An assessment of the role of soil organic matter in pasture resilience

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Abstract

This paper assesses the role of soil organic matter (SOM) in pasture resilience and longevity. New Zealand pasture soils have high levels of SOM, which contribute to soil structural stability and nutrient cycling, functions that support resilient pasture. It is concluded that pasture resilience requires (a) a pasture-soil system that returns regular amounts of fresh, 'labile' carbon (C) since this younger SOM fraction plays a significant role in these processes, and (b) a thriving soil biota that can rapidly turn over this labile C. Pasture itself also plays a critical role as the major pathway for C transfer into the soil rhizosphere, with differences between species in amounts and composition of C returns. Resident (older) SOM should not be ignored and plays a role in sustaining soil structure, but the younger SOM is the fraction that turns over more often and plays a key role in nutrient supply.

Soil organic matter is not a single solution to increasing pasture resilience since soil type and summer rainfall have been previously identified as key factors also. However, other identified factors such as plant nitrogen status, plant population dynamics and grazing management either influence or are influenced by the turnover of SOM, suggesting its role in pasture resilience should not be underestimated.

Keywords: microbial biomass, nitrogen, soil structure

Background

In New Zealand (NZ) ruminant-based enterprises, productive pastures are central to building farm business resilience (Neal & Roche 2020). Maintaining the longevity of a productive pasture will provide added resilience ('Bounce Back-ability'), and support environmental sustainability, given that pasture renewal adds cost and increases risk of losses of nutrients and sediment to the wider environment (de Klein et al. 2021).

Clark (2011) suggested the primary influencers of pasture persistence are soil type, summer rainfall, plant nutrient status (especially nitrogen, N)) and plant population dynamics. Secondary factors include weeds, insect pests and diseases, and grazing management. This paper focuses on the role of soil – particularly the role of soil organic matter (SOM) – in pasture persistence and resilience. Soil organic matter comprises about 60% carbon (C) on average, hence much of the research conducted and cited here focuses on this component. This topic has added relevance, given concerns around the degradation of the planet's soils (Montanarella et al. 2015) and discussions around grasslands as an important C sink to mitigate elevated atmospheric CO_2 levels (Smith 2014).

Over 100 years of international research has focused on understanding the nature of SOM and soil C, and how they develop and degrade in soil. Consequently, it is understood that: SOM quantity varies between soils; it is heterogeneously dispersed through the soil; composition of SOM is highly variable and complex; it is physically and chemically protected in the soil; and it is central to C, N, phosphorus (P) and sulphur (S) cycling through the soil-plant-animal system. This paper assesses how SOM mediates both the soil physical environment and plant nutrient status and discusses practical implications for pasture persistence and resilience in NZ.

Soil organic matter quantity

Theoretically, organic material entering the soil should be highly degradable, yet some components of SOM have residence times of thousands of years (Schmidt et al. 2011). This 'survival' of SOM is due to environmental and biological factors that stabilise organic material in the soil. The key drivers of SOM levels in soil are well known and are primarily soil type, climate (temperature and moisture) and land use (Scott et al. 2002). In general, there is 13-14 t/ha more C in long-term pasture soils than forest soils (Schipper et al. 2017). Median values for long-term pasture soil C contents in the NZ National Soils Database vary with soil order: 72 (Recent), 88 (Granular), 98 (Melanic) and 132 t C/ha (Allophanic) to 20 cm depth (Sparling et al. 2003). A survey of NZ grassland soils (0-15 cm depth) measured c. 4.6% C, on average, for non-allophanic soils (McNally et al. 2018). Depending on the soil bulk density, this approximates to 70-90 t C/ha and in the order of 6000 kg N/ha, 900 kg P/ha and 900 kg S/ha.

The increase in SOM content of NZ pasture soils as they transition from scrubland or forest to fertile pastures to a new steady state is well documented and represents situations where the soils are accumulating more C and

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associated nutrients than they are mineralising (Figure 1). These changes in total SOM content tend to occur slowly. For example, Jackman (1964) estimated that it took about 30 years to transition from a topsoil C concentration of 4.5% under scrubland to 8.5% under pasture (Figure 1).

The rate of increase in SOM will be less dependent on time, more dependent on the balance between C inputs and C mineralisation (Stockdale et al. 2002); the greater the accumulation, the shorter the period of time to a new plateau of SOM. However, soils cannot accumulate C indefinitely and have a finite capacity for C capture (McNally et al. 2017) and, eventually, a steady state is achieved where there is a switch from C accumulation to C equilibration (Schipper et al. 2017). New Zealand pasture systems generally have moderate to high C stocks in the top 15 cm of soil, so there is little opportunity for further accumulation (Whitehead et al. 2018), though some management practices can decrease SOM levels, including cultivation and possibly, irrigation (Mudge et al. 2017), though the mechanism for the latter is not fully understood (Whitehead et al. 2018).

The accumulation of SOM, containing mainly C (as well as N, P, and other nutrients) under grazed pastoral farming is derived from (a) the plant itself and (b) feedbacks between high-quality pasture and the grazing animals that recycle nutrients stored in the pasture, back into the soil. Urine and dung are important sources of nutrients recycled by the second mechanism.

However, the main source of C entering the soil is via fixation of atmospheric C through photosynthesis, and then transfer below ground. The two sources of C input into soil are: humification of root and shoot remains after death; and root exudates and other organic substances released by roots during plant growth (rhizodeposits) (Kuzyakov & Domanski 2000). The proportion of assimilated C transferred below ground depends on many factors but these authors concluded that it is of the order of 30-50% for pasture; and, of that proportion, half is found in roots, with 30% lost via respiration, and 20% incorporated in SOM and microbes. Saggar & Hedley (2001) found that under NZ conditions, "for each kg of [above-ground] pasture C produced, perennial pastures incorporate a little more than a kg C below-ground in root material", which is in line with the 50% transfer rate, above.

Roots can therefore influence return of C to the soil through their mass (quantity), placement (overall depth and mass distribution), chemistry (e.g., nutrient composition, C:N ratio, quality, and recalcitrance of C), and morphology/architecture (diameter, branching patterns etc.). The presence of an active arbuscular mycorrhiza (AM) also provides a route for C to flow into the rhizosphere (Johnson et al. 2003; Kell 2011).

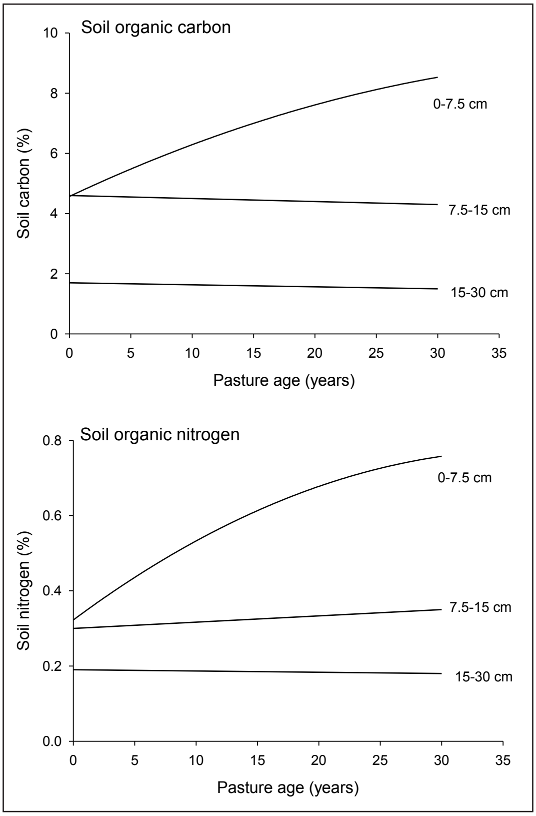

Figure 1 An example of organic carbon and nitrogen accumulation over time when soil is converted from scrub to pasture (Taupo pumice, redrawn from Jackman 1964).

Poirier et al. (2018) identified 18 root traits that influence SOM stabilisation, although some of these also destabilise SOM. These include associations with AM and N-fixing bacteria, as well as root architecture, morphology, physiology, and chemistry. The mean residence time of root-derived C has been estimated at 2.4-times longer than that from shoots (Rasse et al. 2005).

As outlined in this review, the benefits that SOM provide to a soil are the result of a complex interaction of soil C, soil biota and the soil environment (Figure 2). Consequently, to understand the role that SOM can play in pasture resilience, it is necessary to consider SOM quality, the role of the soil biota (as a mediator of SOM) and the role of the plant (as a source of C).

Soil organic matter fractions or pools

Soil organic matter is a complex material ranging from recently dead roots and plant matter through to extremely old, well decomposed, and stable organic matter. Soil organic matter exists in the soil in different forms: associated with the soil's silt and clay fractions

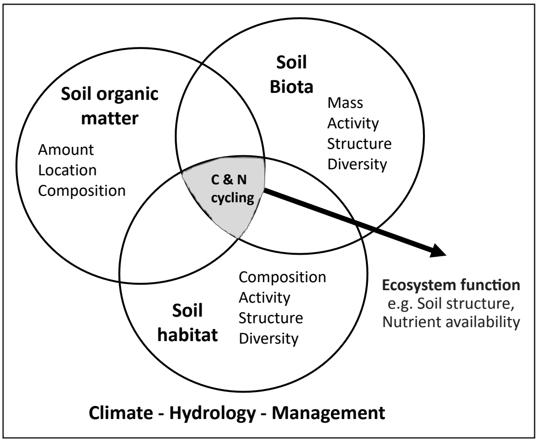

Figure 2 A conceptual model of the interaction of soil organic matter, soil biota and environment to deliver ecosystem services that support, for example, pasture resilience. Adapted from Stockdale & Murphy (2017).

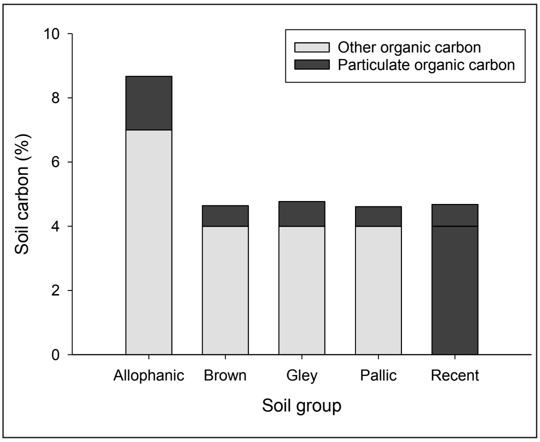

Figure 3 Total organic carbon separated into particulate and ‘other’ fractions, under pasture (redrawn from McNally et al. 2018). Particulate organic carbon is the fraction of soil organic carbon >50 μm. Soil depth was 15 cm.

(‘organo-mineral’); within micro-or macro-aggregates; and as free macro-organic matter (Carter 2000).

To deal with this complexity, researchers tend to separate SOM into ‘pools’, which are ‘conceptual in nature and not directly related to measurable entities’ (Curtin et al. 2019) but assist in developing models of SOM turnover. Pool definitions distinguish and quantify SOM fractions that differ in their form and in their function, such as nutrient release. Over decades of research, anything from two pools (rapid and slow degradation – or ‘turnover’ of SOM) through to five or more have been used to differentiate degree of degradability of the SOM-C (Shepherd et al. 2002).

For this review, a simple view of two pools is proposed: a slow degradation pool and a rapid degradation pool (also known as a ‘labile’, or an ‘active’, or a ‘readily mineralizable’ pool), which is more dynamic and susceptible to change. The active pool is of primary interest because of its significant role in short- to medium-term nutrient availability and soil structural stability (Gosling et al. 2013) and this is why researchers have shown interest in quantifying this fraction using biological or chemical tests. Common methods include using size differentiation (‘Particulate organic matter’, >50 um) or separating by density (‘Light fraction’). Though not perfect (for example, biologically active SOM also exists below this 50-µm size fraction, Curtin et al. 2010), the measurements provide valuable understanding of the functioning of SOM.

Particulate organic matter, microbial biomass and root exudates contribute most to the rapidly degradable pool. The labile pool is a small proportion of the total SOM. In a survey of 82 pasture soils across NZ, particulate organic C comprised about 15-19% of total organic C across the soil groups surveyed (McNally et al. 2018, Figure 3). Curtin et al. (2019) estimated that particulate organic matter holds 10-25% of the soil’s C. Most change occurs in this labile pool after cultivation (e.g., Figure 4), and this is the pool where effects of management practices on SOM can be seen early, as this pool changes more rapidly than other recalcitrant SOM fractions (McNally et al. 2018).

In summary, not all SOM is the same. Even though it is common to think in terms of a soil’s total SOM content, the question then is: *“Should or can the pasture system be managed to optimise returns of labile C?”*.

This is not to say that the old SOM does not have a role in soil structure and nutrient cycling. This stable fraction of SOM is protected from biota-mediated degradation processes by physical stabilisation in micro-aggregates, or through association with silt and clay particles; and it can be biochemically stabilised by forming recalcitrant compounds (Six et al. 2004). However, labile C is clearly important for continual SOM turnover and its contribution to nutrient cycling and soil structure, as described below.

Soil biota

Aside from physical and chemical complexing of SOM with soil particles, the agent of change is the soil biota, ranging from macrofauna such as earthworms, to mites and nematodes, through to the microbial biomass comprising fungi and bacteria. Arbuscular mycorrhizae also play a role in C cycling (Kell 2011). Fungi and bacteria play the key role in breakdown of the plant material due to their ability to generate enzymes that breakdown molecular structures of SOM components

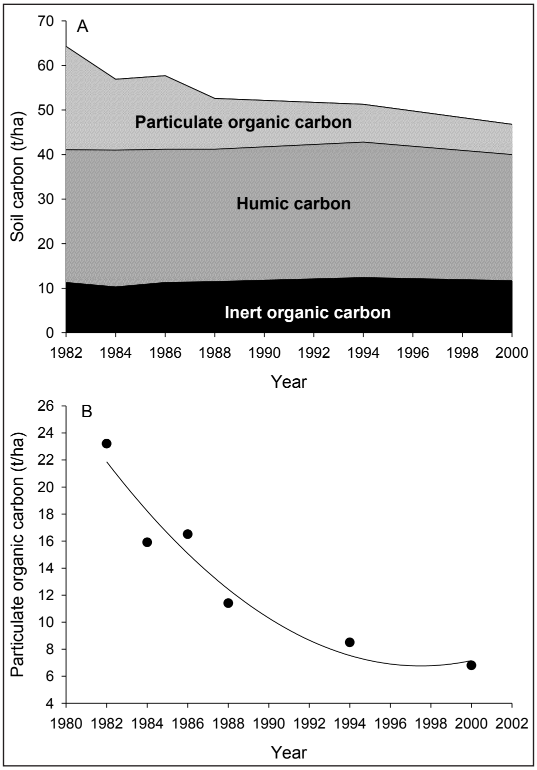

Figure 4 Change in soil carbon fractions after conversion of pasture to arable (A). (B) presents data for the particulate organic matter carbon fraction separately (redrawn from data presented in Skjemstad et al. 2004).

(Romani et al. 2006). Soil organic matter turnover is very much a 'team effort' of a range of biota; the presence of soil animals in addition to microbes has been shown to increase SOM decomposition rates (Nielsen et al. 2011). Therefore, a favourable soil environment that supports a diverse biota will enable a rapid turnover of SOM. Consequently, considering the soil biota community as a single black box is too simplistic

Microbial communities can be diverse and range from species that are fast growing and adapted to nutrient-rich environments through to slow growing and adapted to low-nutrient conditions (Wakelin et al. 2017). Fast-growing species predominate in the nutrient-rich environment of the rhizosphere, slow-growing species concentrate in the nutrient-poor area beyond the rhizosphere as they are better adapted to breaking down more complex molecules (Wakelin et al. 2017). Soil microbes are generally C-limited (Soong et al. 2020), so equating nutrient rich or poor zones with proximity to the rhizosphere (a major C source) would make sense, though Wakelin et al. (2017) contend that other nutrient availability is also important (especially P). Of course, this could either be a direct effect of the nutrient on the microbes or an indirect effect via the growing vegetation.

As well as size and activity of the microbial biomass, there is also interest in its diversity. Although some studies show a benefit of microbial biomass diversity on soil C cycling, it is probable that species diversity is more important where microbial biomass communities have a low starting diversity (Nielsen et al. 2011). This would support the concept of 'functional redundancy' in most populations. Furthermore, even if it was possible to target management that encourages diversity, benefits tend only to accrue where environmental conditions favour microbial activity (e.g., adequate soil moisture, Domeignoz-Horta et al. 2020); abiotic factors also have a huge influence on the activity and diversity of the microbial biomass.

Pasture management can influence the size and activity of the microbial biomass; for example, manure application (Neufeld et al. 2017) or P fertiliser (Wakelin et al. 2017). Direct effects were attributed to provision of soluble C to the biomass in the manure and P fertiliser directly addressing microbial P shortage on a low fertility soil. In these examples, it is probable that there were also secondary effects from the greater amount of pasture grown (and C captured) from the added nutrients.

In summary, soil food webs are diverse systems that underpin the decomposition of organic material and nutrient recycling. The food web is extremely complex, still with many research gaps (Coleman et al. 2017). However, simply: a pasture system and soil environment that provides a good habitat and that supplies inputs of labile C will support an active soil biota that, in turn, enables rapid turnover of SOM (Figure 2).

Pasture and pasture roots

Pasture, as the major substrate for C accumulation, plays a key role in SOM formation and turnover. For example, plant community diversity affects the size and activity of the microbial biomass (Johnson et al. 2003). Causes for this vary but can include species such as legumes returning better quality, N-rich, organic matter for degradation (Zhao et al. 2015) or more above-ground production generating more below-ground labile C. Different pasture species have resulted in different net N mineralisation rates, attributed to their influence on amount and quality of the SOM (Wedin & Tilman 1990).

In terms of C return to the rhizosphere, most NZ pastures are very shallow rooted. From data on dairy soils, often with >80% of roots in the top 100 mm of the soil profile (Dodd et al. 2011), there is potential to move C into deeper layers of the profile, which have low C saturation, by increasing rooting depth or changing root mass distribution. This may be achieved by use of deeper-rooted species (McNally et al. 2015), or by increasing rooting depth and improving root distribution in major pasture species through breeding (Crush et al. 2010). At least in some environments and soils, C components from roots are more stable in deeper soil due to mineral protection and low microbial degradation (Ma et al. 2020). Poirier et al. (2018) show that the contribution of a range of root traits to various aspects of SOM stabilisation (recalcitrance, soil aggregation, and interaction with minerals and metals) varies between topsoil and subsoil. The quantity and composition of root compounds such as lignin and suberin, which may potentially vary among and within species, can also affect the stability of SOM (Crow et al. 2009; Lin & Simpson 2016). This works through effects on recalcitrance or protection. Lin & Simpson (2016) found that the protection of such compounds varied in a range of soils and attributed this to factors such as land use/vegetation, soil characteristics (mineralogy, chemistry, clay content) and cultivation.

Diverse swards increase root biomass, but this does not always result in an increase in soil C stocks, which may reflect the influence of other factors such as grazing management and low levels of legumes (Skinner et al. 2006; Wu et al. 2017). In NZ pastures, the impacts of high N fertiliser use on legume content may also have longer term impacts on SOM and soil structure (see below) which affect the systems' ability to respond to environmental stresses.

Apart from the contribution of root mass to SOM at depth, root morphology and architecture should also be considered due to the complexity of plant-soil-microbe interactions. Tap-rooted species may have greater penetration to depth than fibrous-rooted species, but finer roots have a higher surface area to soil volume ratio. Finer-rooted species or cultivars may therefore have an increased rhizosphere surface area in contact with the soil, to support exudation and microbial processes, although finer roots may also have negative priming effects on SOM stabilisation (Poirier et al. 2018). Similarly, the greater root lengths of fibrous species (or selection within these species for increased root length density) increases the surface area contact with the soil.

In summary, the effects of interactions between root traits and soil characteristics on SOM turnover, including differences between topsoil and subsoil and interactions with microbial populations, is extraordinarily complex and has had little, if any, study for relevant pasture species in NZ soils. Much of the current research focus is also on the use of roots to sequester C deeper in the soil. Further research is needed to understand how strategies to sequester C deeper in the soil will affect SOM dynamics and the consequences for nutrient cycling and soil structural development.

Soil structure and soil nutrient status

Soil structural resilience

Soil organic matter is a key component of soil aggregates and fresh organic matter plays a key role in sustaining aggregate stability through supporting the generation of fungal hyphae, or through polysaccharides, roots and mucigels released by the microbial community and the rhizosphere, i.e., a mixture of biological and chemical factors (Haines & Naidu 1998). Soil with a greater respiration rate and hence greater microbial activity, has a greater amount of soil aggregation (Watts et al. 2001). Thus, it tends to be the 'active' fraction of the SOM that has most effect on aggregate stability (Haynes et al. 1991). However, these SOM constituents tend to have a soil residence time from a few months up to a year (Tisdall & Oades 1982), suggesting that frequent return of fresh residues is needed to support aggregate stability (Shepherd et al. 2002).

Aggregate stability is also affected by soil texture, so that although SOM is a major influencer of stability within a soil group (Haynes et al. 1991), there will still be differences in effect between soil groups, with SOM effects likely to be greater in clay soils than in sandy soils (Ekwue 1992). Concentration of SOM at the soil surface is important for soil structural development (Shepherd et al. 2002). Deep cultivation beyond the topsoil depth would dilute SOM concentration (but not amount in the soil), which would dilute its effects. Alternatively, strategies that aim to place C deeper into the soil might have benefits for soil structural development to greater depth.

Bulk density and available water capacity

High soil bulk density (BD) is an indicator of soil compaction and low soil porosity, with possible negative implications for root growth, and movement of air and water through the soil. Generally, increasing the SOM level decreases soil BD (e.g., Bauer & Black 1992).

When assessing effects of SOM on soil water content it is necessary to consider overall water holding capacity (WHC), and the fraction of the total WHC that is plant available (available water capacity, AWC), where

$$AWC = FC - PWP$$

and FC = water content at field capacity; PWP = water content at permanent wilting point.

The relationship between SOM content and AWC is complex (Olness & Archer 2005), confounded by interactions with soil textural composition (Hudson 1994). Although it is often perceived that high SOM levels benefit AWC, the evidence is less conclusive.

Olness & Archer (2005) concluded that increases in AWC were typically only 2.5-5% per 1% increase in organic C, in soils up to 2.5% organic C. In a more recent and larger meta-analysis of past experiments, Minasny & McBratney (2018) report that 75% of studies showed an increase of only 0.7-2.1% in AWC from an increase of 1% in soil C; the remaining 25% of studies showed a decrease in AWC. Even the upper value of 5% suggested by Olness & Archer (2005) is not large and it seems that the potential benefit to water supply from SOM is overstated.

Given that many long-term NZ pasture soils will be above this 2.5% threshold, benefits tend to accrue more in soils in transition from cropping to pasture. However, any benefits can easily be negated by poor management. For example, compaction caused by animals or heavy machinery will increase BD and have negative impacts on AWC.

Nitrogen cycling

In this review, N is used as the example of the nutrient dynamics of SOM turnover, given its importance for both pasture growth and potential environmental impact. Mineral N is released ('mineralised') as microorganisms utilise organic residues by soil as an energy source. Mineralisation is always coupled with immobilisation, whereby some of the released N is rapidly re-assimilated into the microbial biomass (Jarvis et al. 1996). The difference between gross mineralisation and immobilisation rates (net mineralisation) influences the available N for plant uptake or loss processes. Gross mineralisation rates can be 3-12 times faster than net rates (Ledgard et al. 1998), showing that N is rapidly recycling through the soil biomass, with only a fraction becoming available at any time for plant uptake. Net mineralisation rates are extremely difficult to measure, with absolute values dependent on the method used (Jarvis et al. 1996). In-field measurements under pasture show typical rates of 0.3-1.0 kg N/ha/day, but with large seasonal variation, as well as the N status of the sward (Ledgard et al. 1998), i.e., in the order of 100-300 kg N/ha supplied annually to pasture.

The quantity of N mineralised is determined by the amount and concentration of N in the SOM (Jenkinson et al. 1990). Both tend to increase with time in pasture and amount of N applied, with the accumulation due to long-term recycling through the plant-animal system (Ledgard et al. 1998). For example, Whitehead et al. (1990) measured an increase in labile C and N with increasing age of pasture (more accurately 'N status' of pasture, Figure 5). Note that N and C accumulation with cut pasture was less than with grazed pasture, due to less N cycling through the paddock as much of the C and N is exported in the harvested pasture, rather than returned by grazing animals as dung and urine. In the grazed pasture, N accumulation increased with total length of time in grass.

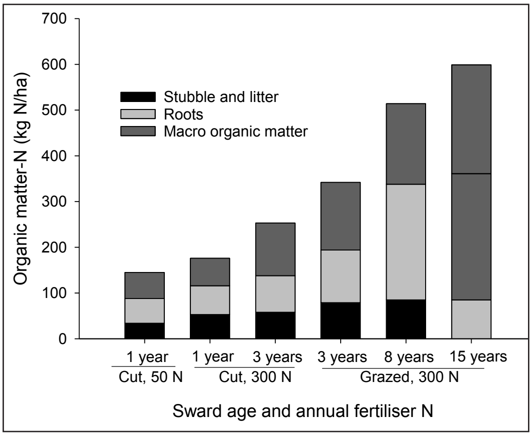

Figure 5 Estimates of the amounts of organic nitrogen (N) in stubble/litter, roots and macro-organic matter (as a measure of readily available N) in soil after cultivation, as affected by management and age of pasture (redrawn from Whitehead et al. 1990).

Pasture, with its permanent cover and established root system, is well placed to capture much of the mineralised N. However, there is significant risk of loss of soil mineral N when pastures are cultivated. Cultivation reduces protection of organic matter, opening access to residues for the soil biota to exploit (Silgram & Shepherd 1999). Large reserves of SOM-N (particularly in the un-stabilised younger SOM) can be mineralised, with sources including litter and roots from the sward, and dung from grazing, as well as the newly exposed SOM.

The enhanced mineralisation from cultivation also coincides with a period of zero or low-crop cover after cultivation. Consequently, considerable amounts of N can be leached after cultivation of a sward, with amounts primarily driven by the N status (defined above) of the pasture. Francis (1995) measured losses of up to 100 kg N/ha from ploughing a short-term ley in Canterbury. Shepherd et al. (2001) showed the importance of N history and pasture age when they measured losses of 60 kg N/ha (2-year-old pasture) and 173 kg N/ha (50-year-old pasture). However, once returned to pasture, losses declined to less than 20 kg N/ha in the following winter, showing that effects of cultivation are short-lived, compared with annual cultivation. Losses can be reduced by delaying cultivation to late winter or spring, but the practical challenges of cultivation and establishing pasture in sub-optimal moisture conditions is an issue. Less intensive tillage can also decrease N leaching (Fraser et al. 2013).

In summary, the benefits of a large labile SOM pool able to sustain pasture growth through improved soil structural stability and provision of N (and other nutrients) becomes a significant risk for N loss to the wider environment if the sink for net N mineralisation is removed.

Other than cultivation, the major source of N leaching from grazed pasture is via the urine patch where high N deposition rates in small hotspots greatly exceed the pasture's capacity to capture and recycle much of the deposited N. De Klein et al. (2021) discuss this aspect in more detail.

Discussion: implications for pasture resilience

There are a number of ways in which SOM can support resilient pastures, as identified in this paper. It is concluded that the cycling of labile C through the biomass is central to soil structure development and nutrient cycling. Though only in the order of 20% of the total organic C pool, this labile fraction is particularly valuable for soil physical benefits, and nutrient cycling. The benefits of increasing the SOM content of soil are especially relevant to soils low in SOM, such as cropping, rather than NZ pastures with SOM levels that are at or close to steady-state. Hence managing the pasture system for the specific active fraction might be more meaningful than considering total SOM. This supposition is, to some extent, supported by the suggestion that estimation of hot water-extractable N (HWN) and C (HWC) be included (in addition to soil total C) in the key soil quality indicators recommended by the National Land Monitoring Forum for inclusion in Regional Council State of the Environment monitoring programmes (Lawrence-Smith et al. 2018). Hot water-extractable N and C provide measures of bioavailable fractions of N and C and can provide early insight into impacts, for example, of fertilisation and grazing (Ghani et al. 2003). The difficulty, however, is being able to provide quantitative relationships between SOM concentrations and soil functions or ecosystem services because there are so many confounding variables that change and contribute to plant growth, so that isolating SOM effects is nearly impossible. The consensus to date appears to be that quantitative evidence for thresholds is slight (e.g., Loveland & Webb 2003). Sparling et al. (2003) contend that the statement "more [SOM] is better" holds when considering C sequestration but is less straightforward when considering productivity of soils. In that case, a minimum threshold (below which there is a loss of function) might be more helpful than a maximum (Sparling et al. 2003); yet, those thresholds and their theoretical basis, still need to be identified.

The turnover of organic C by the microbial biomass ensures that soil aggregate stability is sustained, building physical resilience by protecting against soil structural degradation and by supplying an aerated environment for root development. Aggregate stability further aids surface structure, stability and porosity and benefits water infiltration. Fresh organic matter additions and good structure also provide an environment for other soil animals to thrive such as earthworms, with further benefits through channel creation to the surface, aiding drainage. Fresh organic matter is a rich source of N, P and S and provides resilience through nutrient supply. The turnover of fresh returns of organic matter by the microbial biomass releases these nutrients for uptake by pasture and further recycling through the soil-plant-animal continuum.

There is mixed evidence that increasing SOM levels increases AWC. As detailed in this paper, the reported effects are small (or even negative). Benefits are probably more relevant to soils still accumulating SOM, as opposed to many NZ pastures that are well supplied with organic C.

In summary: 'SOM is a nutrient source for plants, a food supply for soil organisms and a site for nutrient sorption and makes a significant contribution to sustaining structural stability of soils' (Johnston 1991). However, this tends to understate that the benefits from fresh organic matter are realised through its interaction with the soil biota, via continual turnover of organic material entering the soil; and, that the younger components of SOM play a key role ('not all SOM is the same'). With much of the labile C recycled through plant roots, the rhizosphere, as the interface between plant and soil, is the main environment for these transformations (Hinsinger 2009; Kell 2011).

An active biota is central to the turnover and recycling of organic residues and the benefits that gain from these activities. In support of the importance of the biota as the agent of change, Stockdale & Murphy (2017) suggest the concept of managing soil microbial biomass as a focus for sustainable agro-ecosystems. It is recommended here that this concept is extended to managing for the whole-soil biota, not just the microbial component. The AM component of the biota also plays a significant role (Kell 2011).

Management practices that favour a productive pasture sward will also assist the soil biota; the two cannot be considered in isolation, since both require a favourable biophysical environment. Thus, practices such as diligent grazing management and drainage that minimise soil compaction and ensure aeration of the soil, provide favourable conditions both for pasture root development and the soil biota. This in turn favours microbial activity but, also, the resulting greater pasture growth will return more C via the roots into the rhizosphere to support the soil biota.

Adequate soil fertility to support a healthy sward is also important. Larger and more active microbial communities have been measured under the swards with adequate soil P status in the Winchmore long-term fertiliser trial (Wakelin et al. 2017), explained by ensuring (a) a P supply that sustains the microbes, and (b) a return of more labile C via the more productive sward.

Other sources of labile C will also help the soil biomass. For example, Neufeld et al. (2017) found that manure applications to pasture over 10 years significantly increased microbial biomass and their cellulose-degrading activity, compared with unfertilised or N fertiliser-only treatments. This was explained as differences in labile C supply. Others have found similar effects on biomass amount and composition (Bittman et al. 2005). Although these were specifically solid or liquid manure applications, similar responses would be expected from dung/urine as these also supply labile C.

Maintaining a healthy sward through adequate soil fertility also includes liming. Calcium carbonate-based liming benefits soil structure by stimulating growth of plant roots and fungal hyphae, and input of above-ground crop residues, as well as the calcium also playing a direct role in soil structural development through soil chemistry (Holland et al. 2018).

Finally, as well as pasture species and grazing management affecting the persistence of pastures (Clark 2011), the plant itself is also a key factor in moderating the C cycle and turnover of SOM. The pasture serves as a conduit for C return into the rhizosphere through root exudates and root turnover, and root architecture itself plays a significant role in physically imparting soil structural benefits (Hinsinger 2009). Several studies have seen better soil structure and higher drainage under white clover than perennial ryegrass (Mytton et al. 1993; Holtham et al. 2007). The importance of roots as host to AM is also critical as AM play a vital role in C cycling (Kell 2011). The impacts of roots on soil physical conditions potentially feedback to nutrient cycling, root growth, root penetration etc., and hence to SOM. For example, by effects on soil aggregates and pore spaces which may be driven by root morphology, architecture, chemistry, and physiology or by root symbioses - for example, mucilage produced by microbes associated with roots (Poirier et al. 2018).

Conclusions

A biologically active soil, due to the process of organic matter turnover, ensures properties such as structural stability and nutrient cycling can be sustained. To maximise this opportunity to build pasture resilience requires (a) a pasture-soil system that returns regular amounts of labile C (and other nutrients) since the younger part of the SOM plays a leading role in these processes, and (b) a soil biota able to turnover this labile C. Older SOM should not be ignored and plays a role in soil structure, but the younger SOM is the fraction that changes more rapidly.

New Zealand long-term pasture soils have high levels of total SOM, so perhaps thinking in terms of management systems that optimise the generation of ‘active’ (younger) SOM could provide extra benefit for pasture resilience. That is, building a system where the soil physical and biological functions help pasture growth. This, in return, (a) benefits the soil biota by recycling C and nutrients back into the rhizosphere, and (b) helps to physically stabilise soil through a strong root architecture. To protect and enhance this cycle:

- Maintain an adequate base nutrient status to support good pasture growth, including lime;
- Manage grazing, drainage, and other traffic to minimise soil compaction to ensure a healthy root system and a healthy rhizosphere environment;
- Include legumes to increase the quality of organic returns into the soil;
- Supply other sources of labile C such as dung and manure; and
- Protect SOM by minimising the frequency and intensity of cultivation.

Pasture species can affect SOM turnover and accumulation, for example through the quality and quantity of C returns to the soil, or through root architecture and interaction with the soil. There is interest in species that can sequester C deep in the soil profile, but further research is needed to understand (a) whether this is possible, and (b) what role recalcitrant C compounds play in SOM turnover, nutrient cycling, and soil physical resilience.

The value of soil organic C (and N) and its role in ecosystem functioning is well-recognised. However, there is difficulty in being able to provide quantitative relationships between SOM concentrations and soil functions or ecosystem services. This is a broad problem for the literature with little of this type of information reported, often because there are so many confounding variables that change and contribute to plant growth that isolating SOM effects is nearly impossible.

Soil organic matter is not the single solution to pasture resilience; soil type and summer rainfall have been previously identified as key factors (Clark 2011). However, other identified factors such as plant N status, plant population dynamics, pasture species and grazing management either influence or are influenced by the turnover of SOM, suggesting its role in pasture resilience should not be underestimated.

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