasture.

Pasture renewal

The need for renewal of a pasture sward with the primary motivation of improving production results in a loss of C during the renovation process (Rutledge et al. 2014, 2017a; Ammann et al. 2020). Application of herbicide to kill the pasture reduces the photosynthetic C inputs to near zero, but the heterotrophic respiratory losses from the soil continue, resulting in a net loss of C. Factors contributing to the total losses of C during pasture renewal include soil moisture status, and perhaps of more importance, the length of time taken to get the new pasture established (Rutledge et al. 2017a). Rutledge et al. (2014) found that the rate of soil C loss during pasture renewal scaled with soil moisture content, whereby soil C loss increased with increasing moisture content. Evidence suggests that the method of renewal – full cultivation or direct drill – had little direct effect on the rate of C loss for New Zealand soils, but any increased length of time taken to re-establish the sward during full cultivation will increase total losses (Rutledge et al. 2017a). While there is a definite loss of C during the pasture renewal process, there is scant information as to whether, and how quickly, lost C is regained in the subsequent year(s). Of the few longer-term (1-3 years post-renewal) studies (Rutledge et al. 2015, 2017b; Ammann et al. 2020), only Rutledge et al. (2015) identified no longer-term loss of C, primarily due to manure and effluent amendments (with embodied C) applied during the renewal process, which compensated for the respiratory C lost. It is worth noting that there is evidence of lost soil C being regained following conversion of cropland to pasture (Conant et al. 2017; Lin et al. 2020), but it is unclear whether the same response could be expected from pasture-to-pasture transitions. In contrast to measurements, modelling of pasture renewal suggests that more frequent renewal can lead to gains in soil C (Liang et al. 2020) through regular increased allocation of fixed C to root development rather than above-ground foliage production. Further modelling by Giltrap et al. (2021) suggested a 10-year renewal frequency as optimal for pasture production with minimal change in soil C. Based on current measurements, reducing the frequency of pasture renewal required to maintain production would reduce the instances of known soil C losses, and thus the need for this lost C to be recovered. Frequent pasture renewal could reduce C stocks if recovery of the lost C takes longer than the renewal interval (Figure 4).

Diverse pastures

Use of pasture swards with increased diversity (both number and type of species) has been suggested regularly to increase soil C stocks, particularly with the inclusion of deeper-rooting species providing a mechanism for more C to be stored at greater depth (McNally et al. 2015). Internationally, increased sward diversity has been linked to increased soil C (e.g., Fornara & Tilman 2008; Yang et al. 2019), particularly during the restoration of degraded soils albeit without grazing. Within New Zealand, McNally et al. (2015) calculated a 1.2 t C/ha/yr greater input of root biomass C to the soil from a moderately diverse pasture containing 6 species relative to the ryegrass-clover control 2 years after establishment but did not report soil C stocks. In a separate study, Rutledge et al. (2017b) specifically compared the impact of a diverse sward (8 species) on C stocks at paddock scale on a commercial dairy farm and concluded pasture renewal to a sward with

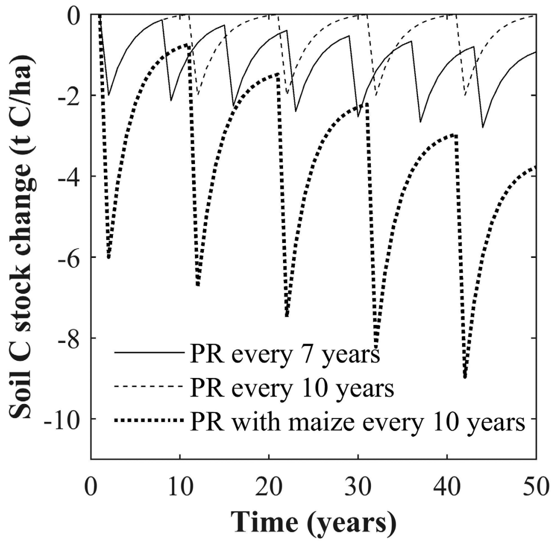

Figure 4 Conceptual sketch of potential carbon (C) losses and recovery for different scenarios illustrating how too frequent pasture renewal (PR; with an immediate loss of 2 t C/ha) or renewal with supplemental feed cropping (in this case maize with an immediate loss of 6 t C/ha) may lead to soil C losses.

increased diversity might have been more beneficial than renewal to a ryegrass-clover sward. However, recent recalculation suggests no difference between the swards in the first 3 years after establishment. Of particular note here, Rutledge et al. (2017b) measured a reduction in diversity with time after establishment, which may have decreased any potential benefits associated with increased diversity. Although it is thus far uncertain whether increasing sward diversity increases soil C stocks of New Zealand pasture soils, there is evidence of increased root C inputs (McNally et al. 2015) and the ability of such pastures to maintain equivalent pasture production (Woodward et al. 2013) indicating a potential benefit. Any long-term benefit for soil C due to increased species diversity requires agronomy that allows farmers to easily manage such a sward while retaining diversity.

Cropping

Current New Zealand farming practice often utilises supplementary feeds to compensate for any shortfall of pasture during times of slow growth (Roche et al. 2017). Production of these supplementary feeds can have negative effects on soil C stocks, and New Zealand's permanent cropland soils have significantly less C than pasture soils (McNeill et al. 2014). For example, maize silage grown for supplemental feed and included in the pasture renewal process can reduce C stocks by 4 to 8 t C/ha in a single year (Wall et al. 2020a). Harvested supplemental feed crops (e.g., maize silage) can assimilate considerable C during growth, however, the biomass is then exported precluding the cycling of C by the grazers that would return a significant proportion of the biomass C to the soil. In contrast, supplementary feed crops grazed on site have returns of C as excreta and wastage, although these also experience considerable periods with limited CO_2 uptake during establishment and/or following grazing – especially where the crop is strip-grazed over many days or weeks – resulting in extended periods of likely C loss. The true impact of grazed crops on soil C remains uncertain and is an area of future focus. Given that these crops, whether harvested or grazed, are utilised to compensate for decreased pasture availability, improved resilience of pasture to conditions that would ordinarily result in decreased pasture production has the potential to offset the need for cropped supplemental feeds, and therefore minimise associated soil C losses (e.g., Figure 4).

Irrigation

In some parts of New Zealand, irrigation is required to maintain pasture production goals and allow profitable farming. Increasing water availability to promote growth results in increased GPP, but also a corresponding increase in ER (Hunt et al. 2016). Where measured, net CO_2 uptake was greater in irrigated than non-irrigated pastures (Laubach & Hunt 2018; Laubach et al. 2019), but this did not necessarily correspond with increases in soil C. Indeed, spatially extensive sampling by Mudge et al. (2017) found that on average, irrigated pastures have significantly less soil C than adjacent unirrigated pastures, although individual sites may have gained, lost or had no change in C stocks. The variable C stock changes obtained from sampling irrigated pasture soils may be a function of variation in associated management changes confounded by local climate. For example, the use of irrigation may require additional N inputs, and/or the additional pasture produced likely leads to increased stocking intensity (Parsons et al. 2009). Meanwhile, the role of climate is also important to consider. For example, C stocks of irrigated soils in more arid climates are more likely to increase whereas those in humid climates are more likely to remain the same or decrease (Trost et al. 2013; Whitehead et al. 2018). Avoiding the need for irrigation to stimulate pasture growth and compensate for summer-dry periods in regions where irrigation is otherwise unnecessary through the use of more drought-tolerant pasture species, has the potential to minimise loss of soil C through more consistent C inputs. Furthermore, the use of deeper-rooting species allowing increased access to moisture may have dual benefits of promoting C storage deeper in the soil, and reducing potential losses due to irrigation, although these species would only be useful provided the sward persisted year-to-year.

Ancillary benefits and trade-offs

While the focus of this paper has been on the role that managed pastures play in altering soil C stocks, modification of pasture systems can have ancillary benefits and/or other trade-offs. Increased ability of pastures to cope with climatic variation that leads to increased plant cover year-round can reduce the nitrous oxide (N_2O) emissions associated with bare ground (Bowatte et al. 2018). Increasing pasture growth at times of otherwise poor growth leads to a decreased reliance on external inputs such as supplemental feed and fertiliser, which can reduce the C footprint of grazing systems by reducing or eliminating GHG emissions associated with the production and transport of these inputs (Ledgard & Falconer 2015; Ledgard et al. 2020). Establishing plantain, a deeper-rooted species may benefit soil C, but it also has benefits for reducing nitrate leaching (Carlton et al. 2019; Bryant et al. 2020) and N_2O emissions (Luo et al. 2018) provided it could be established and maintained at a sufficient proportion within the sward to be effective. However, the reduction in N_2O emissions may be cancelled out by increased CO_2 emissions (and soil C loss) associated with the establishment of the plantain (or any other beneficial plant species). Consequently, while various options may have additional benefits, all aspects need to be considered to ensure overall betterment and avoidance of pollution swapping.

Conclusion

From a soil C perspective, a resilient pasture maximises C inputs under a range of conditions, and therefore minimises the need for interventions with detrimental effects on soil C. Effective photosynthetic C uptake by pastures is the primary mechanism by which agricultural grasslands sequester C, and improved growth by more pastures can increase gross photosynthetic uptake. However, simple increases in CO_2 uptake do not necessarily correspond to increased soil C, particularly as respiration losses need to be considered and any additional C partitioned to above-ground biomass is available as animal feed with most subsequently lost back to the atmosphere. Moreover, the relationship between pasture and management can have both positive and negative effects on soil C stocks. Pastures resilient to climatic variability can reduce the need for management practices identified as being detrimental to soil C stocks including the use of cropped supplemental feeds and irrigation. Similarly, a pasture that requires less frequent pasture renewal will reduce known losses of soil C. Increased diversity of pasture swards may also be beneficial for soil C stocks, particularly through the inclusion of deeper-rooting species, provided the increased diversity can be maintained long-term. However, with any change other GHGs (e.g., N_2O) and/or environmental indicators also need to be assessed to ensure overall benefit. A key area of research for resilient pastures from a soil C perspective is the agronomy of plants with desired traits to maintain their abundance in a sward. Additionally, increasing root:shoot ratios would allow for increased inputs of C into the soil, although measurements would be required to assess the impact of any change. Finally, from a practical standpoint, any of these options will only be viable provided biomass production is sufficient to avoid any drop in farm profitability. Improved resilience of pastures requires traits that are beneficial not only to the environment but also for production.

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