Manaaki Whenua
Landcare Research

Soil health in the context of Regenerative Agriculture

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Our Land and Water National Science Challenge & the NEXT Foundation

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'Think piece' on Regenerative Agriculture in Aotearoa New Zealand: project overview and statement of purpose

Gwen Grelet & Sam Lang

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Find the full project overview, white paper and topic reports at ourlandandwater.nz/regenag and www.landcareresearch.co.nz/publications/regenag

This report is one of a series of topic reports written as part of a 'think piece' project on Regenerative Agriculture (RA) in Aotearoa New Zealand (NZ). This think piece aims to provide a framework that can be used to develop a scientific evidence base and research questions specific to RA. It is the result of a large collaborative effort across the New Zealand agri-food system over the course of 6 months in 2020 that included representatives of the research community, farming industry bodies, farmers and RA practitioners, consultants, governmental organisations, and the social/environmental entrepreneurial sector.

The think piece outputs included this series of topic reports and a white paper providing a high-level summary of the context and main outcomes from each topic report. All topic reports have been peer-reviewed by at least one named topic expert and the relevant research portfolio leader within MWLR.

Foreword from the project leads

Regenerative Agriculture (RA) is emerging as a grassroot-led movement that extends far beyond the farmgate. Underpinning the movement is a vision of agriculture that regenerates the natural world while producing 'nutrient-dense' food and providing farmers with good livelihoods. There are a growing number of farmers, NGOs, governmental institutions, and big corporations backing RA as a solution to many of the systemic challenges faced by humanity, including climate change, food system disfunction, biodiversity loss and human health (to name a few). It has now become a movement. Momentum is building at all levels of the food supply and value chain. Now is an exciting time for scientists and practitioners to work together towards a better understanding of RA, and what benefits may or not arise from the adoption of RA in NZ.

RA's definitions are fluid and numerous – and vary depending on places and cultures. The lack of a crystal-clear definition makes it a challenging study subject. RA is not a 'thing' that can be put in a clearly defined experimental box nor be dissected methodically. In a way, RA calls for a more prominent acknowledgement of the diversity and creativity that is characteristic of farming – a call for reclaiming farming not only as a skilled profession but also as an art, constantly evolving and adapting, based on a multitude of theoretical and practical expertise.

RA research can similarly enact itself as a braided river of interlinked disciplines and knowledge types, spanning all aspects of health (planet, people, and economy) – where curiosity and open-mindedness prevail. The intent for this think piece was to explore and demonstrate what this braided river could look like in the context of a short-term (6 month) research project. It is with this intent that Sam Lang and Gwen Grelet have initially approached the many collaborators that contributed to this series of topic reports – for all bring their unique knowledge, expertise, values and worldviews or perspectives on the topic of RA.

How was the work stream of this think piece organised?

The project's structure was jointly designed by a project steering committee comprised of the two project leads (Dr Gwen Grelet[1] and Sam Lang[2]); a representative of the NZ Ministry for Primary Industries (Sustainable Food and Fibre Futures lead Jeremy Pos); OLW's Director (Dr Ken Taylor and then Dr Jenny Webster-Brown), chief scientist (Professor Rich McDowell), and Kaihāpai Māori (Naomi Aporo); NEXT's environmental director (Jan Hania); and MWLR's General Manager Science and knowledge translation (Graham Sevicke-Jones). OLW's science theme leader for the programme 'Incentives for change' (Dr Bill Kaye-Blake) oversaw the project from start to completion.

The work stream was modular and essentially inspired by theories underpinning agent-based modelling (Gilbert 2008) that have been developed to study coupled human and nature systems, by which the actions and interactions of multiple actors within a complex system are implicitly recognised as being autonomous, and characterised by unique traits (e.g. methodological approaches, world views, values, goals, etc.) while interacting with each other through prescribed rules (An 2012).

Multiple working groups were formed, each deliberately including a single type of actor (e.g. researchers and technical experts only or regenerative practitioners only) or as wide a variety of actors as possible (e.g. representatives of multiple professions within an agricultural sector). The groups were tasked with making specific contributions to the think piece. While the tasks performed by each group were prescribed by the project lead researchers, each group had a high level of autonomy in the manner it chose to assemble, operate, and deliver its contribution to the think piece. Typically, the groups deployed methods such as literature and website reviews, online focus groups, online workshops, thematic analyses, and iterative feedback between groups as time permitted (given the short duration of the project.

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[1] Senior scientist at MWLR, with a background in soil ecology and plant ecophysiology - appointed as an un-paid member of Quorum Sense board of governors and part-time seconded to Toha Foundry while the think piece was being completed

[2] Sheep & beef farmer, independent social researcher, and project extension manager for Quorum Sense

Soil health in the context of Regenerative Agriculture

Contract Report: LC3954-13

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1 Summary

We define soil health as the sum of soil chemical, physical and biological attributes that allow the continued capacity of a soil to function as a vital living ecosystem. Soil health is embodied within the concept of soil security, and embody soils' *Mauri, Mana, Mahinga kai and Maara kai, and Oranga ora.* We propose a core list of soil health indicators applicable to New Zealand (NZ) soils under various uses and management regimes, including Regenerative Agriculture (RA). The set includes measures suitable for on-farm monitoring, as well as for research purposes, and also includes indicators commonly used by RA practitioners. The indicators listed go beyond standard soil fertility tests commonly used on-farm, and include organic matter properties, soil physical condition, and biological properties. Although there are many studies on soil health, there is a paucity of studies evaluating the effect of RA on soil health at the paddock scale and at a farm-system level.

We examine the rationale underpinning the proposed impacts of RA and highlight key knowledge gaps relating to:

- evaluating changes in soil organic matter content that may occur via alteration of the ratio of the different carbon pools, particularly labile carbon entering the soil and via modification of the profile distribution of carbon
- quantifying changes in water-holding capacity and water utilisation as a result of suggested changes in carbon content, and use of biology to potentially increase plant water uptake
- assessing the (longer term) ability to maintain nitrogen and phosphorus availability with fewer inputs, where a greater reliance on free and symbiotic nitrogen fixation as well as phosphorus mobilisation across the different pools is suggested
- characterising any changes in mineral balance, leading to potential improvements in plant nutritional quality for animal health, as well as possible resistance to pests and disease
- testing the impact of bio-stimulants and bio-amendments on plant performance and ecosystem functions, including the role of bio-stimulants in soil microbial quorum sensing and quenching, and whether bio-amendments improve the efficacy of fertiliser inputs, reduce herbicide resistance and enhance detoxification ability
- assessing any improvements to soil structure, through associated alterations in soil organic matter, plant diversity and grazing regimes
- determining whether effects on biological activity and diversity improve or gain ecosystem functions, and gaining greater understanding of the soil biology required for us to manage the biology and maximise its function.

Soils are living systems and are inherently complex. This, combined with the diversity of soils and the complexity of farm systems, does not make addressing these knowledge gaps easy. As with any stakeholder group, it will be important to consult and co-develop indicators with RA practitioners to gain new insights, develop a shared understanding, and ensure the indicator suite is scientifically robust. It will also be important to understand the mechanisms

that explain any verified impacts of RA, so that the benefits can be promoted and any adverse effects mitigated under a wider range of conditions (e.g. in different farm systems).

In order to advance our understanding of soil health knowledge, we highlight the importance of linking measured indicators with both management practices and outcomes, and how these affect changes in soil functions (e.g. soil nutrient supply, soil water storage, soil carbon stabilisation, nitrous oxide emissions). As with all farming systems, it will be important to consider indicators that can be applied at different temporal and spatial scales, including the entire farm system.

2 Definition and importance of soil health

Soil health can be defined as 'The continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals, and humans' (USDA 2012). The terms 'soil health' and 'soil quality' are often used interchangeably, and while some argue that they are synonymous (Bünemann et al. 2018), others suggest soil health expands the traditional concept of soil quality and puts greater emphasis on the living components and the soil's ability to function (Lehmann et al. 2020; Pankhurst et al. 1997). It is the complex interactions between soil properties that underpin numerous ecosystem services, such as the provision of food, the regulation of water and air quality, and a reserve of biodiversity (Coleman et al. 2004; Dominati et al. 2010).

Improved soil health benefits farm productivity, but also the wider environment through improved water quality, filtration, and storage; support for biodiversity; increased carbon storage; and reduced greenhouse gas emissions (Doran 2002). In contrast, as soils degrade, their ability to function and provide essential ecosystem services becomes compromised, resulting in environmental degradation (MEA 2005). National State of Environment monitoring of soil quality in NZ has revealed that over half the monitored sites across NZ have levels of phosphorus outside the target range, or a restricted soil physical state (MfE 2018). The increasing recognition of the critical importance of soil resources is being emphasised with the emerging concept of soil security (McBratney et al. 2014). This concept allows soil to be considered a common good, similar to water and air.

A NZ perspective on soil health is emerging that incorporates not only the regulating and provisioning aspects of ecosystem services, but also the social and cultural dynamics (Dominati et al. 2010; Stronge et al. 2020). Dominati et al. (2010) developed the idea of the links between soils' natural capital stocks and the flow of services or benefits (including provisioning, regulating, and cultural) with the notion that as the condition (i.e. health) of stocks change, so too do the services. Stronge et al. (2020) suggest placing soil health at the centre of the different capitals, as defined in the NZ Living Standards framework (Figure 1).

Harmsworth (2018) further emphasises principles that have emerged as being integral to the understanding of soil health from a Māori perspective, considering that Māori have had a long connection to and understanding of soil (Figure 2). These principles include:

- mauri – internal essence, life force, assessment, local knowledge

- mana – authority to manage and make decisions, but it can also imply the mana of a soil as a living entity (i.e. mana to the soil in this context indicates giving respect and importance to the soil to function as a soil ecosystem/living entity)
- mahinga kai and māra kai – the ability of the soil to provide sustenance, food sovereignty, and prosperity
- oranga ora – a measure of food safety and food health from soil.

These approaches provide a more diverse and inclusive knowledge base and perspective to better inform the development of integrative policy.

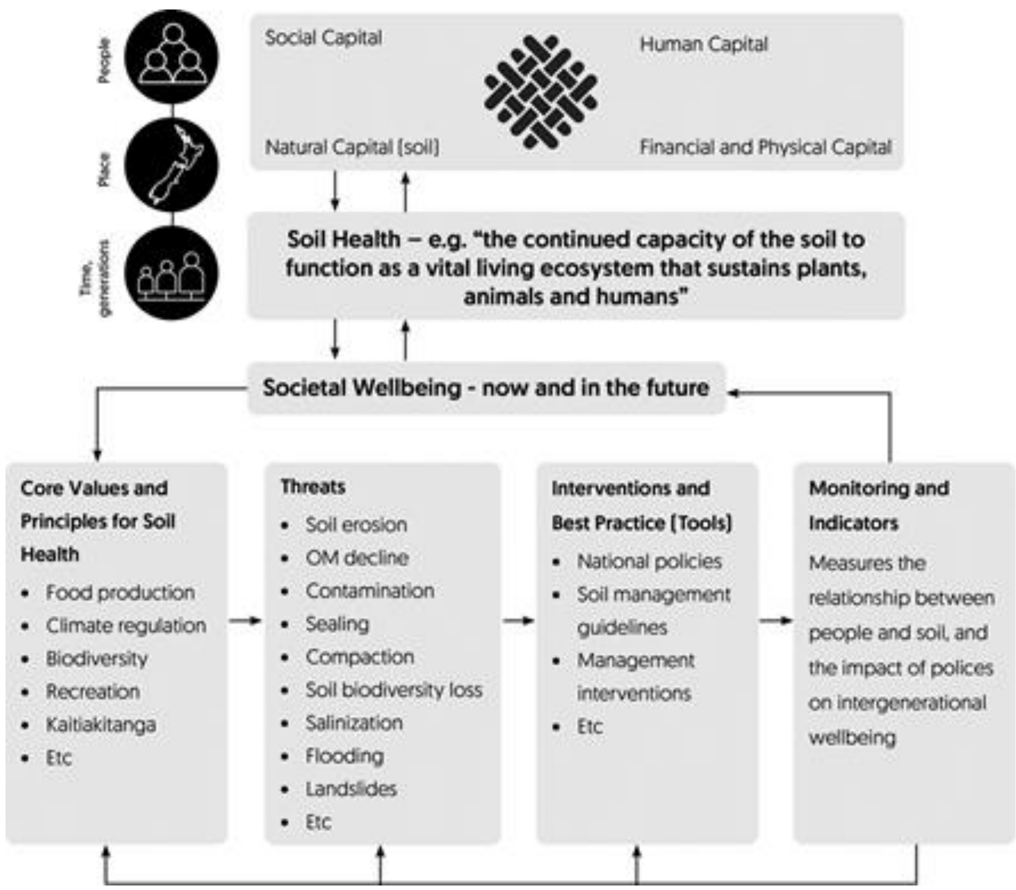

Figure 1. A conceptual framework placing soil (its health and its security) in the context of broader wellbeing and planetary capitals (source: Stronge et al. 2020).

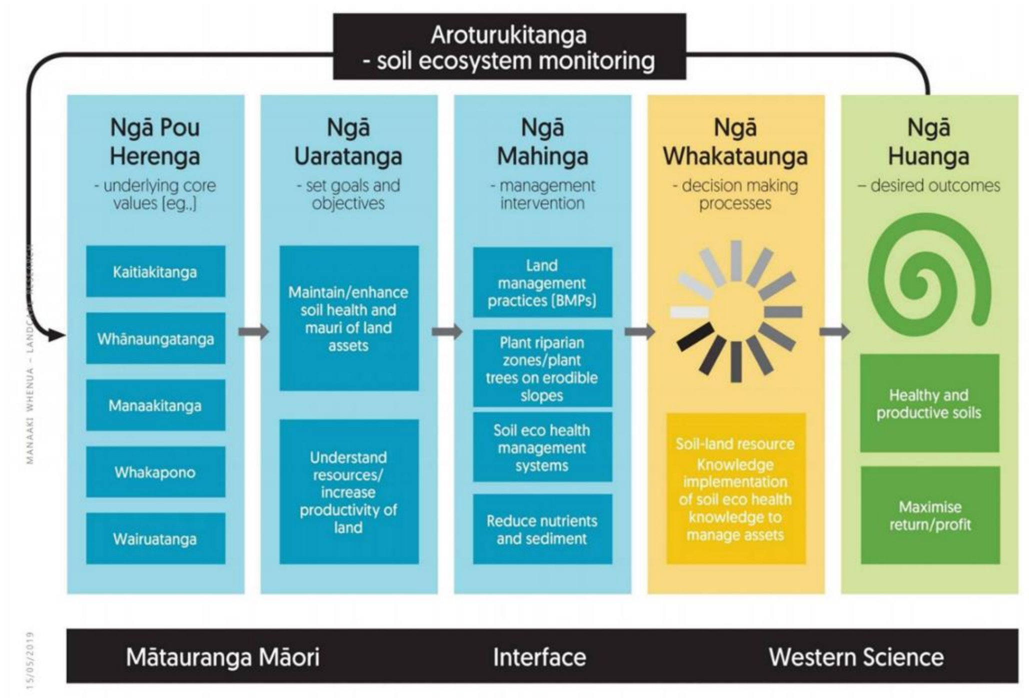

Figure 2. A framework for integrating mātauranga Māori into soil health (Harmsworth 2018).

RA is a system of farming principles and practices that seeks to increase biodiversity, enrich soils and accumulate carbon, improve watersheds, and enhance ecosystem services, while aiming to reduce or offset greenhouse gas emissions (Terra Genesis International 2020). Schreefel et al. (2020) reviewed academic studies on RA and concluded that the primary objective of RA is to 'enhance not only the environmental, but also the social and economic dimensions of sustainable food production', and argued that 'the soil is the base' for achieving this objective. Hence RA speaks directly to the concepts of soil health and soil security (McBratney et al. 2014), and also aligns to the soil health approach suggested by Stronge et al. (2020).

In this chapter we assess the influence of RA on soil chemical, physical and biological attributes that are at the nexus of soil health and soil security, and embody, in a uniquely NZ context, the soil's mauri, mana, mahinga kai and māra kai, and oranga ora. We consider soil health as an overarching principle that contributes to sustainability goals, rather than merely as a property to measure (Lehmann et al. 2020).

3 Soil health indicators

Despite the importance of soil health, there is no universal standard, indicator or methodology for its assessment. This is partly because soils are inherently heterogenous and have different properties depending on the parent material, landscape, vegetation type, and climate. This is also because soils fulfil a range of purposes that differ between land uses and sectors, which demand different requirements from the soil. Furthermore, the varying ecosystem services supported by soils have sometimes conflicting or competing needs (Bünemann et al. 2018; Lehmann et al. 2020). Hence, the idea of a universal standard of soil health is somewhat nonsensical, and in productive landscapes, especially, a healthy soil might be better described as a soil that is 'fit-for-purpose'. On the other hand, the European Union, in its upcoming Healthy Soils strategy (part of the EU biodiversity strategy for 2030), proposes to focus on defining what constitutes 'good ecological status' for soils – which might provide a more flexible, yet unified, standard for soil health.

Various core sets of soil health indicators have been developed around the world for national-scale monitoring as well as for the assessment of soil health at a local scale, such as on an individual farm (e.g. the Cornell Soil Health test). Bünemann et al. (2018) and Lehmann et al. (2020) provide a critical review of such assessments. Across the range of soil health assessments examined, the most common indicators are based on soil chemical properties, and to a lesser extent on soil physical properties, with very little inclusion of indicators accounting for soil biological properties (Lehmann et al. 2020). The most common indicators of soil health include measures of soil carbon, pH, and phosphorus availability, and then water storage and bulk density (Bünemann et al. 2018).

The lack of biological indicators in most soil health assessments reflects the fact that they often require context-specific ecological knowledge, are difficult to assess and interpret because they are not benchmarked, and are not always readily available through routine sampling and laboratory testing (van Leeuwen et al. 2017). This is also true for NZ, where the National State of Environment reporting by regional councils draws on a narrow suite of indicators as a minimum data set developed from a project spanning 500 soils. Here the indicator sets include soil acidity (pH), soil fertility (Olsen P), organic resources (including total soil carbon, total soil nitrogen, and anaerobically mineralisable nitrogen (AMN); plus two physical qualities: bulk density and macroporosity (Sparling et al. 2008; Drewry et al. 2017). Although there are no direct biological indicators, AMN is used as a 'pseudo' biological indicator since it is highly correlated to soil microbial biomass (Sparling & Schipper 2004; Stevenson et al. 2016).

In Table 1 we propose a priority set of indicators to assess soil health status, and include those commonly used under RA. We acknowledge other reviews trying to reduce this list to a common set in other countries (e.g. the Soil Health Institute; Apfelbaum et al. 2019; Norris et al. 2020). Most soil analyses or measurements can potentially be indicators, but ideally, they should satisfy certain criteria to do so. The Our Land and Water working group (https://ourlandandwater.nz/incentives-for-change/indicators-working-group/) provides a set of general guidelines for indicator selection (though not all criteria need necessarily be met): validity, accessibility, easily communicated, clearly defined, widely accepted, and performance based. For soil health indicators, Lehman et al. (2020) proposes focusing on four attributes: whether indicators are 'informative, sensitive, effective and relevant'. We acknowledge that in some cases (e.g. biological indicators) these criteria are difficult to meet and further research is required. For example, many biological indicators are not commercially available, and those that are may not be calibrated for NZ soils (e.g. Microbewise) or standardised across multiple labs (e.g. soil food web).

We also note that some indicators used by RA practitioners are used internationally but not traditionally used in New Zealand (e.g. Morgan P), so an understanding of how these measures relate to responses in NZ systems is missing. Constructively progressing research on the influence of RA on soil health requires an understanding of how different measures (e.g. Olsen P vs Morgan P) relate to each and to responses in NZ soils in order to gain acceptability of the research by all parties. Although most indicators are useable across the different sectors, some are more relevant for particular sectors, and this is indicated in Table 1. Target ranges may also vary across sectors to ensure soils are 'fit-for-purpose' across different land uses. For example, soil fertility requirements under viticulture are different from those for dairy.

In our list of indicators (Table 1.) we highlight those that would be most useful for on-farm assessment and research purposes. The indicators proposed build on those recommended for soil quality assessment in NZ (Sparling & Schipper 2002) and include observational indicators such as the Visual Soil Assessment (VSA) (Shepherd 2000) and structural condition score (Beare & Tregurtha 2004). Observational indicators are routinely used by farmers and landowners (although not necessarily recorded) to monitor soil health as part of the feedback loop between practice, observation, and practice change. Recent work has proposed a biological indicator of soil health for pastoral soils (Schon et al. 2020) and a soil health package, which adds soil biological, organic matter, and physical measures along the transects currently used for monitoring soil fertility in a pastoral system (Bilotto et al. 2020).

The spatial design adopted for soil sampling will vary depending on the purpose of the soil health assessment and the spatial variability inherent to the soil properties/indicators targeted. However, commonly deployed spatial designs are often transect- or grid-based, representative across a land management unit (Shepherd 2000; Beare & Tregurtha 2004; Land Monitoring Forum 2009; Roberts & Morton 2016). Samples need to be collected at the right time of year, and at the same time of year to allow for valid comparisons.

Table 1. Indicators and methods used to assess soil health across the different sectors. Indicators are given either a 1 or 2, depending on their priority for assessing soil health for research purposes and on-farm. Methods shown in bold have been benchmarked for NZ soils, although target ranges may vary across the different sectors, and * indicates commercially available in NZ. Methods underscored are commonly used by RA practitioners. For valid comparisons, samples need to be representative of a land management area and collected at the right time of year

Indicator	*Research priority*	*Farm priority*	*Possible methods*	*Comments*
Soil organic matter				**Adequate measure of soil horizon depth/mass change over time is difficult.**
Total soil carbon	1	1	**Combustion***	To determine stocks, sampling depth must be at least 30 cm, preferably 60 cm, and comparisons must be made on equivalent soil mass basis.
Total soil nitrogen	1	1	**Combustion***	
Available nitrogen	1	1	**Anaerobically mineralisable nitrogen (AMN)*** Potentially mineralisable nitrogen, hot water extractable nitrogen (HWEN) *	Potential for near-future NZ benchmarks.
Available carbon	1	RA, 1	Hot water extractable carbon (HWEC)	Potential for near-future NZ benchmarks.
Carbon fractions	2		Size or density fraction of soil (e.g. particulate organic carbon, mineral associated, macro/micro aggregate)	
Chemical properties				**Differences between total and bioavailable forms of minerals.**
Soil pH	1	1	1:2.5 water	
Available phosphorus	1	RA, 1	**Olsen P*** Total available P/ Morgan P	Olsen P may not be suitable for all pH levels but has been benchmarked against plant yield in NZ.
Total phosphorus	1		Total P/ organic P	
Phosphorus fractions	1		P fractionation	
Available sulphur	2	2	**Sulphate-S*/ Extractable org S***	Variable
Total sulphur	2		Total S*	
Base saturation/CEC	1	RA, 1	Base saturation/cation exchange capacity*	
Soil cations	1	1	**K**, Ca, **Mg**, Na *	

Indicator	*Research priority*	*Farm priority*	*Possible methods*	*Comments*
P retention/ASC	1		P retention/Anion sorption capacity*	
Trace elements (essential and contaminant elements)	1	1	Acid-extractable total recoverable* in soil and/or leaf tissue, plant-available (e.g. Mehlich-III*) concentrations in soil, Vis-NIR	Difference between concentrations in soil and plant tissues. Target ranges available from leaf analysis for some plant species only (e.g. clover).
Stoichiometric ratios	1	1	e.g. C:N, C:N:P, cation ratios	Some basic stoichiometric ratios are dependent on question.
Soil physical properties				
Soil texture	1	2	Particle size analysis, visNIR/MIR (near infra-red, mid infra-red)	Soil type can sometimes substitute. Soil texture influences s range of soil properties (e.g. CEC, trace element availability).
Soil compaction	1	2	**Bulk density***/ Penetrometer	Penetrometer highly influenced by soil moisture.
Soil porosity	1	2	**Macroporosity***	
Water infiltration	1	RA, 2	Single or double ring	Influenced by soil moisture; can pre-wet soil with standard volume of water to counteract legacy from previous rainfall condition.
Water-holding capacity	1	2	Available water*	Baseline important for irrigation on farm.
Hydrophobicity	2			
Aggregate size & stability	1	RA, 2	**AgStab***/miniVSA-turbidity/slaking test	Especially important for arable, vegetable and horticulture; miniVSA qualitative and subjective.
Rooting depth	1	2	Rooting depth	Comparisons only meaningful if between same soil types.
Visual soil assessment	1	RA, 1	Standard soil VSA (visual soil assessment) score cards / Structural Condition Score	The relevant scoring guideline must be chosen based on land use. Scoring qualitative and subjective.
Soil biological				**Major research gap, seasonal**
Microbial biomass	1	2	**AMN*** /HWEC*/ microbial biomass C & N	Not a direct measure of microbial biomass.
Bacterial:fungal ratio	1	RA, 2	PLFA* or soil food web direct count* or qPCR ratio (eDNA)	Not a measure of activity. Requires time series and adequate replication.

Indicator	*Research priority*	*Farm priority*	*Possible methods*	*Comments*
Biodiversity	2	2	eDNA using amplicons or shotgun metagenomics	No routine interpretation available for NZ soils. Requires investment in bioinformatics.
Soil pathogens & pests	1	2	Disease assays or qPCR/observation of soil disease / **insect pest count**	Important for arable, vegetable and horticulture. DNA techniques commercially available overseas (e.g. Predicta B).
<u>Nematode community</u>	<u>1</u>		<u>Wet extraction and microscopic ID*</u>	
<u>Earthworms</u>	<u>1</u>	<u>1</u>	<u>**Earthworm count & diversity**</u>	<u>Dependent on soil moisture; seasonal.</u>
Food-web	1	2	Network analysis & energy fluxes	Expensive. Requires a high number of samples, and a high degree of expertise to process samples and interpret data. Potential for reduction of cost and expertise requirements by combining with machine learning.
Soil functions				
Soil respiration	1		Soil surface CO_2 efflux	Measured in situ in absence of vegetation. Labour-intensive, climate-sensitive.
Soil microbial respiration	2		Colorimetric or CO_2 evolved	Measured ex situ, so limited relevance. Results variable and difficult to relate to function. Substrate-induced respiration may provide insights.
Nitrogen mineralisation	1	1	HWEC/HWEN* or aerobic N mineralisation	Important for arable and vegetable. Potential for near-future NZ benchmarks.
Decomposition	2	2	Cellulose, cotton strip or tea-bag test	In situ – requires months of incubation and challenging recovery under multispecies pastures. Results can be difficult to interpret.
Functional activity	1	2	Enzyme activity, qPCR, RT-qPCR, qPCR ratio	Selection depends on question being asked. DNA techniques such as lab-in-a-chip may provide future for on-farm assessment.

There are in fact dozens of indicators of soil health, each providing a snapshot of one single aspect of soil health, and interpreting these holistically can be difficult. There have been many attempts to reduce these assessments into a single number or index that is simpler to interpret (Karlen & Stott 1994; Andrews et al. 2004). However, by doing so, we lose some of the most useful information. An alternative is the use of visual aids, such as radar plots (Rutgers et al. 2012; Schon & Roberts 2020) to show the distance from optimal ranges for each indicator. Understanding which indicators are not within their target range can provide information about the soil functions and ecosystem services that may be most at risk (Lilburne et al. 2020), and this should be considered in any assessment of soil health. Landscape-scale assessments are challenging, and emerging technologies (such as sensor technologies) may also prove useful in advancing the assessment of soil health (Veum et al. 2017).

4 Soil health research gaps in the context of Regenerative Agriculture

The importance given to soil within RA would suggest that benefits to soil properties and functioning should be inevitable. Indeed, there are several studies pointing towards positive feedbacks between individual regenerative farming practices and selected indicators of soil health (LaCanne & Lundgren 2018; Teague & Kreuter 2020). Many studies have described or reviewed evidence for the positive impact of individual RA practices. In arable systems these practices include reduced or minimum tillage, no-tillage, cover crops, companion planting, and use of compost. Increased plant diversity, deferred grazing, and organic amendments are more important within the pastoral systems for RA. There are, however, few comparisons that have explored the impact of RA on soil health and accounted for simultaneous changes of multiple practices, or that have investigated the effect of RA at the farm system level. RA practitioners, whether established or newly transitioning to RA, are making anecdotal observations of improved soil health, and formulating hypotheses to explain these observations, which warrant further research. Key research gaps, especially in the pasture and arable sectors, are depicted in Figure 3 and discussed below.

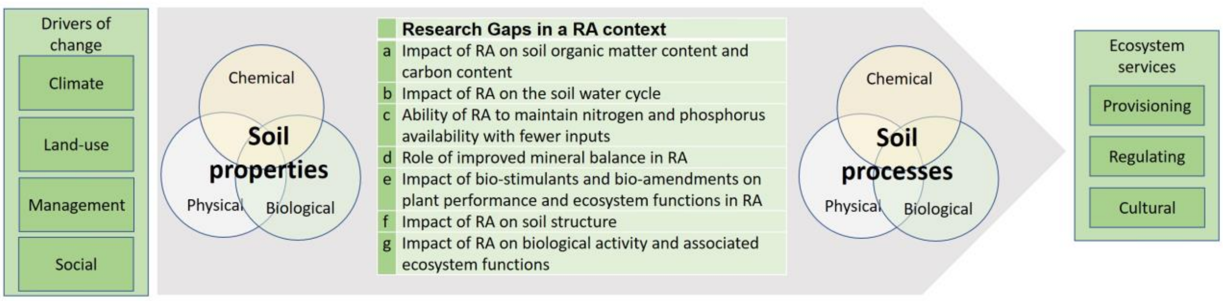

Figure 3. Key research gaps, especially in pasture and arable sectors, relating to RA and how these are linked to drivers and ecosystem services.

4.1 Impact of RA on soil organic matter and carbon content

Soil organic matter is a key component of soil, influencing the soil's chemical, physical, and biological properties, which provide key ecosystem services and functions. Most agricultural NZ soils are relatively early in development and have moderately high levels of organic matter/soil carbon compared to soils in overseas countries where RA adoption is being actively promoted. Furthermore, some NZ agricultural landscapes have been established on drained peatland – which initially had some of the world's highest carbon content. For context, the average stocks of soil carbon in the top 30 cm of NZ soils is 90 t/ha, compared with 30 t/ha in Australia and 45 t/ha in the US (FAO 2019). Higher amounts of soil carbon translate to the soil having a greater organic matter content, improved structure, and a greater capacity to store and supply both nutrients and water to plants. Equally, it is recognised that increasing soil organic matter for some land uses (e.g. viticulture), may or not be desirable, and management practices need to consider what is 'fit-for-purpose'.

While the concentration of soil carbon can provide an indication of function, we emphasise that this is not a measure of carbon stocks, which require a measure of soil bulk density (Laubach et al. 2021). Accurate soil organic carbon stocks estimates need to be based on equivalent soil mass to allow comparison between treatments or land uses (Wendt & Hauser 2013; Laubach et al. 2021). As a further note, the measure of total carbon stocks in most NZ soils provides a good measure of organic carbon stocks, with the exception for soils formed on calcareous parent material as these may contain a significant component of inorganic carbon (e.g. carbonates).

In NZ pastoral systems, soil carbon trends are affected by land use and soil type (Schipper et al. 2017). Under long-term permanent pasture there is little evidence to show that either phosphorus fertiliser inputs or grazing practices influence soil carbon stocks (Condron et al. 2012; Mackay et al. 2021). Further, although the adoption of reduced or no-tillage practices can sometimes benefit soil carbon, particularly in arable systems (Lal 2004), the benefits are not clear, and depend on soil type, environmental conditions, and the given crop production system. One of the aims of RA is to increase soil organic matter content (e.g. through greater carbon inputs at depth from deep roots, slower carbon turnover, or enhanced microbial carbon use efficiency).

Mechanisms of soil carbon accrual are still not fully understood. With changing management, soils may become sources or sinks of carbon. Recently the debate has shifted from considering the recalcitrance of soil organic matter to decomposition to considering its protection against decomposition via physical, chemical or biological stabilisation (Dungait et al. 2012). A large proportion of this stabilisation is known to occur via adsorption onto mineral surfaces, leading to the concept that the fine mineral fraction (e.g. silt plus clay) of soils can become 'saturated' with stabilised carbon (Six et al. 2002; McNally et al. 2017). However, recent modelling studies suggest that the 'C saturation concept' may not apply to the whole soil (Kirschbaum et al. 2020), as the labile particulate fraction can continue to increase despite the mineral fraction of soil saturating (Cotrufo et al. 2019). This additional C can be stored as particulate organic matter, largely unbound to mineral surfaces and less stable to decomposition (Cotrufo et al. 2019). Further, recent modelling and experimental studies suggest accumulation of microbial necromass is an important driver of soil carbon accruals, especially in systems with high biodiversity (Miltner et al. 2012; Liu et al 2018). Whether and how NZ soil carbon may increase, and in which form, is an area of active research.

Assessing whether the composition of soil carbon changes with the adoption of RA practices may help improve our understanding of the impact of RA on the soil and resulting ecosystem services, but also further our understanding of the mechanisms underpinning soil carbon accumulation and stabilisation. This includes understanding how RA affects the amount and placement of carbon deposited from plant roots and the rate of soil carbon turnover. There is growing evidence that the maintenance of labile (i.e. active) pools of carbon and nitrogen are important for soil health and function and an important resource for soil biota (Lavallee et al. 2020).

There are a number of different analyses that measure aspects of the labile carbon and nitrogen pool (Table 1. Hot-water extractable carbon (HWEC) and nitrogen (HWEN) have gained popularity as accepted measures of labile carbon and nitrogen in NZ, as they are good predictors of nitrogen mineralisation (Curtin et al. 2017), though anaerobically mineralisable nitrogen is a somewhat better predictor of microbial biomass (Stevenson et al. 2016). There is also evidence that both mineral surface area and HWEC can be useful indicators of the vulnerability of soil carbon to loss (mineralisation) (McNally et al. 2018). How the composition of soil carbon influences the soil biology and their ability to utilise carbon substrate, and the subsequent impact this has on soil functioning (e.g. nutrient availability, greenhouse gas emission, water-holding capacity – see below) is not well understood.

4.2 Impact of RA on the soil water cycle

Regenerative farmers report maintaining soil moisture during summer and improved resilience to extreme rainfall patterns. The relationship between soil carbon and water-holding capacity has been described as linear for soils with a low soil carbon content, though there has been some recent debate on this (Minasny & McBratney 2018). Indeed, the linear relationship between soil carbon content and water-holding capacities is not supported for all soils, such as finer clay soils or carbon-rich soils other than wetland and peatbog soils (Morris 2004). Anecdotal reports of improvement in water-holding capacity have been attributed to increased soil carbon under RA, which has been referred to as the 'carbon sponge' phenomenon (Jehne 2020). Recent research carried out in the MBIE Endeavour-funded Soil Health and Resilience programme has shown that increases in soil carbon can improve the available water capacity (AWC) of soils, especially the water available under drought-stressed conditions (M. Beare, pers. comm.). Scientific papers from this work are forthcoming.

Aligned to increasing the soil's water-holding capacity is the ability to improve the effectiveness of plants to take up water. One possible driver of increased water utilisation under RA is an increase in the abundance and network connectivity of soil fungi – including mycorrhizal and saprotrophic species. Fungal networks are known to move water horizontally across the landscape, and also to mobilise water from depth and from within soil spaces that plant roots cannot readily access (Querejeta 2017). Many fungi and microbes excrete a range of compounds leading to the formation of hydrophobic polymers such as glomalin-like proteins and mucilage, which may contribute to soil moisture retention and resilience against drought (Udom & Omovbude 2019). However, fungal mycelia also all contain hydrophobins, which are ubiquitous fungal protein with versatile surfactant properties, capable of forming self-assemblage at hydrophobic–hydrophilic interfaces, whose role in water-holding capacity and/or water hydrophobicity is little understood

(Rillig 2005). Here the potential impact of RA on soil water-holding capacity, water utilisation and hydrophobicity is key to understanding its potential prospects under future climate change.

4.3 Ability of RA to maintain nitrogen and phosphorus availability with fewer inputs

Soil fertility is the most commonly assessed measure of soil health in our agricultural landscapes. Our understanding of optimal soil nutrient levels allows for farmers to adjust these levels through the addition (or not) of fertiliser. As farmers alter their management towards RA, this may be associated with some reduction in inorganic fertilisers. Understanding how a reduction in nutrient inputs affects plant nutrient availability in the short term, but more critically in the long term, is a key question that needs to be answered.

Reducing fertiliser inputs of some nutrients can also reduce the amount of other nutrients supplied by the soils. For example, results from the long-term superphosphate trial at Winchmore showed that long-term restriction of phosphorus fertiliser led to a reduction in the capacity of soils to release plant-available nitrogen (Curtin et al. 2018). Further, we need to understand the interaction with changes in soil carbon, and consequent changes in cation exchange capacity and biological activity, and their potential to affect nutrient availability, including increasing nutrient cycling and losses via both leaching and gaseous emissions.

4.3.1 Nitrogen

Nitrogen is essential for plant growth, and its application through fertiliser has been increasing. With reduced (or in some cases no) nitrogen inorganic fertiliser inputs under RA, nitrogen demands are proposed to be met by increased nitrogen fixation, increased nitrogen use efficiency, rhizophagy (White et al. 2018), microbial interactions (Bonkowski & Clarholm 2012), and biologically mediated reductions in losses to the environment (Griffiths & Young 1994; Asghari & Cavagnaro 2012), especially from urine patches (e.g. leaching and nitrous oxide). Understanding potential drivers is important, especially the links with the soil microbial community and potential increase in soil carbon. Perhaps one promising aspect of RA is the opportunity to study the contribution of free-living nitrogen fixation (FLNF). The majority of FLNF occurs in the rhizosphere, where carbon accessibility is higher, involving a wider variety of soil micro-organisms, operating in a wider range of soil oxygen, phosphorus, and micronutrient availabilities than symbiotic nitrogen fixation (Smercina et al. 2019).

FLNF has relatively recently been recognised as a major contributor to ecosystem nitrogen balance. The evidence suggests that FLNF falls within the range of symbiotic biological nitrogen fixation (Reed et al. 2011), contributing to half of nitrogen fixation in unimproved hill country at Ballantrae (Grant & Lambert 1979). Despite growing interest and the potential for FLNF to support food production in low-input systems (including, but not restricted to, RA), we still have very little understanding of its ecological controls. Exploring FLNF in a managed system designed to increase soil carbon accessibility to soil biota may offer insights into this process.

4.3.2 Phosphorus

Internationally, it has been suggested there is enough phosphorus stored in soil from previous overuse of phosphorus to last at least 10 years or more without plant phosphorus deficiency (Rosen 2020). Understanding which soils, land uses and landscapes may also have excess phosphorus in NZ needs to be quantified, and estimates made of how long these stocks can last. In terms of understanding how restricting phosphorus inputs can affect nitrogen availability, plant growth and pasture quality, we can draw on long-term studies such as those at Ballantrae and Winchmore (Parfitt et al. 2010; Mackay & Lambert 2011; Curtin et al. 2018; Schon et al. 2019).

Further, what the association is between total phosphorus, plant-available phosphorus and the processes that make this phosphorus bioavailable needs to be understood. As phosphorus levels decrease, there may be a greater role of processes such as phosphate-solubilising organisms and phosphorus-hydrolysing enzyme (Alori et al. 2017). Fractionation techniques can be used to obtain different pools of elements, either by using successively stronger solutions to extract the different pools (common for measuring different phosphorus fractions) or by isolating different size or density fractions of the soil (more common for carbon and nitrogen). While identifying these different fractions can be useful, changes in different pools can often be difficult to interpret.

Olsen P is the most widely used test for NZ agricultural soils, primarily to assess fertility requirements for crops and pastures. Olsen P is the test most systematically calibrated against plant performance for NZ pastoral, cropping, and horticultural systems. A number of other tests, such as Bray-P, Mehlich-3, and Resin P, are also available in commercial analytical laboratories and have been linked to fertility requirements overseas (Fixen & Grove 1990), but they have not been calibrated for NZ soils, or only for specific uses (e.g. Bray-P for forestry, Resin-P for the use of RPR in pastoral systems).

Olsen P is a bicarbonate extraction at pH 8.5 which is used extensively throughout the world. The use of the Olsen P test in NZ originated from studies (Grigg 1977; Saunders et al. 1987a) comparing different phosphorus tests, where they concluded that Olsen P tests provided the best relationship for plant-available phosphorus. Since then, all assessments of the effect of phosphorus fertiliser application on crop and pasture productivity, and hence fertiliser recommendations, are based on Olsen P (Saunders et al. 1987b; Sinclair et al. 1997; Edmeades et al. 2006). In contrast, a recent continental-scale assessment of soil tests in the US found that Olsen P extraction was not the best test for soils with pH <7.2 in America (Sikora & Moore 2014). Further research may be required to understand how other phosphorus tests (such as Morgan P, which is commonly used by RA practitioners in the US) relate to Olsen P measures extensively calibrated against plant responses in NZ soils.

Furthermore, in a microcosm experiment, phosphorus leaching after a simulated rainfall event was shown to be significantly increased with reduced plant diversity, and reduced diversity of soil microbes and fauna (Wagg et al. 2014). Presumably diversity might also affect phosphorus mobilisation. Further research is needed to understand how phosphorus availability is linked to aboveground and belowground diversity, given the role of biodiversity in RA systems.

4.4 Role of improved mineral balance in RA

An important aspiration of RA is to ensure 'mineral balance' (i.e. soil mineral stoichiometry) is optimal for a range of outcomes, including building SOM, plant growth, nutritious plants for humans/animals, as well as plants' resistance to pests and diseases. This can be influenced by several factors (e.g. soil carbon and the soils' cation exchange capacity). The C:N / C:N:P ratios control the balance between mineralisation (plant availability, leaching and gaseous emissions) and immobilisation of these elements (Griffiths et al. 2012).

Understanding how soil stoichiometry influences nutrient supply and plant access to nutrients, especially in the diverse pastures used by RA, appears likely to be important. Adequate stoichiometry in herbage is important to avoid animal health issues. One example is high pasture potassium levels, which can reduce the dietary adsorption of magnesium and induce a deficiency (often called grass staggers). Maintaining the balance of cations in the soil is also deemed important, and the soil Ca:Mg ratio was an early indicator that is still used by some farmers and RA consultants. However, Kopittke and Menzies (2007) report that there is no ideal cation saturation ratio, and the emphasis should be to ensure sufficient but not excessive levels of cations in the soil.

In addition to the macronutrients, soil micronutrients are increasingly recognised for their importance to plant growth and animal health. This includes a range of micronutrients, such as copper, zinc, boron, iron, manganese, and molybdenum for plants, and cobalt, the latter of which is more important for animal health. Plant availability of trace elements is influenced by factors such as soil pH, organic matter content, plant species and soil type (Cavanagh et al. 2019). If concentrations in the soil are insufficient, plants or animals may become deficient, and many agricultural sectors use plant tissue concentrations to determine whether micronutrient additions are needed. However, some micronutrients may also be present at too high concentrations (e.g. copper as a result of the use of copper fungicides; and zinc from the use of facial eczema treatments) and they may elicit negative effects on plant growth and animal health, in which case they then become contaminants.

Some trace elements are not essential for plant or animal growth and are more commonly recognised as contaminants. In agricultural soils these include cadmium, uranium, and fluorine, which are present as contaminants in phosphate fertilisers, and arsenic and lead, arising from the historical usage of lead arsenate as a pesticide. These elements are naturally occurring and therefore will always be detected in the soil. The more critical question is whether they are present at concentrations that may have detrimental impacts. To help in this assessment, soil guideline values to protect soil biota (including microbes, plants and invertebrates) have been developed for NZ (Cavanagh 2019).

Farmers transitioning to RA anecdotally report resilient plants, with reduced losses to pests and diseases as soil health and plant nutrition purportedly improve. Elemental stoichiometry may be key to this, with strong inter-relationships between soil fertility, plant mineral composition, and disease (Datnoff et al. 2007). Indeed, when plants experience any type of physiological stress, including mineral deficiency, pools of all amino acids are much induced (Hildebrandt et al. 2015). Tissues with high levels of amino acids can be a preferred food source for pest herbivores (Busch & Phelan 1999; Bala et al. 2018). There is also evidence that minerally imbalanced plants produce fewer proteinase inhibitors, an enzyme plants use to defend themselves against insect pests (Beanland et al. 2003). Other processes, such as changes in soil biodiversity and increased predators may also be important. Understanding whether there are particular nutrients and conditions that can improve the resistance and resilience of plants to pests and diseases is important for a future where there may be reduced chemical inputs.

Combining soil test results and herbage tests (e.g. petiole analysis or leaf tissue analyses) is currently the most common way of determining mineral imbalances that may affect plants (Jones 1985; Hochmuth 1994). Sap mineral concentration is currently mostly used for research purposes, especially in horticulture, to investigate nutrient uptake and mobility in plants (Rellán-Álvarez et al. 2011; Li et al. 2016) and to determine the nutritional status of trees (Stark et al. 1985). Currently, the horticulture sector and commercial labs are developing standardised methodologies and benchmark data to enable diagnostic sap testing (Ávila-Juárez & Rodríguez-Ruiz 2020). In more recent years there has been a call by RA farmers to expand the range of commercially available laboratory tests to include sap analysis.

On the farm, some RA practitioners use BRIX tests: using a hand-held refractometer, they extract the 'sap' of plant tissue and interpret BRIX measures in terms of plant nutrition.[3] BRIX testing is calibrated for assessing the maturity of fruits and grapes and a few crops, such as rice (Okamura et al. 2016). This test is considered more important for the horticultural sector. Lemus & White (2014) found no significant relationships between BRIX and measures of pasture quality, such as metabolisable energy. However, commercial labs are now offering sap composition testing - providing the opportunity not only to investigate whether BRIX test relates to sap composition in pasture species, but also to explore the impact a diverse pasture has on feed quality, and on the resilience to plant pests and diseases.

4.5 Impact of bio-stimulants and bio-amendments on plant performance and ecosystem functions in RA

4.5.1 Bio-stimulants

A variety of bio-stimulants (including vermicompost, fish and animal hydrolysates, compost teas, and compost water extracts) are used by RA practitioners. The role of bio-stimulants (substances that are suggested to stimulate soil biological activity and promote plant growth) to improve plant performance is an area of interest motivating much debate in the scientific literature. Edmeades (2002) suggests that the effects of liquid fertilisers are ineffective at eliciting a plant growth response in pastoral systems, while Merfield and Marion (2016) encourage on-farm experimentation to determine what works for a particular farm system and location.

Indeed, there is a diversity of literature providing evidence on the benefit of seaweed extracts (Shukla et al. 2019), foliar fertilisers derived from protein hydrolysates (Colla et al. 2017), vermicompost (Blouin et al. 2019), and dilute compost teas (Khan et al. 2018) on plant growth, especially on perennial crops. It is hypothesised that such bio-stimulants may promote seed

[3] See https://bionutrient.org/site/bionutrient-rich-food/brix

germination and nutrient mobilisation, and suppress pathogens and diseases. Plant growth bio-stimulants are also now considered an attractive business opportunity (El Boukhari et al. 2020). However, we still lack consensus on the mechanistic understanding of their effectiveness, concentration and amount required, the extent of their effectiveness, and the context in which they might or might not be effective, including in NZ.

One of the mechanisms by which these products have been proposed to be effective (beyond nutrient application) is through 'quorum sensing', or the increase in or interference with the signalling pathways of microbial communities (Turan et al. 2017), and its counteracting mechanism, quorum quenching (Maddela et al. 2020). Volatile organic compounds may also have ecological significance (in terms of signalling) for synchronous activities (Insam & Seewald 2010). An emerging system that is considered to result in up-regulation of microbial signalling genes is the biologically enhanced agricultural management (BEAM) reactor (Johnson et al. 2015), which is currently being trialled worldwide by RA practitioners, including some in NZ. The BEAM reactor produces compost with a high fungal:bacteria ratio, with the most common usage in NZ being as an extract used for seed coating.

4.5.2 Bio-amendments

Bio-amendments, such as carbon-rich products ('humates', 'humic acid', and 'fulvic acid'), are also used by RA practitioners to lower fertiliser or herbicide application rates, which they assert can be made more effective when applied in conjunction with these bio-amendments (Khan et al. 2018; Gao et al. 2020). The use of humic substances, such as humates, peat or compost extracts, has been correlated with enhanced uptake of macronutrients (Pukalchik et al. 2019), along with increased nutrient use efficiency and plant growth responses, mediated via changes in shoot–root biomass allocation in maize (Hussain et al. 2019). Humates are complex organic chemicals formed by the microbial breakdown of dead plant material, with the main constituents being humic acids, fulvic acids, and humin. They are reported to have many actions in the soil, including stimulating biological activity, enhancing water-holding capacity, and making nutrients more available to plants. Increased amounts of humates in soil are said to make the soil more productive, with some studies showing relatively large increases in plant growth at low application rates (Rose et al., 2014). However this is not properly understood.

One way of increasing humates in soil is to add compost, which generally has a moderately high humate content. Another way, which has been used for at least 70 years in NZ and much longer elsewhere, is application of ground-up, soft, weathered coal, by-products of coal extraction, that has a very high humate content. Products such as 'black urea', a urea pril coated in potassium complexed with humate, have been available overseas for over a decade. This reportedly enables the controlled release of nutrients, resulting in equivalent wheat yields at reduced rates of nitrogen, and a reduced nitrogen losses to the environment (Hassan 2018).

A recent NZ study (Espie & Ridgway 2020) demonstrated that humates improved nitrogen fertiliser efficiency in pasture; the study showed a significant shift in soil microbial diversity and function. Their conclusion stated that 'humate increased N retention suggesting microbial sequestration may lower N leaching and volatilisation losses'. It has been suggested that a small fraction of lower molecular weight components in humic substances increase cell membrane permeability, thereby acting like carbon nanoparticles (Mihajlović et al. 2019). Carbon nanoparticles are also formed with biochar amendments, and this process is used to increase plant growth response to nutrient addition and as a delivery mechanism for agri-inputs (Sashidhar et al. 2020). Our understanding of the mechanisms involved in the use of carbon-rich products is lacking.

Adjuvants are used as a means to improve herbicide efficiency (Pacanoski 2015). The RA practitioners mix herbicides with humic substances apparently to enhance their efficacy by increasing uptake rate in the target organism, thereby lowering the effective application rate. They further assert that humic substances can temporarily suppress certain soil organisms and increase the activity of others to promote the breakdown of herbicides and lowering their toxic impact on non-target organisms. Biochar has also been suggested for use in mitigating the effect of high levels of accumulated herbicides in agricultural soils (Meng et al. 2019).

In parallel, a NZ-based study (Müller et al. 2014) indicated that the soil capacity to filter herbicides (e.g. 2,4-dichlorophenoxyacetic acid, or 2,4-D) is affected by its SOC content and soil biological activity, and driven by its water repellency. Understanding this further is important, given that herbicide resistance is an increasingly urgent worldwide problem. In NZ, resistance to more than 25 herbicides in eight chemical classes was found in 13 plant taxa (Buddenhagen et al. 2020). The use of bio-stimulants, such as dilute compost or vermicast extracts, may provide further solutions to the problem of herbicide resistance, with RA farmers anecdotally reporting that these reduce herbicide-resistant weeds after cumulative applications (Zulet-González et al. 2020). More research on these dynamics is required, and, if substantiated, might provide a pathway forward to address herbicide resistance in weeds.

Other bio-amendments, such as compost, have been shown to mitigate heavy metal toxicity. For example, Raiesi and Dayani (2020) showed that soil amendment with compost decreased cadmium availability by 48–76%, depending upon the total soil cadmium content. Farmers in Australia have also reported using humic acid and/or compost/vermicompost extracts to overcome the limitations to growth found in saline or sodic soil environments (Akladious & Mohamed 2018; Liu et al. 2020). Although these various studies have shown that humic substances can improve plant growth in greenhouse and growth chambers, there are large knowledge gaps about their practicality and efficacy in the field. Further, bio-amendments will be largely controlled by what is used in their production, and without any regulation or standards, commercial humate products can vary widely in their quality and active ingredients, presenting major challenges for consumers.

4.6 Impact of RA on soil structure

Soil structure describes how the solids and the voids in soil are arranged, as well as their aggregation and mechanical state (Romero-Ruiz et al. 2018). Soil physical properties are important to ensure adequate water and air movement through the soil, and to ensure that plant roots can penetrate the soil to reach the resources stored in the soil organic matter. Connectivity of the pore network is also a key parameter for soil biota, as well as plant growth, by improving water and gas transport, and enhancing water infiltration to also benefit the wider environment. Not only is soil structure critically important for the provision of physical stability and support for plant growth, it is also commonly associated with the provision of a range of ecosystem services, such as storing and filtering water, nutrient cycling, biomass production, storage of carbon, and as a habitat for soil biodiversity (Dominati et al. 2010; Rabot et al. 2018). Soil structure is associated with soil carbon, and, as mentioned previously, the potential for increased soil carbon and its water-holding capacity would benefit these ecosystem services.

On a global scale, around 20% of the world's pasture and rangeland soils have been found to be degraded, which has been associated with overgrazing, erosion, and soil compaction caused by livestock treading (Steinfeld et al. 2006). In NZ, restricted soil macroporosity has been highlighted through national monitoring (MfE 2018), with compaction from livestock treading and compaction and cultivation playing a part in this degradation (Hu et al 2021). Erosion and loss of soil remain an issue, especially in hill country. The continued use of heavy and intensive action machinery has also been shown to have degraded large areas of arable soils in Europe (Oldeman et al. 1991). Since it is a slow and difficult process to remediate degraded soil, avoidance is a good strategy.

Under RA and other sustainable systems, the principles of keeping the land covered (e.g. the use of cover crops) and reducing the amounts of tillage are likely to bring benefits to soil structure (e.g. aggregate stability, soil porosity) (Haynes & Francis 1990; Beare et al. 1994). Further, organic matter returns, and less physical soil disruption can benefit soil biology, and their activity (e.g. fungal networks and earthworm burrowing) can enhance soil structure. These principles are already used in NZ and are not specific to RA, and are also relevant to pastoral systems. Although there is a wealth of literature on the impacts of pasture management on soil structure (Greenwood & McKenzie 2001; Drewry 2006; Houlbrooke & Laurenson 2013), understanding the impacts of altered grazing management on soil structure is interesting. High-intensity grazing, while maintaining high plant residuals, has received little research attention in NZ. Further, how the use of diverse pasture species and mixes with complementing rooting characteristics, including deep-rooting herbs, can help improve soil physical properties is worthy of further investigation. This topic is covered in chapter 5.9 on resilience to drought/flood and soil erodibility.

4.7 Impact of RA on biological activity and associated ecosystem functions

Soil biology is extremely diverse, encompassing microscopic micro-organisms through to earthworms, and so interpreting the soil biology and their interactions remains difficult. Often soil biology research is limited to specific groups, so our understanding of how soil biodiversity responds to management in the variety of landscapes in which farmers operate is incomplete. RA aims to enhance soil biodiversity, and in so doing, has the potential to influence a range of functions as described throughout this chapter (e.g. enhancing water-use efficiency, nitrogen and phosphorus availability, soil structure, as well as interaction between plants and pests & diseases, and the fate of bio-stimulants and bio-amendments).

In order to fully understand the impact of RA on soil biology and the diversity of functions supported by soil organisms, we need to better understand the complex and interconnected food webs within the soil. Typically, the aim of RA is to increase soil biological activity and diversity, with the premise that a diverse assemblage of species will have a greater ability to suppress or control populations of pests and diseases, and/or mitigate any detrimental impact of undesirable species (e.g. pests and diseases, weeds; see Barnes et al 2020). However, we still lack systematic knowledge of where and when this might be the case.

Increasing biological activity and diversity may be achieved by limiting soil physical disturbance, increasing the amount of plant litter available, the use of cover crops; or increased crop / pasture diversity, and improving the organic matter available (through direct application of manures, composts, and bio-amendments). Increasing plant functional diversity (either pasture or trees) alters carbon inputs as well as the habitats available to the soil biology, ultimately influencing the soil community (Yeates et al. 2000; Orwin et al. 2020). Limited research has been conducted on the role of plant diversity on soil functional diversity within the context of NZ pasture systems. Current research is limited to investigation of pasture systems with less than 10 species (Woodward et al 2013; Orwin et al 2018). We still have limited understanding of the extent to which plant diversity and changing grazing management, which are key aspects of RA systems, affect above- and belowground inputs and cycling of carbon from plants (Canarini et al. 2019, Whitehead 2020).

Understanding how enhancing biological abundance affects soil biodiversity and its functioning is critical if we are to progress our ability to manage our farm systems better. This includes understanding how management affects key functional groups and their functions. Although there is a high degree of apparent functional redundancy within soil micro-organisms, there are some processes that are instigated by a relatively low diversity of micro-organisms, and we need to ensure these functional groups are maintained. How changing management affects these essential micro-organisms is important.

Further, although earthworm population sizes can be much higher in NZ pastures than in other temperate regions around the world, we know that earthworm species diversity is relatively low in managed pastures in NZ (Springett 1992; Fraser et al. 1996), and current research is assessing the merits of introducing missing ecological groups into such pastures (Schon et al. 2011). The lack of diversity in agricultural land is partly as a result of the accidental introduction of only around 17 exotic earthworm species into NZ by the European settlers. (There are nearly 200 species of earthworms in NZ, but the majority of species tend to be endemic and mainly found in our less disturbed and/or native ecosystems). How these historical deeds, including deliberate introductions, influence other soil biology within our managed landscapes is largely unexplored.

In order to advance our understanding of how RA and other practices affect soil biology, and whether soils under RA might fare better than others against rising stressors such as pollutants or climatic extremes, a wider food-web approach may be considered. Nematode community analysis allows the assessment across all trophic groups within soil food webs. Nematodes represent a range of trophic groups and life histories, as well as including both beneficial organisms and those that can have a negative impact on soil and plant functions, such as plant parasites. Indices are used to summarise changes in the nematode community (Ferris et al. 2001). Under RA there is an aim to increase fungi within the soil, aiming for lower bacterial:fungal ratios. The literature suggests that increasing dominance of fungi within the soil can be expected in systems with slower nutrient cycling and lower losses to the environment (Wardle et al. 2004). Aiming for a ratio of 1:1 has been suggested within the RA community, based on anecdotal evidence. Bacteria and fungi, and their grazers, respond to changes in soil fertility (Parfitt et al. 2012), but greater clarity on what is optimal and possible across different land uses and soil types would be helpful. The use of emerging technologies (e.g. eDNA and network analysis) to assess the entire soil biological communities and their interactions could be powerful if this is able to be linked to soil functioning and wider ecosystem services, and this requires further enquiry. Combining our knowledge of biological communities with modelling approaches may be another way to advance our understanding of this complex system (Gauzens et al. 2019).

Beyond improving our knowledge of soil biodiversity and its functioning, is understanding how the soil microbiome impacts the plant and animal microbiomes and *vice versa* (Wagg et al. 2019; Wubs et al. 2019). The potential for manipulating the soil microbiome to influence the plant and animal microbiome is intriguing, but would be very challenging given the complexity of soil.

5 Advancing soil health knowledge in the context of RA

We have detailed the key knowledge gaps in relation to soil health under RA. These include:

- quantifying soil organic matter content changes
- determining whether water-holding capacity is increased and water utilisation improved
- assessing (longer term) ability to maintain nitrogen and phosphorus availability with fewer inorganic inputs
- understanding the role of changes in soil mineral balance
- assessing the impact of bio-stimulants and bio-amendments on plant performance and ecosystem functions
- quantifying any improvements and/or better maintenance of soil structure
- determining whether soil biological activity and diversity are enhanced, and thereby ecosystem functions gained.

In order to move forward in our understanding of how RA and other soil health initiatives might influence these knowledge gaps, questions need to be addressed using a combination of approaches. Soils are living systems, and hence are inherently complex. This, combined with the complexity of a farm system, does not make for an easy task. The methodological approach will depend on the questions being asked and may include comparisons of established RA operations using low-cost methodologies, as well as the validation of results using precise, accurate and recognised methodologies. Field-based and lab-based experiments may be employed to test hypotheses, and empirical modelling used to help explain patterns. Further details on these approaches are discussed in an accompanying report within the same series. Crucial to improving our understanding are consultation and co-development with RA practitioners throughout the process.

In order to advance our understanding of soil health knowledge, we highlight the importance of linking indicators measured with both management and outcomes. There is already a wealth of information about how management practices affect soil health, and we need to understand which practices in combination can give us the biggest gains in regard to soil health, so that practitioners have the best information to improve their soil resource. As with all farming systems, it will be important to consider indicators that can be applied at different temporal and spatial scales. The interpretation of any patterns and / or trends displayed by soil health indicators will also require understanding of how the whole farm system is being managed and how it performs.

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