

Soil structure: its importance to resilient pastures in New Zealand (review)

David J. HOULBROOKE^{1,*}, John J. DREWRY², Wei HU³, Seth LAURENSEN⁴ and Sam T. CARRICK⁵

¹*AgResearch, 10 Bisley Lane, Ruakura Research Centre, Hamilton, New Zealand*

²*Manaaki Whenua Landcare Research, Riddet Road, Massey University, Palmerston North, New Zealand*

³*Plant and Food Research, Gerald St, Lincoln, New Zealand*

⁴*AgResearch, 1365 Springs Road, Lincoln, New Zealand*

⁵*Manaaki Whenua Landcare Research, 54 Gerald Street, Lincoln, New Zealand*

*Corresponding author: David.Houlbrooke@agresearch.co.nz

Abstract

Soil structure is critical to soil quality due to its influence on many soil processes and functions, including water storage and transport, the oxygen supply, the emission of greenhouse gases, and biological processes such as carbon and nitrogen mineralisation, nitrification and denitrification. These soil functions underpin key ecosystem services such as pasture production, nutrient cycling and mitigation of contaminant losses to receiving waters. The paper discusses key soil physical indicators relevant to pasture performance and the environment, including soil porosity, bulk density and hydraulic conductivity. In regions with robust programs for monitoring soil quality, e.g., Waikato, Canterbury, Auckland, Marlborough and Wellington, soil compaction is found to be widespread under pastoral land-use. The specific consequences of degraded soil quality on pasture production and financial implications remain unclear, at farm, regional and national levels. The range of impacts of soil structural damage on pasture yield, persistence, farm system response, and management practices that minimise or repair damage are presented. Knowledge gaps and further research needs are also summarised.

Keywords: compaction, indicators, management, pugging, soil quality

Overview

This paper reviews the literature on soil structure and its subsequent effect on pasture growth and performance in New Zealand. We examine the factors that drive a decline or improvement in soil structure. We also describe one of the key soil physical indicators, macroporosity, used by regional councils in ‘State of the Environment’ (SOE) monitoring, and other regional surveys, and explain why these are also informative for on-farm management. The impact of soil structural damage on pasture yield and persistence, and methods to minimise or repair damage, are briefly covered. Finally, research and knowledge gaps are summarised.

Soil structure and soil structural degradation

Soil structure is defined as the “spatial arrangement of solids and voids of soil across different scales without considering the chemical heterogeneity of the solid phase” (Rabot et al. 2018). Soil structure can thus be simplified as the combination of soil aggregates and air- or water-filled pore space. Characterisation of soil structure usually involves an assessment of the extent of soil aggregation and the associated features of the pore network (Figure 1). However, characterisation is always challenging because soil structure is not only about the distribution of aggregate or pore size, but also the shape and arrangement of aggregates or pores, which has direct implications for the movement of air and water. There is no universally accepted indicator to describe soil structure (Diaz-Zorita et al. 2002). For instance, in New Zealand, total porosity (or bulk density) and macroporosity (pore diameter >30 or 60 µm) are usually used to assess soil structure in pastures (Drewry et al. 2008), while aggregate size distribution has also been measured (Singleton & Addison 1999; Singleton et al. 2000), as well as qualitative visual soil structure assessment methods (Shepherd 2003). The New Zealand Soil Description Handbook (Milne et al. 1995) uses shape, arrangement and size classes of aggregates and pores.

Soil structure can vary due to the extent of various biotic (e.g., roots and soil fauna), abiotic (e.g., wetting-drying, soil forming process), and human (e.g., management practices such as cultivation and grazing) activities that take place at a given location (Romero-Ruiz et al. 2018). Therefore, processes of soil structural development and decline vary across different temporal and spatial scales (e.g., paddock, catchment, and region). There is a growing awareness of the key role that soil structure plays in regulating soil processes or soil functions. These include water storage and transport (Houlbrooke & Laurenson 2013; Hu et al. 2018), gas exchanges (Bartholomeus et al. 2008), root penetration and thus access to water and nutrients (Bengough et al. 2006), and biological processes such as carbon/nitrogen (C/N) mineralisation, nitrification

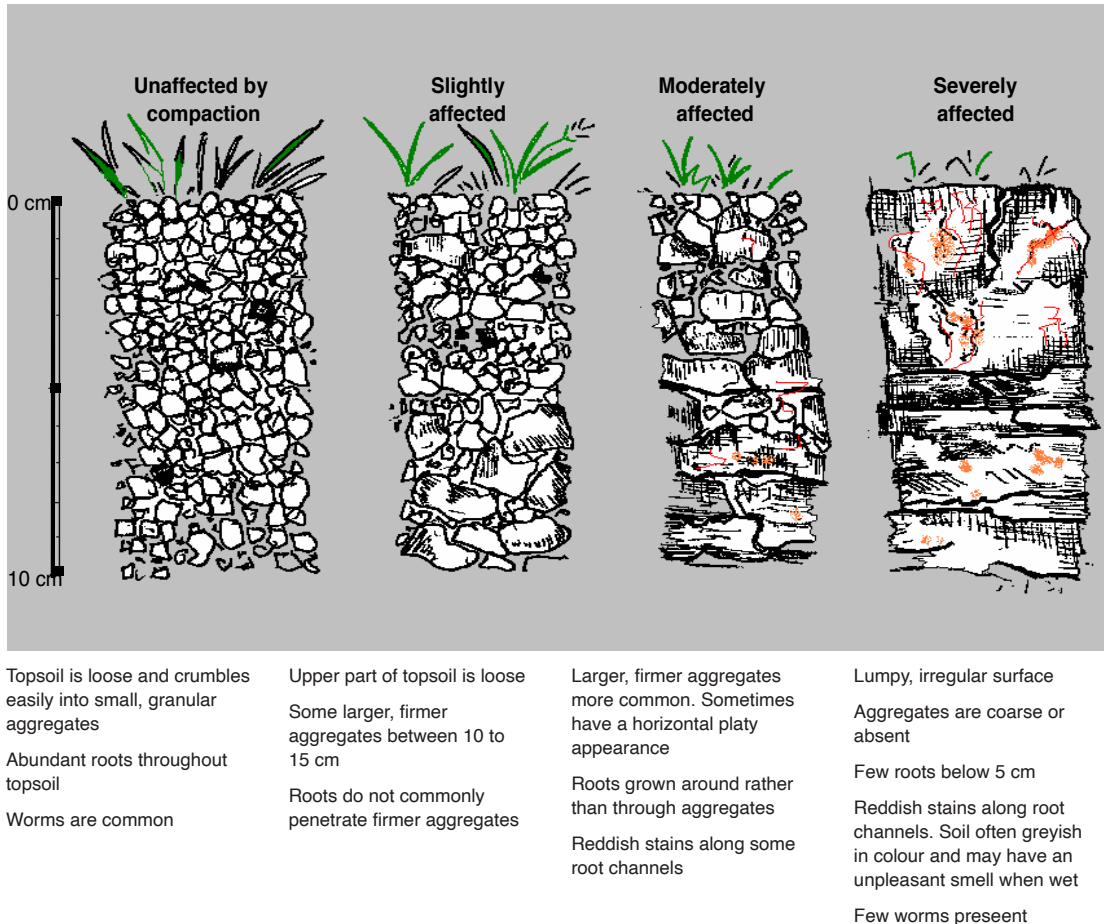


Figure 1 Illustration of soil damage with increasing soil compaction (adapted from Betteridge et al. 2003).

and denitrification (Ladd et al. 1996). These soil functions underpin key ecosystem services such as pasture nutrition and production, and contaminant loss regulation.

Soil structural degradation occurs when the force associated with the weight of the grazing animal or vehicles exceeds the soil's bearing strength. Soil compaction results in compressed soil aggregates and reduced soil pore air space (particularly large macropores), whereas soil pugging is the deformation and remoulding of soil (Drewry et al. 2008; Houlbrooke & Laurenson 2011). Soil's susceptibility to compaction is greater on unsaturated or low- to moderately-saturated soil, while susceptibility to soil pugging is typically greater on soils that are saturated or near saturation. Compacted soils often have a level surface whereas pugging invariably results in a very rough soil surface. Compaction also commonly occurs directly beneath the pugged surface where the hoof presses on firmer ground.

Factors influencing soil damage

There are five critical factors which influence the degree/magnitude of soil damage under livestock pastoral grazing (Bilotta et al. 2007; Drewry et al. 2008; Donovan & Monaghan 2021):

- Inherent soil susceptibility to damage (strength);
- Soil wetness;
- Livestock loading (weight/hoof contact area);
- Grazing management: intensity (animals/ha), duration (time on soil), and livestock movement (stationary or walking); and
- Vegetative cover.

The inherent properties of a soil will influence its resistance to forces of soil compaction. Soil texture and mineralogy influence the way in which particles align with one another; fine-grained soil such as clay loams for instance contain smaller, more uniform, particles than coarse-grained sandy soils and therefore pack tighter, leaving smaller pore spaces. The soil texture, clay mineralogy and exchangeable cation composition

also influence drainage and the cohesive strength between particles when wet. Poorly-drained soils with high clay and/or silt content tend to be more prone to damage from livestock grazing because they remain wetter for longer and wet soils have less resistance to the pressure exerted by external forces. In contrast, well-drained soils with a high content of iron oxides and mineralogy such as allophane and smectitic clays are usually more resistant to compaction and structural degradation (Hewitt & Shepherd 1997; Parfitt et al. 2002). Soil organic matter increases soil aggregate strength and stability by adding greater internal friction to particle movement, thereby helping soils to resist the external forces of livestock treading. The influence of vegetative cover within a typical perennial ryegrass and white clover pasture can play a part in minimising the impact of soil compaction. Some protection is provided by the pasture root mass that promotes aggregate formation, and in turn improves structural stability and pore space. Dense or long pastures can protect soils from treading damage to some extent and reduce sediment loss compared with very short pasture (Betteridge et al. 1999; Donovan & Monaghan 2021).

Grazing duration and stock density can have a large effect on the extent of soil damage that occurs during a single grazing event (Bilotta et al. 2007; Drewry et al. 2008; Donovan & Monaghan 2021). These two factors can be controlled through appropriate stock management. The treading effect of an animal is also related to its mass and whether it is stationary or moving. Long and high-density cattle grazing events on wet soils tend to result in extreme pugging that causes severe damage to the pasture sward and a decrease in pasture production in the short term (Meneer et al. 2001). In comparison, long-term compaction damage is often driven by the cumulative effect of livestock loading on soils during times when moisture conditions allow for soil compaction (Houlbrooke et al. 2011).

Identifying and measuring soil structural damage

Key indicators

Various indicators have been used to characterise soil structure in New Zealand pasture across a range of studies. Bulk density and macroporosity were measured in 23 studies conducted in pasture sites including dairy pasture, dry stock (sheep/beef) pasture, and forage crops (Hu et al. 2021). Bulk density can reflect the changes in total porosity but does not show changes in the distribution of the different pore sizes (i.e., a shift from few large drainage pores to several small water-holding pores) or pore continuity. Previous research by Drewry et al. (2008) has shown that macropores are the most sensitive to soil structural degradation and demonstrated relationships between pasture yield

and macroporosity (usually measured by tension table under matric potential of -3 to -10 kPa). Macroporosity has largely been accepted as the most common soil structure indicator and a lower threshold of 10% for macroporosity (pore diameter >30 μm) is widely used in New Zealand pastoral farm systems. Drewry et al. (2008) state that the threshold macroporosity for pasture production is 10%, however the relevance or validity of this value for many other ecosystem services (e.g., water infiltration, nitrate leaching, N_2O emissions) has not been tested in New Zealand conditions.

About 70% of studies reported by Hu et al. (2021, 16 of 23) have measured saturated (K_s) and/or near-saturated (K_{ns} at 0.1 to 1 kPa) hydraulic conductivity, which quantifies the rate at which water can move within soil. Hydraulic conductivity reflects not only the quantity of macropores but also the connection, shape, and tortuosity of different pores. This suggests that K_s or K_{ns} may be better than macroporosity for characterising changes in soil structure and more accurately reflects changes in function (Greenwood 1989). However, measurements of K_s or K_{ns} are usually more time consuming, skill-demanding and usually require more replications to overcome larger spatial and temporal variability than other static soil physical properties (e.g., macroporosity). Other less frequently used indicators include penetration resistance (Drewry et al. 2001), soil water content at field capacity (Houlbrooke et al. 2009), available water capacity (Houlbrooke & Laurenson 2013), structural condition score (Houlbrooke et al. 2011), aggregate size (<20 mm and >60 mm) distribution (Singleton et al. 2000), aggregate stability (Taylor et al. 2010), and surface roughness (Houlbrooke et al. 2011). These properties can be used to distinguish between damaged and undamaged soils, but they have not been well or widely evaluated or related to soil functions or ecosystem services in pasture.

Methods for visual assessment of soil structure are often sought by farmers and agribusiness professionals as a way of benchmarking soil quality against expected industry norms and as a means of evaluating the state and direction of change in soil quality as affected by farm system and management practices (Shepherd 2003). However, these assessments are semi-quantitative and class boundaries can be subjective. Therefore, visual soil assessment can be a useful generalised field assessment tool but has technical limitations as a robust measure of soil structure.

Soil quality surveys and State of the Environment monitoring

Soil physical quality has been assessed in several one-off surveys across several regions. These have concentrated on soil physical properties (e.g., bulk

density, macroporosity, aggregate stability, hydraulic conductivity) and their assessment under different practices, land uses or soil orders. Surveys in Waikato and Northland measured soil compaction under multiple treading regimes (Singleton & Addison 1999; Singleton et al. 2000), and in North Otago compaction under cattle, sheep and dryland or irrigation on farms was compared (Houlbrooke et al. 2008), and similar comparisons were made under dairy and sheep farming in Southland (Drewry et al. 2000a).

Many, but not all regional and unitary councils monitor soil quality on a regular basis as part of SOE monitoring. Soil physical properties (bulk density and macroporosity at 0-10 cm depth) are included as SOE indicators. Soil macroporosity at 0-10 cm for different regions and the whole nation was summarised in Hu et al. (2021). They found up to 75-88% of pastoral sites were degraded (soils had less than 10% macroporosity) in some regions such as Marlborough, Wellington, and Waikato. Here we mainly focus on more recent SOE reports where soil compaction is reported as a key issue in the Waikato, Auckland, Marlborough and Wellington regions (Drewry et al. 2017; Taylor et al. 2017; Curran-Cournane 2020; Oliver & McMillan 2020). Typically, sites are below the threshold for macroporosity.

In the wider Marlborough region, soil compaction/pugging was identified as an issue, so 51 dairy sites were sampled under permanent pasture and fence-lines. All sites (away from fence-lines) showed evidence of soil compaction (Gray 2011). The dairy sites had a median macroporosity (>30 μm) of 5.3% v/v throughout the period of 2007 to 2012. In contrast, 32 of 37 sites under drystock pasture had soil macroporosity values within the target range (10-30% v/v), suggesting good soil physical condition (Gray 2012). In the Auckland region, mean macroporosity was least for the dairy sites (6% v/v), followed by drystock (8% v/v), and lifestyle blocks (9% v/v). Between 2013 and 2017, 71% of pasture sites showed evidence of compaction and were outside the target range (below 10% or above 30% v/v) for macroporosity (Curran-Cournane 2020).

Regional reporting by councils is aggregated for national reporting. Monitoring data from 11 regions showed that 44% of all sites, and a total of 65% of dairy sites, were below the target range for macroporosity (Ministry for the Environment & Stats NZ 2018; Hu et al. 2021). It is not clear what the implications of soil compaction are for pasture production or finances at either the whole-farm, regional or national levels.

Impact of soil structural damage on the environment and pasture performance

Impacts of soil structural damage on the environment
A comprehensive review of the effects of soil structure degradation on agricultural production

and environmental outcomes in various land uses including pasture is available (e.g., Hu et al. 2021). Soil structural degradation resulting from reduced macroporosity restricts gaseous exchanges between soil and atmosphere. This can facilitate the formation of anoxic zones in the soil which can decrease nitrification and enhance denitrification and nitrous oxide (N_2O) emissions (Batey 2009; Beare et al. 2009; Thomas et al. 2019). For instance, field plot data have indicated that compaction from livestock treading can increase N_2O emissions by 51 to 814% compared with a 'no-treading treading' treatment (Hu et al. 2021). Enhanced denitrification processes are usually accompanied by decreased nitrification and subsequently a lower proportion of N lost via nitrate leaching (Hill et al. 2015; Thomas et al. 2019). Denitrification also reduces the amount of soil nitrate and can cause pasture N deficiency. Sulphur can also be lost from the soil as H_2SO_4 . Wet soil conditions fill pores with water, further reducing gaseous exchange and in combination with reduced macroporosity can cause strong anoxic conditions that deplete levels of nitrate and sulphur in the soil.

In New Zealand, several studies (mainly from the Otago region) have indicated that grazing under certain conditions (i.e., intensive stocking on wet soils) significantly decreases infiltration capacity, increases surface runoff volumes and with-it phosphorus, sediment, and *Escherichia coli* loss (McDowell et al. 2003a, b; Lucci et al. 2010, 2012; Monaghan et al. 2017). Contaminant losses from compacted land are likely to increase with a greater incidence of extreme weather expected under climate change in New Zealand (Mullan et al. 2016; Keller et al. 2019).

Pugging can also cause soil damage, hence detrimental effects (e.g., increase in bare ground and contaminant losses, weeds, reduction in root volumes, pasture pulling, and rough ground surface). Therefore, managing soil to prevent or decrease the occurrence of pugging has until recently been at the farmer's discretion. However, the recent introduction of the Essential Freshwater Resource Management (National Environmental Standards for Freshwater) Regulations 2020, means that intensive winter grazing on a paddock will need to comply with strict rules. Farmers will need to ensure that pugging at any one point is not deeper than 20 cm and pugging of any depth does not cover more than 50% of the paddock (Reddy 2020). Failure to keep within this pugging standard would necessitate a resource consent to undertake this farming activity. The farm management implications of this new rule are not yet understood, and farmers will require strong guidance if they are to meet these criteria. The authors hypothesise that this rule may have a future impact on the types of stock management deemed suitable

for future winter grazing activity. The rule appears to be aimed at animal welfare and not soil management. Pugging depth of 20 cm may be still too deep from the aspect of soil (or pasture) management. More data on the effects of pugging depth and coverage on soil structural degradation, the environment and pasture management, are required to address the appropriateness of this pugging rule for better managing soil structure in pasture.

Pasture response to soil damage from compaction

A range of studies have investigated the wide variety of grazing management options and/or compaction mitigation strategies and their impacts on pasture yield (Drewry et al. 2004; Houlbrooke et al. 2009). Several studies have reviewed the impacts of compaction by grazing animals, particularly on legume performance (Menneer et al. 2004), pasture yield, soil physical properties (Drewry et al. 2008), soil quality, and water quality (Bilotta et al. 2007).

In a study designed to prevent compaction damage, different dairy cattle grazing strategies were assessed in Southland to examine their effect on soil physical properties and pasture yield over three lactation seasons. There were only small increases in pasture yields for the strategies (various restricted grazing regimes) tested (Houlbrooke et al. 2009). The study also demonstrated the susceptibility of soil to compaction damage during the wetter spring period and identified the need for tools to assist with grazing management decision-making. A penetrometer was tested as a tool to trigger the preventative measures, but it did not decrease soil degradation from occurring, particularly during wet spring periods (Houlbrooke et al. 2009).

Pasture response to soil damage from pugging

A range of studies have investigated the effects of poaching and/or pugging on pasture (Menneer et al. 2005; Tuohy et al. 2015). Many studies have concentrated on single treading events (Herbin et al. 2011). In a pugging-event trial on a poor draining Te Kowhai silt loam (Gley Soil) in the Waikato region, annual pasture yield was reduced by 16% and 34% following moderate and severe pugging, and clover yield was reduced by 9% and 52%, respectively (Menneer et al. 2005). Similarly, in another study, annual pasture yield was reduced by 21% and 45% following moderate and severe pugging (Menneer et al. 2001). A pugging event on a well-structured Kereone silt loam (Allophanic Soil) reduced pasture production by 38% compared with a control for the first harvest, 23 days after pugging. Pugging on a Te Kowhai silt loam (Gley Soil) reduced pasture production by 54% (421 kg dry matter (DM)/ha) compared with the control for the first harvest, 39 days after pugging. At two Ruakura

sites (Te Kowhai silt loam; Gley Soil) the reduction in yield caused by pugging over the two harvests up to 90 days post-pugging, was 29% and 24% (Drewry et al. 2003). Severe soil structural damage from pugging may require resowing of the pasture. The pasture impacts arising from direct damage to the sward versus impacts from damaged soil structure are not usually determined in pugging studies.

Farm- and system-scale pasture response

Restricting livestock from grazing during 'wet' periods is a strategy that farmers can use to help reduce treading damage (Houlbrooke et al. 2009). However, this choice also results in increased capital and operating expenditures due to the construction of off-paddock facilities and the cost of conserving more pasture due to inflated feed surpluses. Required upgrades to the effluent management system, potentially more labour and the quantity and quality of the supplementary feed required are also important considerations. Therefore, the benefit gained from managing cows to avoid or minimise grazing on wet soils will differ across locations in response to site-specific variables. For instance, in climates such as Southland where soils remain consistently wet throughout the winter and spring, restricted grazing strategies have been reported to improve soil structure and pasture production across farms (Drewry & Paton 2000). However, in comparatively drier environments the benefits of wet soil protection to whole-farm production is less as the changes in production are often insufficient to offset the financial costs associated with standing cows off pasture (i.e., provision of a stand-off facility and operational costs). In North Otago, for instance, there was no significant difference in annual pasture production between standard grazing (17.0 t DM/ha/yr) and restricted grazing (17.9 t DM/ha/yr, Laurenson et al. 2015).

The potential advantages of removing cows from wet paddocks will vary in response to milk price, soil type and the pasture production that is lost under 'standard' managements where no soil protection is provided. In drier regions, the impact of treading damage across the whole farm will be low and so production and financial gains may often be less than the costs of implementing improved grazing strategies. However, there can be valuable environmental gains in terms of contaminant reductions in surface runoff and for maintaining adequate infiltration on effluent paddocks.

Farm management practices that repair or prevent soil structural damage

Soil structural degradation under winter forage crop grazing is frequently raised as a concern for sustaining soil health. In South Island dairy systems, winter forage

cropping is commonly used to overcome winter feed deficits and as such is incorporated into the pasture renewal process. The type of wintering system varies, so soil management, effects of conditions on soil, and mitigation strategies will vary (Dalley et al. 2014). Mitigations include strategic grazing and avoiding critical source areas, which can help minimise soil disturbance and effects on water quality (Dalley et al. 2014; Monaghan et al. 2017; Beef and Lamb New Zealand 2019; DairyNZ 2021). With regard to rotational grazing systems, the greatest period of compaction risk is early to mid-spring when soils are frequently wet and rotation lengths are short due to high pasture growth rates (Drewry et al. 2008). However, the extent and impact of wet soils and subsequent treading damage will generally vary considerably across the farm. This in turn influences the subsequent impact on the farm performance both environmentally and productively (Laurenson et al. 2017; Donovan & Monaghan 2021). Furthermore, natural soil recovery during the summer and autumn period can mean the compaction can be short-lived (Drewry et al. 2003).

Given that winter forage cropping and pasture renewal are a part of a modern pasture-based system, then crop establishment method has an important influence on the resilience of pastures. Conventional tillage to establish autumn forage crops tends to reduce bulk density and hence soil strength and resistance to compaction during winter grazing. In contrast, direct drilling to establish autumn forage crop oats was effective in mitigating the soil compaction during a simulated winter grazing (Hu et al. 2018). No-tillage was also found to increase the early growth and water use efficiency of the subsequent barley crop after grazing, resulting in greater marketable grain yield at final harvest (Hu et al. 2020). Once the soil structure was damaged by grazing, establishment of a catch crop at the earliest time can be used to alleviate soil compaction/pugging from winter grazing. It is well documented that catch crops can improve soil physical quality by decreasing bulk density and increasing soil organic C concentration, aggregate stability, available water capacity and infiltration capacity (Keisling et al. 1994; Villamil et al. 2006; Blanco-Canqui et al. 2011, 2015). But their impact can be variable depending on the type of catch crop, soil, tillage and cropping system, and climate (Blanco-Canqui et al. 2011).

Once compacted, soil structure can be restored through natural wetting and drying cycles, freeze-thawing, pasture growth and earthworm activity (Drewry et al. 2003). Depending on the degree of initial damage, this process may take several months, if not years, to restore soil quality and tends to be limited to the top 10 cm of soil where moisture fluctuations, pasture root growth and biological activity are typically greater than deeper in the soil profile.

Mechanical aeration can be used to hasten the recovery process by improving drainage and air diffusion to depths of around 30 cm. The effects of loosening compacted soils by subsoiling (35 and 50 cm depth) were investigated by Greenwood (1989) under dryland and irrigated conditions at four sites (three in North Otago, one in Canterbury). The results showed that subsoiling allowed the crop to extract more water from the subsoil during short-term droughts. A similar benefit from subsoiling a pastoral soil in Canterbury was observed, which improved subsoil conditions in the following spring (10 months later) with significant increases in pasture production over the August to October period (Harrison et al. 1994). However, research on a poorly drained Waikato soil showed no significant yield improvement from subsoiling (Burgess et al. 2000). Similarly, Drewry et al. (2000b) found no significant increase in pasture yield following aeration using conventional tines on a poorly drained Southland soil and a significant negative impact on pasture production when using winged tines, particularly when a dry summer follows the subsoiling. Houlbrooke (1996) also reported a yield penalty from subsoiling three Waikato soil types (one well drained, two poorly drained) in the spring immediately prior to a summer drought period. These research findings highlight the importance of the timing of aeration, with respect to soil moisture in the weeks following implementation, as vital for optimal soil and pasture response. In North Otago, mechanical aeration using ripping equipment was effective in increasing surface soil porosity by 10% to 25% and pasture growth by approximately 2 t DM/ha/yr (13% increase) compared to the non-aerated soils. However, improvements gained from aeration generally did not persist longer than 18 months due to the subsequent grazing pressure from cows. The potential economic benefits of mechanical soil aeration on this site were estimated to be in the region of \$70/ha/yr of winter forage crop paddock that was aerated (Laurenson et al. 2015).

Research and knowledge gaps

There are several knowledge gaps arising from our review of the literature:

- 1) A variety of indicators can be used to assess aspects of soil structure, including macroporosity, bulk density and hydraulic conductivity. However, a number of these have not been well connected to the wider range of soil functions or ecosystem services in pasture, beyond utilisation and yield. Although some New Zealand studies have associated pasture yield with several soil physical properties, further research is needed. Of particular importance is the need to understand how pore connectivity and shape are related to critical and optimum values

- of soil physical properties and their importance beyond pasture yield to environmental performance (i.e., greenhouse gas (GHG) emissions and water quality). This would be valuable as regional soil quality monitoring programmes generally show soil compaction is an issue. There is a need to identify a suite of scientifically robust, measurable, and readily repeatable indicators of soil structure that can be used on-farm, in a more systematic and economical way than existing approaches.
- 2) Several regions including Otago, Southland, Gisborne and West Coast, do not currently monitor or report on soil quality, while Northland, Taranaki and Southland regions have infrequent or limited soil quality monitoring. Several regions (Waikato, Auckland, Marlborough and Wellington) that undertake monitoring report that soil compaction is an issue. Further research is needed on how these regional results relate to pasture production, environmental effects e.g., nutrient leaching, runoff and GHG emissions, and relate to vulnerability or resilience to soil compaction.
 - 3) The farm management implications of a new pugging rule under resource management regulations are not yet fully understood but, in the future, this legislation may limit the soil types which will be suitable for winter grazing. Pugging to 20 cm depth is excessive and would not be recommended for maintaining soil physical quality or water quality. Compaction would occur below this zone and natural recovery would be slower than pugging to shallower depths. Therefore, further research is required across a broader range of soil types to understand the relative vulnerability of different soil types, their critical thresholds to pugging risk, as well as their recovery and response to different management mitigations.
 - 4) Soil structural degradation from compaction and pugging increases the risk of runoff and flooding, so the potential effects e.g., contaminant losses, under a likely greater incidence of extreme weather due to climate change, require further evaluation. Compaction and pugging can lead to changes in pasture composition and in particular to increased weediness.
 - 5) Many practices have been proposed to mitigate the adverse impacts of soil structural degradation on pastoral growth. Their efficiencies across different soils, climates and farm systems need to be tested by both modelling and field experimentation. Care needs to be taken in planning trials - previous studies have shown the results can vary between soil types and climatic conditions (particularly those at the time of treatment application). As highlighted above, the efficacy of mitigation practices should be evaluated across a range of ecosystem services that healthy soil structure influences.

6) There remains a knowledge gap in extrapolating data on soil quality (and the associated impacts of poor soil quality) from plot scale through to impacts at paddock, farm and catchment scales. This is caused by the temporal variability in the state of soil quality with highly damaged areas often accounting for only small proportions of the total farm area. Such extrapolations are further complicated by the temporal cycle of damage and recovery throughout the growing season.

Conclusions

- Soil structure affects many soil processes and functions, including water storage and transport, gas exchanges including oxygen and GHGs, and biological processes such as C and N mineralisation, nitrification and denitrification.
- Soil function underpins key ecosystem services such as pasture production, nutrient cycling and contaminant losses.
- Regional council soil quality monitoring shows that soil compaction is an issue in many regions dominated by pastoral land-use including Waikato, Marlborough, Auckland and Wellington.
- Spatial distribution of soil damage and temporal changes in soil quality mean that it can be difficult to interpret environmental, pasture production and financial implications at farm, catchment and regional levels.

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