Impact of primary sector activities on soil resources

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Summary

Project and client

- The Parliamentary Commissioner for the Environment (PCE) is undertaking a programme of work with the aim of assessing the environmental pressures associated with the extraction, processing, use, and disposal of natural resources.
- The PCE has a particular interest in understanding the impact of primary sector activities on New Zealand's soil, and any implications for ongoing productive capacity and sustainability.
- Manaaki Whenua – Landcare Research were contracted by the PCE to synthesise existing monitoring and research on the impacts of primary sector activities on soil quality and quantity in New Zealand over April to June 2024.

Objective

- To undertake a comprehensive synthesis of the various strands of existing research to provide a coherent account of the impact of primary sector land uses on soil quality and quantity, including qualitative assessment of that impact on limiting the productive capacity of New Zealand soils and commentary on the reversibility of these impacts. In the context of this report 'impact' is defined as the degree of degradation or depletion.

Methods

- We carried out a review of the impact of each key primary sector land use (dairy and dry-stock farming, horticulture [short-rotation and perennial], arable cropping, and exotic forestry) on soil quality, quantity, and availability, along with interviews to provide expert views on land-use impacts.
- The focus for soil quality was soil biota, contaminants, soil carbon, nutrients, pH, and the physical characteristics of soil. Soil quantity is related to soil lost via erosion.
- A qualitative assessment of the impact of each key primary sector land use on the productive capacity of soils was made. The uncertainty was assessed qualitatively using the IPCC[1] uncertainty framework, and key knowledge gaps identified.

Results

- The impacts of primary production on soil resources relate to both land management practices and the intensity of management. Some land management practices (e.g. fertiliser application) are common across most land uses or within a soil order, while others are more specific to individual land uses.

[1] Intergovernmental Panel on Climate Change.

- Legacy activities such as historical land drainage for agriculture and deforestation for pastoral grazing and timber production influence the impacts associated with current land use.
- Land management practices influence the composition and functioning of the soil bacterial community, but the significance of these changes is largely unknown. There is limited knowledge on the distribution and role of soil invertebrates on the productive capacity of primary production soils.
- Cadmium and zinc are most elevated in pastoral dairy soils, but are not at levels anticipated to have negative effects on plants or soil organisms. Management of plant uptake of soil cadmium may be required to ensure compliance with food standards for exported crops. Copper is most elevated in soils used in perennial horticulture.
- Soil carbon is typically highest in pastoral land uses, although irrigation and cropping activities within pastoral systems often reduce soil carbon. Soil carbon is typically lowest in short-rotation cropping (arable and horticultural) land uses as a result of a combination of activities, including fallow periods, tillage, and biomass removal.
- Nutrient depletion on agricultural soils is unlikely, other than in hill- and high-country pastures, and potentially trace element micro-nutrients. Excess nutrients are the greater concern, largely from an environmental rather than a production perspective. In many systems lime is routinely applied to ensure pH is optimal for yield. Economic considerations constrain lime and fertiliser on hill- and high-country farms, while fertiliser application is not routine in forestry.
- Soil compaction has been widely reported. Physical damage occurs deeper in the soil with cattle than with sheep, in some cases to the depth of the topsoil, but is deepest with ground-based forestry. Pastoral areas pugged in winter can take a long time to recover, and soil compaction can affect pasture yield over the longer term.
- Arable cropping increases soil physical degradation, primarily due to cultivation driving loss of soil carbon.
- The main influence on soil quantity, and specifically soil loss, is erosion. Plantation forestry and hill-country grazing are often located on historically deforested, erosion-prone landscapes, that can be subject to erosion by shallow landslides. The productivity of eroded soil can be reduced for decades. Surface erosion processes are dominant. Knowledge of erosion and its control is reasonable, but New Zealand lacks quantitative data to ensure erosion control is targeted.
- The changes in different soil properties are more or less reversible; pH and nutrients are fundamentally reversible through the adjustment of lime and fertiliser (macro and micronutrients) or organic amendments e.g. compost applications to change soil pH and nutrient concentrations; compaction is somewhat reversible through natural and active remedial activities; soil carbon loss is theoretically reversible although in practice this is difficult to achieve. The accumulation of trace elements is essentially irreversible, even for essential elements such as Cu and Zn, where the input is greater than any uptake. Subsidence associated with draining and cultivation of Organic Soils is essentially irreversible as is eroded soil loss to waterways.
- There is insufficient knowledge to gauge the extent of reversibility of changes in soil biology, with some studies suggesting permanent changes arise with changed land use. The impacts and magnitude of pesticide residues and microplastic contamination

in New Zealand primary production soils are largely unknown, as is the reversibility of these issues.

- There is a distinction between changes in soil properties associated with land management activities and the impact of those observed changes on the productive capacity of soils. Although numerous studies identify changes in various soil properties, often associated with different land uses, the significance of those changes, particularly in relation to productive capacity, is rarely identified – most notably for soil carbon.
- Furthermore, some impacts – for example yield decreases due to loss of organic matter, or compaction – may be masked by fertiliser use, and irrigation.
- The key impacts of primary sector industries on the productive capacity of soils that are not readily mitigated (i.e. we consider pH and nutrients are readily manageable) are as follows.
  - ***Dairy.*** Compaction associated with stock grazing can occur and damage soil structure (reducing aeration in the root zone, infiltration, and/or permeability) and reduces pasture yield. Some carbon losses are observed to occur, primarily associated with irrigation and periodic cropping, although the magnitude and impact of this is largely unknown.
  - ***Meat, fibre, breeding.*** Similar effects as for dairy can be observed in more intensive systems, primarily located on flat and rolling hill country. Erosion in hill and high country is the primary effect on the productive capacity of the soil, affecting pasture yield and carbon loss.
  - ***Arable cropping and short-rotation horticulture***. Soil structural degradation can reduce crop yield. There is agreement that soil carbon is lost, but the magnitude and impact of this is largely unknown. Plant uptake of soil cadmium in food crops requires management to ensure compliance with food standards.
  - ***Perennial horticulture.*** Copper has accumulated to concentrations that may cause negative impacts in a few locations, although the spatial extent of elevation is largely unknown. Little information on carbon content or change was found.
  - ***Forestry***. Forestry is often located in erosion-prone areas, which affects productivity. Forests planted on sites with low natural fertility are at greatest risk of nutrient deficiencies. Localised compaction occurs, especially associated with ground-based harvesting.
- All primary industries based on drained Organic Soils (peat wetlands) have productivity linked to the ability to maintain adequate depth to the water table for the selected crop. Where peat is oxidising, future productivity may be limited.

Knowledge gaps

- The key knowledge gaps that arise from our assessment are:
  - quantitative assessments of the impact of changes in various soil properties, notably soil carbon (and its impacts on nutrient provision and cycling, soil biology, water-holding capacity, soil porosity/aggregate stability, and crop or pasture yield) and compaction (and its impacts on infiltration and yield) (all land uses)

- knowledge of the distribution and role of microbes and soil invertebrates in soil, and their relationship to the productive capacity of soils for all land uses
  - the efficacy of management activities for mitigating issues; in particular, reduced pasture or crop yield associated with pugging and compaction (pastoral land uses, cropping land uses)
  - better understanding of the extent to which land management practices that mitigate known impacts are being adopted across New Zealand (predominantly agricultural land-uses)
  - methods and approaches for supporting decision-making on retiring land from primary production where current land use is not sustainable (e.g. erosion prone pastoral and forestry land and drained Organic Soils)
  - the extent and impacts of copper and zinc accumulation (agricultural land uses)
  - the extent and impact of pesticides residues and microplastics in agricultural soils.
- Suggestions for addressing these knowledge gaps are provided in the report.

Conclusions

- A key finding was that there are numerous studies that identify changes in a wide range of soil properties, often associated with different land uses, but the significance and impact of those changes in relation to productive capacity of soil are rarely identified and quantified.
- In relation to soil impacts on the future productive capacity of the dairy industry, soil pugging and compaction affects pasture yield, and the reversibility of this impact is unclear.
- For hill-country pastoral land used for meat and fibre production, and for exotic forestry located in erosion-prone areas, landslides contribute most to soil erosion and in these areas productivity on eroded soil can be reduced for decades.
- For arable cropping and short-rotation horticulture, plant uptake of cadmium in soils requires management to ensure compliance with food standards, while decline in soil structure associated with cultivation and/or compaction by heavy machinery may affect crop yield.
- Copper has accumulated in some perennial horticultural soils, and occasionally to soil concentrations that may cause negative impacts to productive capacity. The accumulation of trace elements is largely irreversible, including for essential elements when input exceed uptake.
- For pH and nutrients (primarily major nutrients, nitrogen, phosphorus, potassium and sulphur), there is considerable knowledge about requirements for production and we consider that existing knowledge is adequate, and systems are largely in place, to manage pH and nutrients in the context of productive capacity for most land uses; hill country pastoral land and some forestry land may be nutrient limited. There is more limited knowledge about micronutrients in the context of productive capacity, particularly with respect to the nutrient content of food products.
- There is largely a dearth of knowledge around the distribution and role of soil fauna on productive capacity of soils used for primary production land uses. There is a

similar dearth of knowledge about the extent and impact of pesticide residues and other contaminants, including microplastics.

- Although there is agreement about the loss of soil carbon under some aspects of dairying operations, and low soil carbon present in cropping soils, the magnitude, and type of impact on productive capacity are largely unknown.

1 Introduction

The Parliamentary Commissioner for the Environment (PCE) is undertaking a programme of work with the aim of assessing the environmental pressures associated with the extraction, processing, use, and disposal of natural resources. The scope of this work includes natural resources that underpin New Zealand's primary sector production.

As part of this investigation the PCE is seeking to understand the impact of primary sector activities on New Zealand's soil, and implications for the ongoing productive capacity and sustainability of this resource, in order to address these central research questions:

a To what extent are primary sector activities resulting in the degradation or depletion of soil quality, quantity, and availability?

b What are the likely implications of these impacts on the ongoing productive capacity of this resource for the future?

The PCE contracted Manaaki Whenua – Landcare Research over April to June 2024 to synthesise existing monitoring and research on the impacts of primary sector activities on soil quality and quantity in New Zealand to help address these questions.

In the context of this report:

- Primary production refers to land-based primary production which is production, from agricultural, pastoral, horticultural, or forestry activities, that is reliant on the soil resource of the land (MfE 2022)
- Productive capacity is the ability of the soil to support land-based primary production over the long term (adapted from MfE 2022).
- Soil quality is defined in the context of the soil being 'fit for purpose' (Schipper & Sparling 2000)
- Impact is the degree of degradation or depletion.

2 Objective

To undertake a comprehensive synthesis of the various strands of existing research to provide a coherent account of the impact of primary sector land uses on soil quality and quantity, including qualitative assessment of that impact on limiting the productive capacity of New Zealand soils, and commentary on the reversibility of these impacts.

3 Methods

A review of the impact of each key primary sector land use specified by the PCE office (dairy and dry-stock farming, horticulture [short-rotation and perennial], arable cropping, and exotic forestry) on soil quality, quantity and availability was undertaken by searching published scientific literature (peer-reviewed) and grey literature (e.g. reports). The focus for the review was to identify the extent to which the primary sector was resulting in the degradation or depletion of soil quality, quantity, and availability.

We also drew on expert knowledge – our own, alongside interviews with Dr Paul Mudge (soil carbon monitoring), Dr Chris Phillips (erosion research), Dr Sam Carrick (S-map, management of soil physical properties), and Dr Linda Lilburne (S-map, land-use suitability) – to provide direction and expert views on the findings on the land-use impacts associated with their respective areas of expertise. These experts also provided written information, key publications, and/or reviewed sections of draft report sections related to their area of expertise. Budgetary constraints limited discussion with experts to those within MWLR.

Regular meetings with the PCE office were held to track progress and clarify scope when required. The following aspects were agreed to be out of scope:

- reduced availability arising from urban encroachment onto highly productive land
- factors influencing greenhouse gas emissions and wider environmental impacts e.g. water quality
- improvements in the soil resource e.g. benefits from improved soil fertility.

Subsequently, all consideration of 'availability' was also dropped from the review. However, it should be noted that *within* the primary sector there may be competition between land uses that may limit the 'availability' for individual primary sector land uses e.g. where pastoral land is converted to forestry or vice versa.

The focuses for soil quality were soil biota, contaminants, soil carbon (C), nutrients, pH, and the physical characteristics of soil. Soil quantity related to the physical amount of soil available in production land, and soil lost via erosion processes.

This review aimed to differentiate effects associated with key soil orders, where possible. An approximation of the total area of primary production on different soil orders was determined using a combination of land-cover information from the Land Cover Database version 5 (LCDB5) and soil order information from S-map; where S-map information does not exist, we used the Fundamental Soil Layers from the Land Resource Inventory System. Summary statistics were then calculated for the area of each unique combination of soil order and land-cover class, based on the following combination of LCDB cover classes:

- pastoral – high producing exotic grassland
- pastoral – low producing and depleted grassland
- perennial horticulture – orchard, vineyard or other perennial crop
- short-rotation arable and vegetable cropping – short-rotation cropland
- forestry – exotic and harvested forestry.

These areas are an approximation only because land-cover information relates to a varying extent to primary production uses, particularly for pastoral land. So while high-producing grassland almost certainly represents primary productive use, not all low-producing and depleted grassland will be under primary production. Also, some tussock land not captured here may be grazed. Additionally, the spatial accuracy of the soil order information varies depending on the underlying soil survey scale, which ranges from 1:10,000 to 1:250,000 (S-map is mapped at 1:50,000, or higher resolution). Nonetheless, this evaluation does provide a good indication of the relative area of different soil orders under primary production uses.

Following the review, a qualitative assessment of the implications of the impact of each key primary sector land use on the productive capacity of New Zealand soils was made, taking into consideration the reversibility of the impacts. The uncertainty associated with the character and magnitude of the impacts of different land-use activities on soil was assessed qualitatively using the IPCC uncertainty framework (IPCC 2010, Figure 1), as specified by the PCE office. The framework 'agreement' and 'evidence' were assessed by the authors, based on expert knowledge and available literature. Key data gaps to better inform assessment are identified, alongside a discussion of the minimal evidence base from which to interpret the impact of primary sector activities on soil quality and quantity.

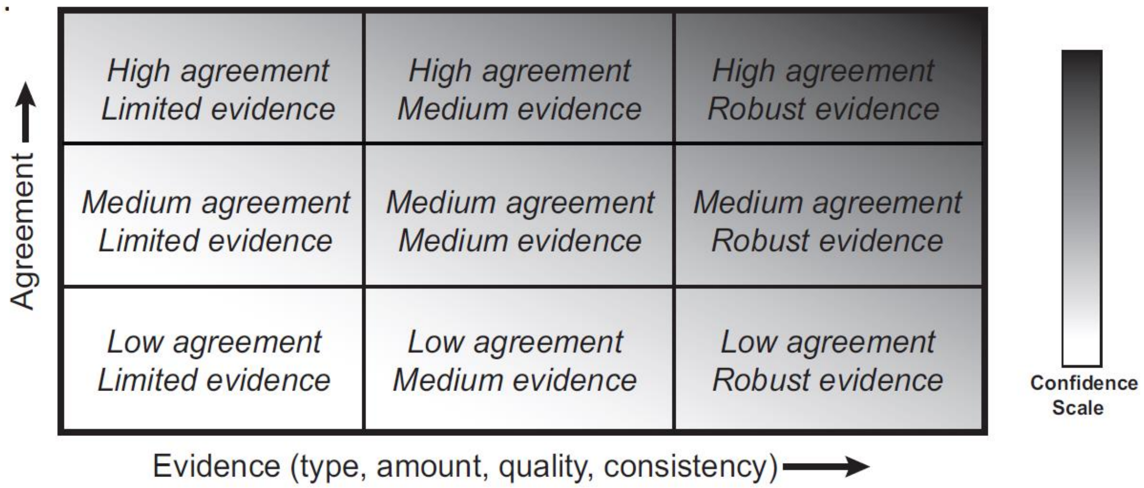

Figure 1. The IPCC uncertainty framework guide for qualitative assessment of uncertainty.

This is a depiction of evidence and agreement statements and their relationship to confidence. Confidence increases towards the top-right corner, as suggested by the increasing strength of shading. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence.

Source: IPCC 2010.

A draft report was reviewed by the PCE office in May 2024 with comments incorporated into the final report provided in June 2024. Following peer review in January 2025, some further minor changes were made to the report.

4 Factors influencing the impacts of primary production land use on soil resources

4.1 Land use and land management practices

Fundamentally, the impacts of primary production on soil resources relate to the way land is used. This includes both the land management practices and the intensity of management. Some land management practices (e.g. fertiliser application) are common across most land uses or within a soil order, while others are more specific to individual land uses (e.g. permanent plantings associated with perennial vine and tree crops). Also, some impacts may arise from the 'disposal' of various waste products (e.g. dairy shed effluent, winery wastewater, and grape marc onto land), or specific impacts are linked to specific land use activities (e.g. higher concentrations of fertiliser-associated contaminants around fertiliser bins associated with hill country top-dressing airstrips (Taylor and Percival 2001), deep compaction at skid sites and tracks within harvested forest stands).

A summary of the land uses covered in this report is given in Table 1. There is a tension between the classical description of land uses and the alignment of those activities with industry sectors. Notably, 'dairy' land use refers to the area on which milking animals are grazed during the milking season. However, land outside the dairy farm (e.g. another farm) may be used to support dairy land use in various ways: for non-lactating (dry) dairy stock, to winter off the dry stock, for young stock replacements for the herd, or to provide supplementary feed that is cut and carried to the milking platform. This land is termed 'dairy support', but the land management activities are commonly more aligned with dry-stock land use or arable and mixed livestock cropping. Thus, the full impacts of the dairy sector are a combination of the impacts associated with dairy land use and dairy support. Also, flat–rolling dairy and sheep & beef land commonly includes arable crops used for supplementary feed and winter forage crops.

Table 1. Description of land-use categories used in this report

Category	Sub-groups	Definition
Dairy	Bovine and non-bovine	Dairy is the pasture area on which milking animals are grazed during the milking season. It may include occasional annual forage crops and maize for silage, and dry-stock grazing and supplementary feeding. Land outside a dairy farm may be used to graze non-lactating dairy stock (dry cows, heifers and calves), or where the dry stock are wintered off, or to provide feed that is cut and carried to the milking platform. Land used for this purpose is termed *dairy support*, and is captured under dry stock or arable cropping, as appropriate.
Dry stock	Flat–rolling	All other (non-milking platform) pasture, including dry-stock farms for sheep, beef, deer, goats, horses, dairy support, and cut and carry. It may include occasional annual arable or vegetable crops. Land on flat–rolling terrain is often managed more intensively than hill- or high-country land. Typically includes slope <15°.

Category	Sub-groups	Definition
	Hill- & high-country	As above for flat–rolling, but designates land on a slope >15°, and anthropogenic inputs are anticipated to be reduced. High-country farming will be captured under production for relatively natural systems. (Note that the slope (degrees) may vary by study and organisations for the definition of hill country).
Perennial horticulture	Tree crops Vine crops Berry fruit	Permanent tree, vine or berry crops.
Short-rotation cropping	Arable and mixed cropping	Predominantly grain, seed or fodder crops; over time may include short-term (c. 1–3 years) pasture and livestock rotations, and/or vegetable rotations. Pasture and livestock rotations may occur up to 50% of the time. Includes maize, barley, wheat, peas, other grain and seed crops, and fodder crops. May be used for dairy support.
	Vegetable cropping	Predominantly annual or more frequent, rotations of vegetable crops grown for human consumption; may include livestock rotations, but less likely.
Plantation forestry	Exotic forestry	Plantations of exotic tree species grown for pulp and timber production, generally radiata pine, but can include other exotic species (e.g. redwood, Douglas fir, eucalyptus). Usually harvested using clear-felling methods, which may be ground-based machinery or a hauler.

Source: adapted from Cavanagh & Whitehead 2023

Common land management practices include fertiliser application, cultivation, drainage, and irrigation. The rate and nature of fertiliser use, such as nitrogen (N), phosphorus (P), and micronutrient trace elements, varies depending on the plant species being grown and the soil type. Lime is also commonly added, as most New Zealand soils are naturally acidic and most introduced species require higher pH to be productive. Pesticide (herbicide, fungicide, insecticide) use varies across land uses, with herbicides typically used in pastoral and forestry systems, along with insecticides to control specific pasture-browsing insects (e.g. porina beetle, grass grub, black field crickets). Fungicides, herbicides, and insecticides are commonly applied in cropping and perennial horticulture. A summary of the key land management activities or practices that occur in each land use is given in Table 2.

Table 2. Summary of key land management activities/practices

Land use	Lime & fertiliser application	Irrigation (Y/N)	Pesticide / animal remedy use (Y/N)	Cultivation (Y/N)	Stock/ stocking intensity*
Dairy	Mainly N, P, lime, K and S. Micronutrients mainly for stock health (Cu, I, Se, etc.) and pasture (Mo) and winter forage growth	Y – on lots of land especially South Island. Also of farm dairy effluent and dairy factory wastewater	Y – mainly glyphosate for pastoral renewal, Zn for facial eczema, and drenches for parasites. Some insecticide use for pasture pest control.	Y – for pasture renewal, direct drill, winter or other forage crops, or to overcome soil drainage limitations (e.g. flipping or 'hump and hollow').	Variable, up to c. 25 stock units/ha.

Land use	Lime & fertiliser application	Irrigation (Y/N)	Pesticide / animal remedy use (Y/N)	Cultivation (Y/N)	Stock/ stocking intensity*
Dry-stock – flat–rolling	Mainly N, P. Micronutrients (where needed), mainly for stock health (Cu, I, Se, etc.) and pasture (Mo) and winter forage growth	Y – on some land.	Y – mainly glyphosate for pastoral renewal, Zn for facial eczema, and drenches for parasites. Some insecticide use for pasture pest control	Y – pasture renewal, direct drill, winter or other forage crops, or to overcome soil drainage limitations (e.g. flipping or 'hump and hollow').	Variable, from 6 to 15 stock units/ha.
Dry-stock – hill & high country	Mainly low N, P, if any. Some P residual from legacy aerial top-dressing.	N	Y – only where hill country is more intensively managed[1]; mainly glyphosate for pastoral renewal and drenches for parasites.	Minimal	Variable, up to 13 stock units/ha.
Cropping (arable and mixed)	Y. Nutrients as needed for specific crops.	Y – not on all land; probably at lower rates than for vegetables and intensive grazing.	Y	Y – typically no more than once every 1–2 years.	Ranging from zero to some livestock rotations, especially in mixed-cropping systems.
Cropping (short-rotation horticulture)	Y. Nutrients as needed for specific crops.	Y – not on all land.	Y – relatively high.	Y – may be more than 1/year for crop establishment, and some crop harvest (e.g. potatoes).	Unlikely.
Perennial horticulture	Y. Nutrients as needed for specific crops.	Y – extensive, but not on all land. Also including winery wastewater.	Y – mainly herbicides, fungicides.	Minimal after crop establishment. Recontouring may occur prior to establishment	Occasionally sheep grazing for grass control.
Forestry	Negligible	N	Negligible	Restricted to some soils and some parts of forests before planting, including deep-ripping	N

* Stock unit is a common unit used to express stocking rate, where one stock unit = one breeding ewe, consuming 550 kg dry matter per year (Morris 2013). Stocking rates for dry stock are from Beef + Lamb NZ 2024, and calculated for dairy from StatsNZ (2019a) and DairyNZ (2022) data.

[1] More intensively managed hill or high country may occur on flatter areas within the general hill/high country area.

N = nitrogen; P = phosphorus; K = potassium; S = sulphur; Cu = copper; I = iodine; Se = selenium; Zn = zinc; Mo = molybdenum.

4.2 Characterisation of soils

New Zealand's landscapes contain an unusually diverse range of soils, which can change over very short distances. These soils have different properties that influence how they are managed for different primary production purposes, and how resilient these soils are to different primary production activities.

The New Zealand Soil Classification (NZSC) (Hewitt 2010) groups soils at the highest level into 15 soil orders. Each soil order has key characteristics that influence its suitability for different land uses, although soils within an order may vary (e.g. in terms of drainage, stoniness and rooting depths). The approximate areas of productive land use under each soil order are shown in Figures 2–5, with the dominant soils under primary production being Brown, Pallic, Podzol, Pumice, Allophanic, Gley, and Recent.

A summary of the key characteristics of the nine key soil orders for primary production, along with comments on their general suitability for use in primary production, is provided in Table 3. Details of all the 15 soil orders are provided in Appendix 1. (Note that these are general comments and may not apply to all soils in a given soil order.)

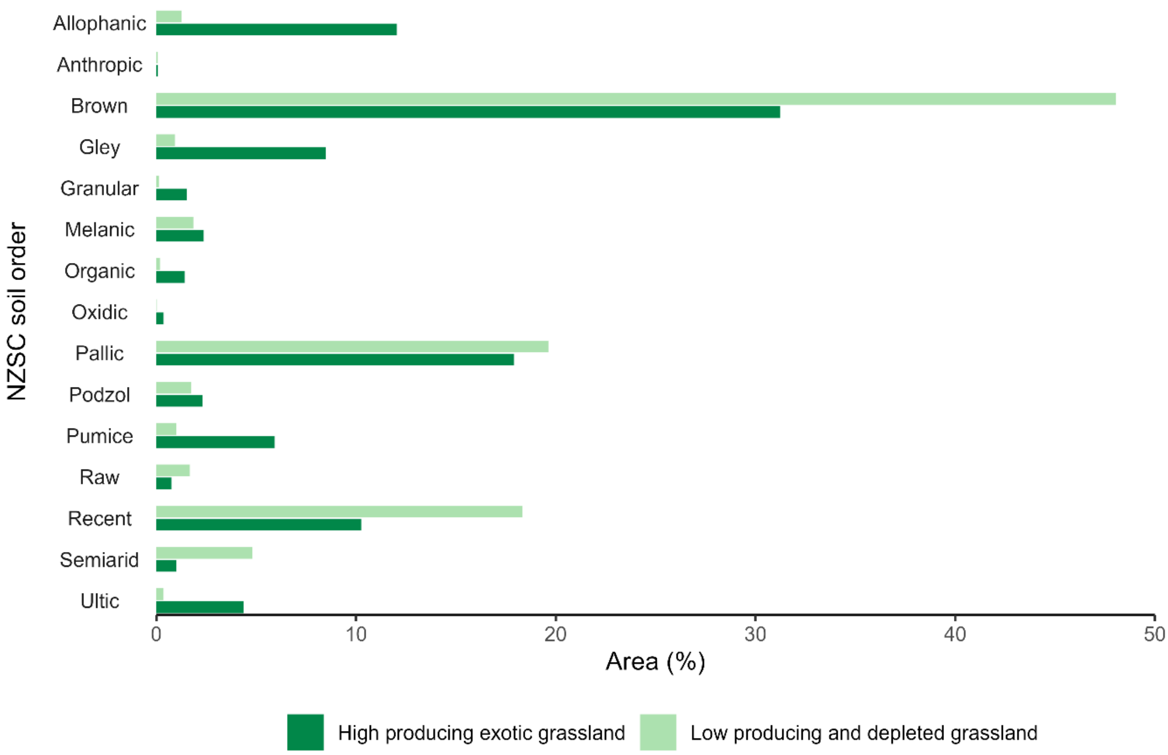

Figure 2. Distribution of high- and low-producing grassland on each soil order. The total area of high-producing exotic grassland is 8.6 million ha, with low-producing grassland comprising 1.9 million ha, based on the LCDB5.

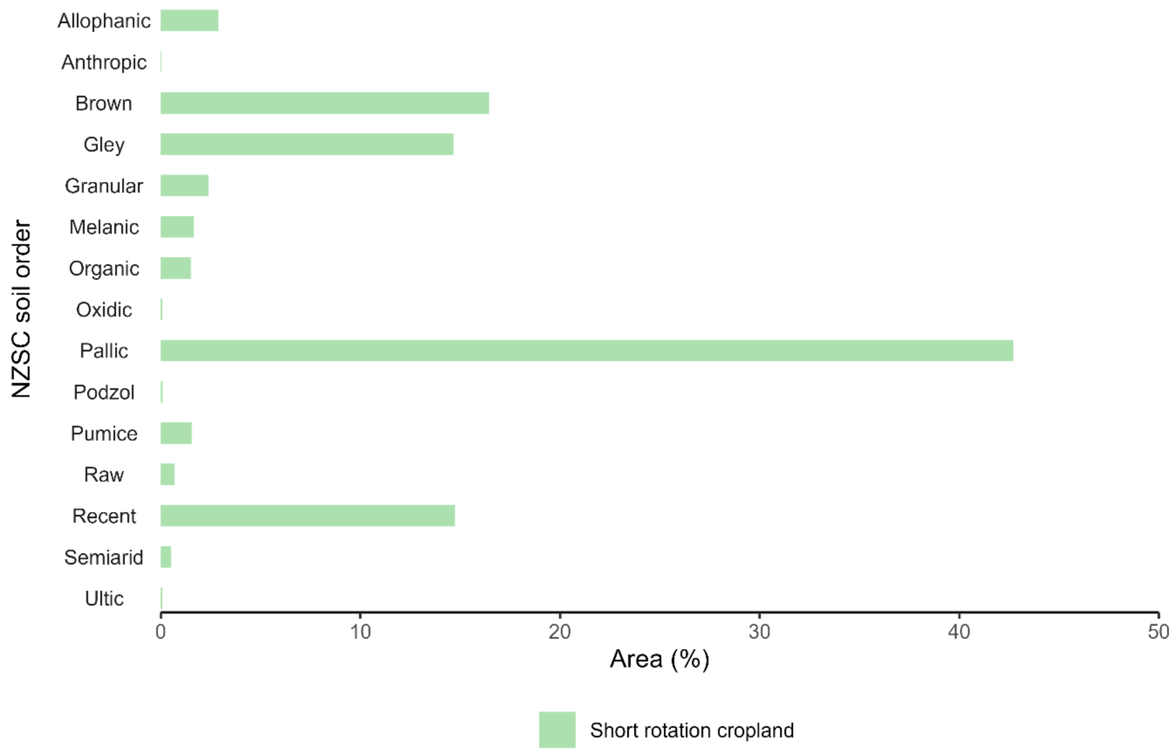

Figure 3. Distribution of short-rotation cropland on each soil order. The total area of land under short-rotation cropland is 368,500 ha, based on the LCDB5.

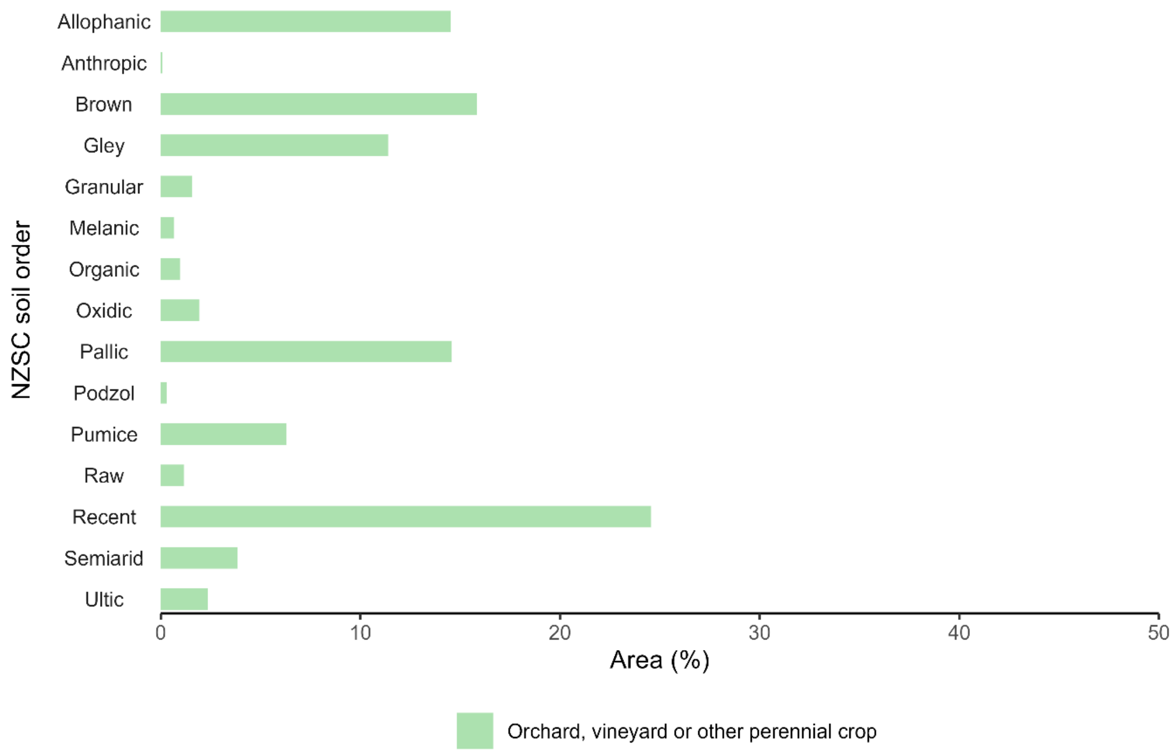

Figure 4. Distribution of perennial horticulture on each soil order. The total area under perennial horticulture is 105,000 ha, based on the LCDB5.

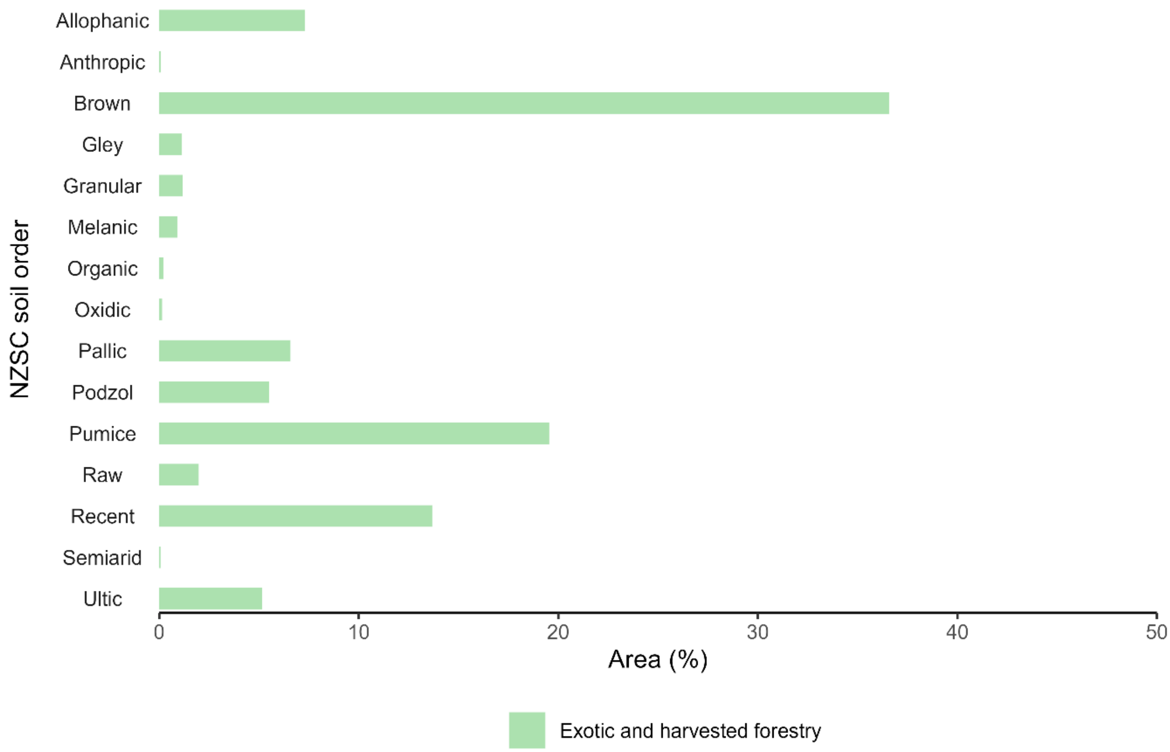

Figure 5. Distribution of exotic forestry land cover on each soil order. The total area under forestry is 2 million ha, based on the LCDB5.

Table 3. Summary of the characteristics of the predominant soil orders and their general suitability/unsuitability for primary industries

Soil order	Characteristics	Suitability for primary industries
Allophanic (5% of New Zealand)	• Very low bulk density, high macroporosity, weak strength, low penetration resistance, high P retention, low natural fertility. • The A horizon contains large populations of soil organisms. • Strongly adsorbs P and S. High carbon (C) storage.	• Highly productive soils for many primary industries. • Physical properties appropriate for supporting plant growth. • Wheel trafficking and handling should be minimised, and rejuvenated through cultivation, to retain permeability and soil aeration. • High water-holding capacity. Natural drainage is predominantly moderately (32%) to well drained (66%), and occurs as matrix flow, reducing risk of leaching.
Brown (43% of New Zealand)	• Well-developed structure, moderate-high bulk density, moderate-high water-holding capacity, low-moderate natural base saturation. • Large populations of soil organisms. • Moderately weathered, with moderate to strong leaching. • Low to moderate natural fertility.	• Highly variable soil order with respect to productive capacity. • Highly productive soils for many primary industries in lowland areas. • Favourable topsoil structure and good physical properties. • Moderate P retention. Often requires fertiliser P for agricultural production. • Natural drainage is predominantly moderately well drained (43%) to well drained (40%).

Soil order	Characteristics	Suitability for primary industries
Gley (3% of New Zealand)	• Chemically reduced. • Affected by waterlogging, anaerobic conditions restrict soil organisms. • Shallow potential rooting depth, high bulk density. • High organic matter, low-medium P retention.	• Formed where soils are saturated for long periods. Trafficability limited when wet. • Where drainage is installed, they can be highly productive for pastoral and cropping. Generally fertile. • Natural drainage is predominantly poorly drained. • High vulnerability to adverse impacts on water from effluent application due to preferential (bypass) flow paths and over-fertilisation, and organic C losses.
Granular (1% of New Zealand)	• Dominated by clay minerals. • High penetration resistance – limited rooting depth. • Moderately permeable, well-developed fine structure, friable, low plasticity. • Low nutrient reserves, low P and S^- in subsoil.	• Important for vegetable production, highly productive. • Limited workability and trafficability when wet. • Resistant to degradation by ploughing. • Naturally low reserves of nutrients such as P, K, Mg. • Wheel trafficking should be minimised and rejuvenated through cultivation to retain permeability. • Natural drainage is predominantly imperfectly drained (36%), moderately well drained (47%) to well drained (17%).
Organic (1% of New Zealand)	• Very low bulk density, low bearing strength, high shrinkage when dried. • High available-water capacity. • Acidic, nutrient deficiencies common, high C:N ratios. • Soil organisms restricted by anaerobic conditions. • High water retention.	• Drainage and high inputs of lime and fertiliser applied to establish productive farming. • Drainage results in ongoing GHG emissions (~8% NZ net GHG emissions) • Prone to subsidence. Cultivation greatly increases the rate of shrinkage and biodegradation. • High fire risk. • Natural drainage is very poorly drained.
Pallic (12% of New Zealand)	• Weak structure, med-high bulk density, slow permeability, limited rooting depth, low organic matter. • Med-high nutrient content (except S), low P retention. • Biological activity and plant root growth often limited by anaerobic conditions in winter. • Often high silt content. • Soils with high bulk density have low water retention which increases vulnerability of crops to drought when combined with subsoil root-zone impediments.	• Some have deep rooting potential, with high available water capacity to support plants, and highly versatile – may support a range of productive uses. • Large areas have high subsoil density that impedes drainage. These soils have been extensively drained with mole & tile drainage and can be unsuitable for wastewater application due to bypass flow. • High potential for erosion due to slaking and dispersion. Susceptible to gully erosion. Lower North Island areas particularly prone to landslide erosion. • Natural drainage is a mix of poorly drained (20%), imperfectly drained (34%), moderately well drained (17%), and well drained (29%).

Soil order	Characteristics	Suitability for primary industries
Pumice (7% of New Zealand)	• Dominated by pumice, rapid drainage, clay content <10%. • Weak strength, low bulk density, high macroporosity, generally deep rooting depths. • Low major nutrient and trace element reserves, medium P retention. • Low soil macroinvertebrate populations. • High water retention.	• Low nutrient and trace element reserves mean additions are required for most production. • Potential for erosion in pasture, and highly susceptible to gully erosion, particularly when soil is not vegetated, and exacerbated by hydrophobicity developing under pasture. • Resistant to light compaction but brittle under heavy compaction. • Natural drainage is predominantly moderately well drained (29%) to well drained (70%); matrix flow.
Recent (6% of New Zealand)	• Weakly developed, spatially variable stoniness and texture, absent or weakly expressed subsoil, deep rooting. • Plant-available water capacity varies with texture and depth to gravels • High natural fertility, low C, and low P retention.	• Naturally fertile. • Many soils at risk of flooding in valleys and floodplains. • Hill slope recent soils prone to hillslope mass movement, streambank erosion. Wind erosion and hydrophobicity can occur on Sandy Recent Soils (dunes). • Natural drainage is predominantly moderately well drained (31%) to well drained (58%).
Ultic (3% of New Zealand)	• Strongly weathered and leached. • Clayey subsoil, low permeability, dispersible surface horizons. • Strongly acidic, low nutrient reserves. • Topsoils have large, active soil organism populations.	• Slow permeability, low soil fertility, shallow rooting depths and low water-holding capacity, along with winter wetness and summer drought, mean the soils are usually challenging to use productively. • Drainage and physical properties are highly spatially variable. • Highly vulnerable to compaction (including livestock treading), and cultivation is only effective over a narrow range of moisture contents. • Not suited to wastewater discharge. • Failure can occur on slopes of 15–20°. Slopes are prone to earthflows and landslides. • Natural drainage is predominantly imperfectly drained (79%).

Notes: Soil order drainage class percentages are based on area per soil order for the five natural drainage classifications (well drained to very poorly drained) available from the Fundamental Soil Layers and S-map (see Appendix 2).

Source: Adapted from Cavanagh & Harmsworth 2023, and includes information from Hewitt 2010, Hewitt et al. 2021, McLaren & Cameron 1996, Molloy & Christie 1993, and Simcock 2009.

Information on the distribution of soils and soil properties is available from the Fundamental Soil Layers, but with S-map providing the most recent and comprehensive mapping (https://smap.landcareresearch.co.nz/) (Lilburne et al. 2012). S-map soil mapping is published at a regional scale (1:50,000) and currently covers 39% of New Zealand, including 70.6% of 'multiple use land'. S-map displays basic soil property data such as depth, stoniness, and clay content, as well as more complex data such as profile-available water capacity and N leaching risk. S-map is generated by expert soil surveyors and informatics systems, assisted by historical soil mapping and new data. Data systems and modelling associated with S-map provide key functions for hydrological modelling associated with New Zealand soils (e.g. McNeill et al. 2024).

S-map has downloadable factsheets for each NZSC soil sibling. The S-map soil factsheets describe the typical average properties of a soil type found in a region. They also include modelled indices, such as vulnerability to N leaching and soil structural vulnerability index, with the latter estimated from the key soil properties: P retention, soil C and clay content, and soil drainage class (Hewitt & Shepherd 1997). The structural vulnerability index (and other indices generated for S-map factsheets) does not consider weather, farm management or adequate representation of C, so some caution should be applied when using this or other indices.

Different classifications of soils may also be used. For example, a different grouping is used in fertiliser application guidance and industry booklets (e.g. Roberts & Morton 2023). Table 4 provides the correlation between the fertiliser industry classifications and NZSC soil orders.

Table 4. Relationship between soil classification used for fertiliser recommendations and soil order

Fertiliser industry soil classification	Corresponding soil order
Sedimentary	Brown, Pallic, Recent, Melanic, Semi-arid
Ash	Allophanic, Granular, some Gleys
Pumice	Pumice, some Gleys
Organic	Organic

Source: Roberts & Morton 2023; these classifications are also used in Reid & Morton 2019, Nicholls et al 2012, and other industry booklets.

4.3 Legacy influences on today's impacts

4.3.1 Drainage

Drainage of soil and wetlands has been a key influence on agricultural development for many primary industries, and it is extensive. Manderson (2018) estimated that approximately 2.5 million ha is currently artificially drained. Across Waikato, Westland, Southland, and Northland, Pronger, Glover et al. (2022) have estimated that 141,190 ha of Organic Soils have been drained and Burge et al. (2023) estimated that c. 3% of New Zealand's remaining wetlands are potentially affected by drainage leading to wetland loss. This adds to the c. 90% reduction of the natural extent of wetlands by drainage that has already occurred in the last 200 years (Burge et al. (2023).

Soil drainage has a long historical context of significant public (e.g. Public Works Act 1876, Land Drainage Act 1908) and individual farmer investment throughout the country, aimed at removing excess water from the soil profile, such as through surface drains, mole channels, and tile drain networks of poorly drained soils. Most regions in New Zealand have a number of community-funded land drainage networks, for example, the Hauraki Plains in the Waikato, and the Taieri Plains in Otago have large schemes. The drained soil was then able to be used for agricultural and horticultural production, including increasing stocking rates, supporting a greater variety of crops through longer periods with adequate soil aeration, and also enabling longer workable periods on soil, and using heavier machinery. However, in the process of draining large soil areas streamflow, nutrient and contaminant losses, and soil properties were all affected (McLaren & Cameron 1996; Monaghan & Smith 2004; Deuss et al. 2023).

Artificial drainage has mainly occurred in Pallic, Gley, Podzol and Organic Soils (Hewitt et al. 2021; Deuss et al. 2023; Pronger, Glover et al. 2022). Mole and tile drainage has predominantly occurred in Pallic Soils in Southland (Deuss et al. 2023), and in Pallic and Gley soils in many other regions, including Manawatu, West Coast, and the upper North Island (Bowler 1980; Francis & Morton 1991; Houlbrooke et al. 2004; Monaghan et al. 2016).

Gley and Organic (peat) Soils are naturally wet and show the extent of former wetlands in the landscape (Hewitt et al. 2021). Organic Soils have been extensively drained for agriculture which causes subsidence, due to shrinkage and consolidation, and oxidation of organic matter resulting in greenhouse gas emissions that likely contribute about 8% of NZs net greenhouse gas emissions from about 1% of NZs land area (Schipper & McLeod 2002; Campbell et al. 2021; Pronger, Glover-Clark et al. 2022). Ongoing oxidation of the organic material in Organic Soils can result in soil at the margins being reclassified as a mineral soil (e.g. Gley Soil; Pronger, Glover-Clarke et al. 2022).

Since about 1980, drainage by 'humping and hollowing[2]' has been used to recontour some Gley, Organic and Podzol Soils in Westland and Waikato to promote surface runoff and increase production (Hewitt et al. 2021). Also, soil 'flipping' (whereby diggers are used to move material from lower in the profile to, or near, the soil surface of Gley Soils and Podzols of the West Coast and parts of the central North Island) has also been used to improve drainage and contribute to increased carbon storage (Thomas et al. 2007; Schiedung et al. 2019; Hewitt et al. 2021). Given the extensive anthropogenic disturbance of soils that have been humped and hollowed or flipped, they are considered to be converted to Anthropic Soils (Hewitt et al. 2021).

Forest site preparation to create sites more favourable for tree seedling establishment can also include drainage with ripping (with or without bedding), V-blading, and spot-mounding. This is predominantly used in the West Coast (Gley Soils and Podzols), Central North Island (Pumice Soils), and Northland/Waikato (Ultic Soils and Podzols).

[2] Hollows are formed by removal of soil that is relocated to build intervening 'humps' in the form of broad gently sloping mounds of sufficient height to provide a rooting zone free of continuous water saturation; the hollows form central open drains, and/or underlying tile drains, that feed runoff, and/or drainage water, into natural streams or community drainage networks (Hewitt et al. 2021).

4.3.2 Forest clearing and erosion

New Zealand has naturally very high erosion rates as a consequence of steep slopes, erodible rocks, generally high rainfall, and deforestation (Basher 2013; Phillips et al. 2020). Much of New Zealand is hilly or mountainous, with 60% of the land being above 300 m elevation and 60% rolling to hilly (7–25º) or steep (>25º). Rainfall ranges from <500 mm to >10 000 mm/yr, with widespread erosion events triggered by frontal storms and ex-tropical cyclones that commonly bring high and intense rainfall (Basher 2013).

The erosion problems in New Zealand are exacerbated by historical removal of the indigenous forest. Polynesian settlers reached New Zealand about 800 years ago and caused widespread deforestation (of about 50% of the forest area), especially in the east of the South Island. After European settlers arrived in the early 19th century, a further 30% of the country, largely in the North Island, was cleared for pastoral farming and timber production (Basher 2013).

After clearing, serious erosion issues became evident, particularly in the soft-rock hill country of both islands and in the eastern South Island high country. Soil erosion had become a matter of national concern by the 1940s, resulting in the passing of the 1941 Soil Conservation and Rivers Control Act and the establishment of catchment boards to manage erosion and sediment problems. Nonetheless, as late as the 1980s farmers were being offered subsidies, through Land Development Encouragement Loans, to convert 'unproductive', steep, erosion-prone hill country, under scrub and forest cover, to pastoral farming (Basher 2013).

After Cyclone Bola (1998) successive governments subsidised planting of severely eroding pasture land into pine, partly through the East Coast Forest Project; over 100,000 ha was planted between 1992 and 1997, stabilising the land (until harvest). Plantation forestry and hill-country grazing are often located on these deforested, erosion-prone landscapes, which has resulted – and continues to result – in erosion of this land in many places (e.g. Basher & Ross 2002; Glade 2003; Marden et al. 2023). Most recently extensive erosion occurred from Cyclone Gabrielle, with widespread landslide damage to hill country land along the North Island East Coast, and downstream damage to floodplain land due to both silt deposition and forestry slash. This damage also resulted in a subsequent government inquiry into land uses associated with the mobilisation of woody debris and sediment (MfE 2023d).

4.3.3 Pesticides

Some pesticides that were previously widely used in primary production have legacy effects. This includes arsenic used in sheep dips and lead arsenate used in orchards, but DDT used for grass-grub control is the most significant. Organochlorine pesticides such as DDT, and its metabolite DDE, can bioaccumulate through the food chain, and the metabolites of DDT continue to be periodically identified in milk and milk products from livestock grazing land (NZFSA 2022). As a result, DDTs are included in the National Programme for the Monitoring of Chemical Residues and Contaminants in Milk (NZFS 2023), and testing for DDTs in soil is a requirement to be a milk supplier for Fonterra (Fonterra 2022).

Elevated arsenic concentrations may be present as hot-spots of soil contamination arising from legacy contamination from old sheep-dip sites and treatments to control cattle ticks (MfE 2006). Residues of the organochlorine pesticides dieldrin and lindane may also be present at old sheep-dip sites (MfE 2006). If present, these contaminants are generally in localised hot-spots and do not present any large-scale issues, affecting only the area of soil in the immediate vicinity of the old sheep-dip sit. MfE have produced guidance on managing this issue (MfE 2006).

5 Impacts of primary production on soil resources

A key finding from our review was that limited information is available to link changes in soil properties associated with primary sector land use with changes in productive capacity; as such this section focusses on the changes in soil properties while section 6 provides more general discussion on the significance of these changes in relation to the productive capacity of soils.

5.1 Soil quality

5.1.1 Soil biota

The biota of a soil includes a wide range of organisms, including microorganisms (bacteria, fungi, protozoa, archaea, algae) and soil fauna (which can be divided into macro-, meso-, and microfauna). Soil biology is recognised as driving many soil functions, including organic matter decomposition, nutrient cycling, and the maintenance of soil structure (Sparling 1997; Creamer et al. 2022; Büneman et al. 2018). Populations of soil biota sensitive to changes in the soil environment can arise through land management (e.g. nutrient loading, structural degradation, intensification, or contaminant concentrations) (Bhaduri et al. 2022). There have been a plethora of biological indicators proposed, but there is still no commonly accepted biological indicator used nationally or internationally (Creamer et al. 2022; Zwetsloot et al. 2022; Büneman et al. 2018; Thompson-Morrison & Cavanagh 2024).

In New Zealand, biological indicators of soils have largely been based on soil microorganisms – ranging from various measures of microbial biomass or function, through measures such as soil respiration or anaerobically mineralisable N (Sparling et al. 2000). The latter is one of the seven soil quality indicators used for regional council state of the environment (SOE) soil quality monitoring.

More recently, research has focused on the potential use of molecular data for developing soil biological quality indicators based on bacterial composition (e.g. Hermans et al. 2017; Hermans, Buckley, Curran-Cournane et al. 2020; Hermans, Taylor et al. 2020; Holdaway et al. 2017; Louisson et al. 2023). Hermans et al. (2017) found that soil bacterial community composition is strongly linked to land use, to the extent that it could correctly determine the type of land use most of the time, and there are strong correlations with some individual soil variables (e.g. soil pH, bulk density). Land-use history, and in particular change in land use, is also reflected in bacterial composition (Hermans, Taylor et al. 2020).

Louisson et al. (2023) also found that the functional potential of bacterial communities could shift as a result of land-use change.

Stevenson et al. (2016) is another of the few studies that assesses soil microbial function in agricultural land, with a focus on soil C characterisation and nutrient ratios across different land uses. However, the significance of changes in bacterial composition on soil functioning is largely unclear.

Beyond microorganisms, earthworms – mostly exotic species – have been the most widely studied soil fauna, primarily in pastoral systems (e.g. Springett 1992; Schon et al 2014, 2016; Schon, Fraser et al. 2023) due to their recognised association with increases in pasture production through improved nutrient cycling and soil physical condition (Stockdill 1982; Schon et al 2016). Only a limited number of studies have also assessed the soil fauna in pastoral soils (e.g. Parfitt et al. 2010; Schon et al. 2011; Orwin et al. 2020).

Outside of pastoral systems there are few studies of soil fauna in agricultural or forestry soils with Yeates et al. (1998) one of those few. These authors assessed the potential use of nematodes and earthworms as indicators of soils quality, by examining the relationships between populations of earthworm, total number of nematodes and predacious nematodes and six soil physical factors, soil C and pH in four New Zealand soils under pastoral and cropping land use. The study showed that earthworm abundance and predacious nematodes had potential use as indicators and also identified interactions between soil physical properties and soil fauna. Nematodes have also previously been proposed as soil indicators (Yeates 2003, ARGOS 2006), although this doesn't appear to have been taken further. Cavanagh et al. (2024), who evaluated the potential impacts of a plant growth regulator on springtails in soils in a kiwifruit orchard soils, appear to provide the first study of soil mesofauna in agricultural soils outside of pastoral systems. There is a similar dearth of knowledge of soil fauna in production forestry systems, with Peterson and Hayman (2018) observing that the only mention of soil fauna in New Zealand plantation forests is from one study on protura by Minor (2008).

There have also been limited investigations of the factors influencing soil biology in primary production systems. Schon, Stevenson et al. (2023) provide a review of the effects of long-term P and N fertiliser application on soil biology, focusing on the Winchmore and Ballantrae long-term trials, and there are a handful of other New Zealand studies that have also assessed the relationship between soil P, N, and soil biology, primarily bacteria and fungi composition and function.

Additions of P to soils have been shown to affect the population composition and function of soil microbes (bacteria and fungi), with strong correlations found between the relative abundance of individual taxa and Olsen P concentrations (Hermans, Buckley et al. 2020). In particular, excess P concentrations suppress the functioning of arbuscular mycorrhizal fungi (Yang et al. 2014) and decrease fungal biomass (Schon, Stevenson et al. 2023). Prolonged additions of P to soils can result in microbial growth becoming C and N limited without ongoing inputs of these elements (Touhami et al. 2022), as well as a decoupling the interactions between soil organisms and plants, whereby plants become reliant on fertiliser P rather than P from biological mineralisation (Massey et al. 2016). Variable response to soil biology under P fertilisation was observed, with differences attributed to contrasting pasture quality and quantity (Schon, Stevenson et al. 2023).

Fertiliser N additions have been shown to affect microbial community composition and function, with both microbial and fungal biomass decreasing with prolonged additions of N (Schon, Stevenson et al. 2023) and fertiliser N additions, leading to lower levels of biological N fixation in soils (Harris & Clark 1996; Vázquez et al. 2022).

More broadly, differences in the composition of the microbial and faunal assemblages are expected because plant communities/species will influence this. It is also generally recognised that land management activities, such as tillage and pesticide application, can negatively affect soil biota. This knowledge led to Ecological Investigation Levels set for agricultural soils in Australia (Heemsbergen et al. 2009), and earlier versions of the ecological soil guideline values for New Zealand for agricultural soils (Cavanagh & Munir 2019) being based on a lower level of protection (80% of species) for soil fauna and microbial communities and 95% protection for plant species.

Finally, soil biota also includes pest species that can cause damage to pasture and crops. For example, Ferguson et al. (2018) estimated that invertebrate pests cause losses of between $1.7 billion and $2.3 billion p.a., of which up to $0.9 billion is on sheep & beef farms and $1.4 billion on dairy farms. Pest species include the native scarab grass grub, the exotic scarab, black beetle, nematodes, and weevils. Schon, Stevenson et al. (2023) provide provisional indicator target abundances for some insect pest species for use on-farm in New Zealand.

Soil biota: key points in relation to primary sector land uses

- The most information on soil biota in primary production systems is available for bacterial communities. There is recognition that land management practices (e.g. lime addition, fertiliser application, crop type) will influence the composition and functioning of the bacterial community, although the significance of the observed changes is largely unknown.
- Beyond exotic earthworms in pastoral systems and pest species, there is a dearth of information on soil fauna in primary production systems.

5.1.2 Contaminants

The range of contaminants in primary production includes:

- trace element contaminants, such as cadmium (Cd) arising from fertiliser, copper (Cu) from fungicide, and zinc (Zn) used for treating facial eczema
- a wide array of organic compounds used in pesticides (herbicides, insecticides, and fungicides)
- emerging organic contaminants, including hormones (primarily associated with dairy cows) and microplastics.

To assist with managing soil contaminants, soil guideline values that indicate different levels of protection for ecological receptors – soil microbes, plants (including agricultural crops) and invertebrates have been developed for key trace element contaminants and some organic contaminants (Cavanagh & Harmsworth 2023). These ecological soil guideline values (eco-SGV) have been developed for use in New Zealand, including the agricultural sector, and provide an indication of whether concentrations measured in primary production soils could be limiting the productive capacity of the soil. The eco-SGVs for the nominal protection of 95% of species are shown in Table 5 to enable comparison with concentrations reported in the following sections.

Table 5. Ecological soil guidelines values for protection of 95% of species for selected trace element contaminants.

	As (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
Eco-SGV	20	1.5	200	95	290	180

As = arsenic; Cd = cadmium; Cr = chromium; Cu = copper; Pb = lead; Zn = zinc.

Eco-SGVs for Cu and Zn are default eco-SGVs for a sensitive soil, as determined through soil pH, cation exchange capacity, and carbon concentration.

Source: Cavanagh & Harmsworth 2023

Trace elements

Trace elements, including Cd, fluorine and uranium can accumulate in New Zealand soils, primarily due to the repeated application of phosphate fertilisers, as these elements are contained as impurities within phosphate rock (Loganathan et al. 2003; Schipper et al. 2011).

Cadmium is a recognised issue for agricultural soils, and a National Cadmium Management Strategy is in place, governed by the Cadmium Management Group, which comprises all key stakeholders in rural production and environmental management (CMG 2019). Gray and Cavanagh (2023) provide a recent and comprehensive review of information on managing Cd in New Zealand agricultural soils.

A key issue that requires management is uptake by food crops and compliance with food standards. There is a wide variation in Cd accumulation by different pastoral, forage, and food crop species and the degree to which Cd is taken up by crops can be crop- and cultivar-specific, but also depends on soil properties, including soil Cd concentrations (Gray & Cavanagh 2023). Certain species (e.g. spinach, wheat) have a greater propensity to accumulate Cd even at low soil Cd concentrations (Cavanagh et al. 2016, 2019; Gray et al. 2019). Beyond species differences, both site and cultivar can markedly influence plant uptake of Cd, both within a region and across regions (Cavanagh et al. 2019; Gray et al. 2019).

At a high level this regional difference appears to be attributable to soil type, with uptake typically lower in Pukekohe and the Waikato regions, which are dominated by Allophanic and Granular Soils, compared with Canterbury and Gisborne, where food cropping soils are dominated by Pallic and Recent Soils (Cavanagh et al. 2016; Gray & Cavanagh 2023). For food crops it is also relevant to consider the applicable food standard (maximum limit) to help determine the relative need to manage Cd uptake. For example, onions are not considered to be high accumulators of Cd, but a significant proportion of onions grown in New Zealand are exported, and the relevant maximum limits are low (Cavanagh et al.

2019). Farmer-oriented information sheets have been co-developed with sectors (e.g. Onions NZ, Potatoes NZ) and are available from MPI's website.

The separate issue of Cd accumulation in soils is currently managed through the Tiered Fertiliser Management System (TFMS) (FANZ 2019), which imposes increasingly stringent controls on the fertiliser type and rate that can be applied if soil Cd concentrations are higher than successive trigger values of 0.6, 1.0, 1.4, and 1.8 mg/kg. In an analysis of Cd concentration data from 5,459 topsoils across New Zealand collected by the fertiliser industry and regional councils, the highest mean Cd concentrations occurred in Taranaki and Waikato, and in dairying soils (Abraham 2020). Soils on sheep & beef farms had the next highest mean Cd concentrations, followed by soils used for cropping, and then soils in orchards and vineyards (Abraham 2020). The same trend in Cd concentrations between land uses is reported by MfE and StatsNZ (2021), which collate regional council SOE soil quality monitoring data.

Elevated Cd concentrations in pastoral soils are influenced by the duration of superphosphate fertiliser application, and, in particular, whether phosphate fertilisers from Nauru were historically applied. Phosphate rock used in fertilisers up until the 1990s was sourced from Nauru and contained some of the highest Cd concentrations in the world (Bramley 1990). Since then New Zealand has imported and used phosphate rock with lower Cd concentrations, and the Cd concentration in fertiliser is monitored weekly.[3] Nonetheless, data from the Winchmore long-term field trials that measured concentrations of Cd – and two other fertiliser-derived contaminants fluorine and uranium – in soils under grazed sheep pasture receiving different rates of superphosphate fertiliser for c. 70 years (Gray 2018; Gray et al. 2022; McDowell 2012) showed that all three trace elements were continuing to accumulate in soils, with higher superphosphate application rates leading to faster accumulation (Gray et al. 2022).

Fluorine, which is present as fluoride (F^-) in soils, has accumulated in some productive soils over time (Loganathan et al. 2001; Cronin et al. 2000). The primary risk associated with fluorine in productive systems is fluorosis in livestock, resulting from grazing pasture directly following fertiliser application and subsequently ingesting high levels of fluorine (Cronin et al. 2000). However, the only published report of livestock deaths from fluorosis is that of Cronin et al. (2003), who reported deaths associated with the Mt Ruapehu volcanic eruption in 1995. It has also been proposed that fluorine accumulation in soils can result in a process called dealumination, whereby, due to effects on soil chemistry, aluminium toxicity to plants can occur (Taylor et al. 2012). Research into this effect is limited, and no impacts of this nature have been widely reported. Similarly, there is limited research on the toxicity of fluorine to soil organisms, including microbes, plants, and invertebrates (Cavanagh & Munir 2019).

Zinc is commonly supplemented to animals (mainly cows, and sometimes sheep) to prevent facial eczema, a disease that is caused by a fungus-borne toxin in pasture. The prevalence of this fungus is climate-driven, and North Island regions are more affected, but climate change may increase its prevalence in the southern North Island and eastern

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[3] (FANZ https://www.fertiliser.org.nz/Site/about-fertiliser/fertiliser_use_in_nz.aspx).

South Island regions (Phillips, Johnson et al. 2023). As a result of Zn supplementation to livestock to prevent facial eczema, excess Zn is excreted by animals in both milk and manure (Mason et al. 2022). Zn has accumulated in some North Island soils: Taylor et al. (2011) estimate that Zn has accumulated in pastoral Waikato soils at a rate of 1.36 mg Zn/kg/yr over the past 25 years, to give an average concentration of 62 mg/kg, and a maximum concentration of 258 mg/kg.

Drewry, Cavanagh et al. (2021) also observed a statistically significant increase in Zn concentrations in soils used for dairy, with median concentrations at the time of last sampling of 80 mg/kg and a maximum of 97 mg/kg. National reporting of regional soil quality monitoring shows that Zn concentrations in pastoral soils from monitored regions are typically below the eco-SGV for Zn that nominally provides protection for 95% of ecological receptors (microbes, plants, invertebrates) of 180 mg/kg (Cavanagh & Harmsworth 2023). Zinc is also toxic in aquatic ecosystems, and movement from soil to freshwater sources is likely with increasing soil concentrations (Vermeulen 2015).

Copper-based fungicide sprays are used in horticulture, primarily in vineyards and kiwifruit orchards in New Zealand (Dean 2016; Jeyakumar et al. 2014; Morgan & Taylor 2004). A survey of vineyards throughout New Zealand in 1999 (Morgan & Taylor 2004) found that approximately two-thirds of those surveyed used Cu sprays, in varying application rates. Copper sprays were less commonly used in Central Otago as fungal infections of vines are less problematic in semi-arid regions. Soil concentrations from these vineyards showed that Cu had accumulated in soils where Cu sprays had been used, but in the majority of cases the soil concentrations were below 75 mg/kg. The eco-SGV for Cu in a sensitive soil is 95 mg/kg (Cavanagh & Harmsworth 2023).

Guinto (2012) reported a non-significant increase in average Cu concentrations of 24 mg/kg in 2000 to 42 mg/kg in 2010 in a small number (five to six) of kiwifruit orchards across the Bay of Plenty. The increase in topsoil Cu concentration was suggested to be due to periodic spraying of Cu-containing compounds in kiwifruit orchards. The average Cu concentration in 20 kiwifruit orchards across the Bay of Plenty in 2012 was 35 mg/kg (Guinto et al. 2013). KVH (2019) report findings from a HortResearch study that looked at Cu in soils across 19 orchards in New Zealand from different districts (Bay of Plenty, Gisborne, Hawke's Bay, Nelson, and Central Otago). Copper concentrations ranged from 70 to 480 mg/kg, with 13 of these orchards having concentrations <120 mg/kg. The information sheet provides general information for kiwifruit growers on Cu sprays and highlights the Zespri Crop Protection Standard requirement for annual Cu usage: conventional orchards are limited to maximum of 8 kg active Cu/ha/year, while organic orchards are limited to a maximum of 3 kg active Cu/ha/year.

Jeon (2023) analysed Cu in the soils of six orchards in New Zealand, including apple, kiwifruit, and cherry orchards, and one vineyard. Mean Cu concentrations in the top 10 cm of soil were over 100 mg/kg in all but one (apple) orchard. There is consensus in the literature on the presence of Cu accumulation in vineyard and orchard soils, but the reported magnitude and relative risk of this accumulation vary across studies.

An additional source of trace elements, often highlighted in vineyards and kiwifruit orchards, is copper-chromium-arsenic (CCA)-treated timber posts. CCA is used as a preservative treatment for timber and has been shown to leach into soils immediately surrounding treated timber posts (Barlow & Prew 2005; Robinson et al. 2006). However, Barlow and Prew (2005) found no impact on bacterial or fungal populations as a result of elevated CCA in soils immediately surrounding posts in kiwifruit orchards. A report from Waikato Regional Council (2018) on risk characterisation and the management of CCA in vineyards and kiwifruit orchards discusses risk in the context of land-use change to residential housing, and concludes that any elevated concentrations should be able to be mitigated by soil mixing during the land-use change process. As such, the impact of CCA on the productive capacity of soils appears to be negligible.

Pesticides

Pesticides can be broadly grouped into fungicides, herbicides, and insecticides, and they are used across a range of productive sectors in New Zealand. Trace element-containing pesticides (i.e. Cu fungicides, Zn for facial eczema) were discussed above, and this section focuses on organic compounds used as pesticides. A wide range of pesticides are registered for use in New Zealand, with a still wider range used in cropping land (arable and horticultural), partly because of the wider range of species grown compared to pastoral or perennial horticultural land use. Herbicides, in particular glyphosate, are commonly used for pasture renewal in pastoral systems.

While some studies have assessed the presence of legacy and trace element pesticides (e.g. Gaw et al. 2006; Boul 1995) or the potential persistence of various active ingredients in pesticides (James & Gaw 2015), there are few studies that assess the presence of contemporary pesticide residues in soils. A pilot pesticide monitoring programme in Greater Wellington using SOE soil quality monitoring samples (Cavanagh & Gordon 2020) appears to be the only published report.

Additional sampling and analysis have been undertaken on SOE soil quality monitoring samples in the Waikato region (M. Taylor, Waikato Regional Council, pers. comm.), and extended sampling and analysis are being undertaken by Greater Wellington Regional Council (B. Lynch, Greater Wellington Regional Council, pers. comm.). These studies show that a range of pesticide residues, including legacy organochlorine pesticides residues, can be detected in soils. Glyphosate and its metabolite, aminomethylphosphonic acid (AMPA), were typically the most frequently detected compounds. Cavanagh and Gordon (2020) found pesticide residues in 14 of the 22 samples, with the greatest frequency of detections and range of residue concentrations occurring in market garden and mixed cropping soils. The pesticides present at the highest concentrations were glyphosate, AMPA, and DDT residues.

Neonicotinoid pesticides are another class of pesticides that have generated environmental concerns, particularly in relation to effects on honeybees and bumblebees (and therefore pollination of agricultural crops) (Wood & Goulson 2017). These pesticides were first introduced globally in the mid-1990s, and they are now the most widely used class of insecticides in the world, with the majority of applications coming from seed dressings (Wood & Goulson 2017), including in New Zealand (EPA 2019). In what appears to be the only study on neonicotinoids in agricultural soils in New Zealand, the neonicotinoid imidacloprid was found in 43 of 45 NZ maize soil samples (from 9 sites) and clothianidin in all samples (Pook & Gritcan 2019). Furthermore, imidacloprid was suggested to persist at significant concentrations for >2yrs.

As discussed above for Cd, food crops may be tested for the presence of pesticide residues to ensure they are below any specified Maximum Residue Limits (MPI 2024). While direct application of some pesticides to a food crop may be the primary source, some residues may also be taken up from the soil. DDT residues, glyphosate, imidacloprid, clothianidin and a wide range of other pesticides and chemical residues are tested through the National Programme for the Monitoring of Chemical Residues and Contaminants in Milk (NZFSA 2023).

Overall, soil concentrations were generally low, and potential negative ecological impacts were not anticipated as a result (Cavanagh & Gordon 2020), although definitive knowledge of the concentrations at which pesticide residues may cause negative effects is largely unknown.

Hormones

Dairy effluent is a source of oestrogenic hormones excreted by dairy cows, and these hormones have been detected in waterways throughout dairy catchments (Tremblay et al. 2018). Dairy effluent is commonly applied to land rather than being discharged to waterways, so any associated hormones are also applied to soils. Most research has focused on the impacts of oestrogenic hormones on aquatic organisms and transport pathways from soil to water, rather than on potential impacts to soil.

Sarmah et al. (2008) concluded that most New Zealand soils have high retention capacity for oestrogenic hormones and that leaching of these compounds to groundwater is therefore unlikely. Lysimeter leaching experiments by Steiner et al. (2010) showed that macropore flow (i.e. leaching), particularly via by-pass flow, was the dominant transport pathway by which two oestrogenic hormones (17β-estradiol and oestrone) were leached through the soil tested (Templeton Silt Loam). The results of an international study indicated that 17β-estradiol and oestrone did not persist in soils and had low bioavailability (Colucci et al. 2001). The degradation of these compounds did not appear to be affected by soil pH, organic matter content, or texture. Studies on the impact of oestrogenic hormones on soil resources are limited, but the results of Colucci et al. (2001) suggest that impacts are minimal.

Microplastics

Plastics – primarily soft plastics – are routinely used in some productive systems (e.g. as silage wrap or as a mulching film / soil cover in horticulture; O'Kelly et al. 2021). These soft plastics can break down into smaller pieces, including microplastics, when weathered. Microplastics can also be contained in composts, biosolids, and wastewater applied to productive land (Büks & Kaupenjohann 2020). Very little research has assessed the extent or impact of microplastics in New Zealand's productive soils; most has focused on beach sediments and waterways (e.g. Bridson et al. 2020; De Bhowmick et al. 2021).

Some general information on the impacts of microplastics is available in the international literature. For example, Boots et al. (2019) assessed the effects of microplastics on above- and below-ground soil ecosystems, measuring ryegrass seed germination, plant biomass (root and shoot), chlorophyll, earthworm biomass, soil pH, organic matter content, and aggregate stability (a measure of soil structure). This study found that the presence of biodegradable polylactic acid microplastics significantly reduced seed germination and shoot height, while conventional high-density polyethylene microplastics significantly reduced both the biomass of rosy-tipped earthworms and soil pH. Aggregate stability was also altered, with significantly different distributions of different-sized aggregates in soils in the presence of microplastics. While we can gain insight into the potential impacts of microplastics on soils and this issue in a global context, we cannot draw any conclusions about the impact of this issue in New Zealand due to a lack of data.

Contaminants: key points relevant to primary sector land uses

- Cadmium is most elevated in some pastoral, primarily dairy, soils. Similarly, zinc is most elevated in pastoral soils, particularly dairy systems. Concentrations are not recognised to be at concentrations that may have negative effects on plants or soil organisms.
- While lower cadmium concentrations are typically associated with arable and short-rotation horticultural soils, management of plant uptake of soil cadmium may be required to ensure compliance with food standards, particularly when food crops are exported. Lower plant uptake tends to occur in Allophanic and Granular Soils, with higher uptake observed in sedimentary soils such as Pallic and Recent Soils.
- Copper, associated with fungicide use, is most frequently elevated in soils associated with perennial horticulture.
- A wider range of pesticide residues of contemporary pesticides have been detected in soils from short-rotation horticulture (vegetable cropping), compared to other land uses, although studies are limited. Legacy pesticides, notably DDT residues, are also still detected in agricultural soils.

5.1.3 Soil carbon

Organic matter is widely recognised as having multiple desirable attributes for soils, such as increased cation exchange capacity, increased moisture storage, as a food source and habitat for soil organisms, and as a contributor to soil structure and aggregate stability (Sparling et al. 2003). Carbon storage is increasingly regarded as a key function of soils because of its significance for climate regulation, and also because it strongly affects many other functions (Weismeier et al. 2019).

Whether soil gains or loses C depends on the balance of photosynthesis by plants and respiration by plants and soil microbes, as well as C inputs (e.g. from plants, animal dung, organic materials, including compost and farm dairy effluent) and removal (e.g. crop harvest). Soil C at a particular site depends on environmental factors (e.g. climate, soil type, topography, which broadly determine the amount of C that can be stored in a particular soil type at a given site), land-use changes, and different land-management practices within a land use.

New Zealand is generally considered to have high soil C compared to other countries at a little over 100 t/ha in the top 30 cm (Mudge 2022).

Agricultural production

There are numerous New Zealand studies on changes in soil C, either as stocks (i.e. the quantity of C in soil to a given depth), or as total C, expressed as a concentration (usually percentage) in soil in primary production systems. This includes a plethora of studies on C change under different land management practices, including different measures of soil C to provide more information on C dynamics and the ability to sequester C (e.g. McNally et al 2017), and the National Soil Carbon Monitoring programme (NSCM), which will provide the first nationally representative assessment of soil C stocks in agricultural soils in New Zealand (Mudge et al. 2022). Currently all sites for the NSCM have been sampled, and the findings from this first round of sampling are due for release in mid-2024. Regional council SOE monitoring includes soil C expressed as total C (%).

Pastoral systems

Wall et al. (2024) undertook a comprehensive assessment of the effect of management practices in grazed dairy grasslands on C stocks by measuring the net ecosystem C balance. Management practices included year-round rotational grazing, differing pasture sward composition, irrigation, periodic supplemental feed cropping, and pasture renewal. The key findings were that, excluding years where supplemental feed cropping occurred, the soil C stocks of these ecosystems were probably near steady-state, and that pasture renewal and transition of pasture to crop resulted in loss of soil C, while in their study, there was no difference between irrigated and non-irrigated pastures. Furthermore, higher soil C levels were maintained under traditional ryegrass/white clover pastures than under the diverse pasture species mixes that have been more recently promoted.

Wall et al. (2020, 2023) similarly found decreased C with pasture renewal, which was attributed to soil respiration with minimal C inputs occurring during establishment periods (i.e. when plant growth is minimal). Schipper et al. (2017), in a review of soil C changes in grazed grassland, also found that pasture renewal and irrigation led to decreases in soil C. Phosphorus fertiliser application did not affect C stocks in soil. However, studies on full inversion tillage practices have reported no net losses in C with pasture renewal (Lawrence-Smith et al. 2021; Calvelo-Pereira et al. 2022), which could lead to a gain in C stocks, although this is yet to be confirmed.

The decrease in soil C under irrigation was substantiated by Mudge et al. (2017) and Mudge et al. (2021), with the latter authors assessing soil profile C and N data collected to 0.6 m depth from 124 paired irrigated and unirrigated grassland sites across different regions and soils in New Zealand. They found that soil C and N stocks were significantly lower in irrigated than in adjacent unirrigated soils; and that there was no evidence for an overall effect of soil order or region on the irrigation effect on C and N, but there was a significant negative relationship between the irrigation effect on soil C and aridity. In this case there was no irrigation effect on soil C at the most arid sites, but as aridity decreased there were increasingly significant C losses from irrigated soils relative to adjacent unirrigated soils – with a suggested threshold (for the top 0.1 m) of an aridity index of around 0.85, or mean annual precipitation of 575 mm.

The mechanism of loss under irrigated soils is suggested to be increased soil respiration (i.e. increased organic matter decomposition) in warm, moist soils. Mudge et al. (2021) highlight the discrepancy of these findings in comparison to the IPCC default C stock change factor, which predicts an increase of 14% when irrigation is introduced to temperate grasslands, and signal an urgent need to resolve this discrepancy given the widespread use of the IPCC guidelines. Data from long-term field trials throughout New Zealand have also agreed with these findings, as both Metherell (2003) and Condron et al. (2014) concluded that increasing irrigation frequency decreased soil C (and N) levels at Winchmore, a long-term, sheep-grazed field site with border-dyke irrigation in Canterbury. This decrease was attributed to increased C mineralisation due to higher soil moisture with increasing irrigation. However, modern spray irrigation systems used in the studies discussed above have now largely replaced border-dyke irrigation (Drewry, Carrick et al. 2021).

Long-term field trials throughout New Zealand report the effects of other land management practices, including pasture development, fertiliser application, and grazing, on soil C. At Ballantrae, a long-term field trial in Manawatū, Metherell (2003) found that pasture development was associated with a decline in soil C, and that higher fertiliser application rates led to only slight increases in soil C compared to lower fertiliser application rates. Metherell (2003) also concluded that at Winchmore C levels under pasture increased immediately following pasture establishment, but after 50 years fertiliser had no effect on soil C. Condron et al. (2012) also assessed C stocks under differing fertiliser rates at Winchmore and found no significant difference between zero, low, and high rates of superphosphate application.

This lack of effect of fertiliser application on soil C stocks was echoed by Schipper et al. (2017) in a review of soil changes in grazed grasslands (both dairy and dry stock). At Tara Hills in the South Island's semi-arid high-country, Metherell (2003) found that increased stocking rates decreased soil C and attributed this to a reduction in litter (organic matter) inputs to the soil from increased grazing. This finding was consistent with that of a shorter-term experiment from Kirwee in Canterbury (Hoglund 1985), which found reductions in soil C and N with increased grazing. However, superphosphate application studied in the Winchmore trials highlights important interactions between soil C and N, showing superphosphate contributes to enhanced pasture production through increased N mineralisation (Curtin et al. 2019).

Metherell (2003) concluded from a review of New Zealand’s long-term field trials that overall increases in pasture productivity do not relate to increases in soil C storage. This finding was repeated by Schipper et al. (2010), who resampled soils over two to three decades finding that soils under dairy pasture had lost C (and N) over time, while grazed hill- and high-country pastures had gained soil C. Two possible causes for increases in soil C and N for hill country were suggested: deposition of eroded topsoil from upper slope positions, and *in situ* accumulation, as pasture plant inputs of C and N were stabilised as soil organic matter.

In pastoral hill country, Hedley et al. (2018) found higher soil C in more stable landscape positions and gullies compared to steep hill sides, with a general increase downslope – except where soil erosion had occurred. Livestock movement also influenced the spatial distribution of soil C, with higher stocks where animals rested (camps) compared to other sites. The influence of this aspect on C stocks varied between regions of New Zealand. Mackay et al. (2021) similarly found the interaction between slope and aspect a key driver of soil C stocks under permanent pasture stocks at the Ballantrae station, but (again) there was no influence of phosphate fertiliser application.

Schipper et al. (2017) reported that grazing on flatland Allophanic, Gley, and Organic soils had resulted in significant decreases in soil C stocks, while there was no significant decrease in soil C due to grazing on Recent, Brown, Pumice, and Pallic Soils. Similarly, Schipper & McLeod (2002), Campbell et al. (2021), and Pronger, Glover et al. (2022) found high loss of C from drained Organic soils. These losses are likely to be ongoing until all the peat is decomposed or drainage ceases (Campbell et al. 2021), through potential mitigation, e.g. long-term re-saturation.

The land application of farm dairy effluent, especially slurries and solids (which are rich in organic matter), can have a beneficial effect on soil properties such as organic matter content, cation exchange capacity, water-holding capacity, and soil structure (Hawke & Summers 2006).

Cropping systems

Lower soil C under cropping systems is consistently reported. These include preliminary soil quality monitoring during the late 1990s to early 2000s (Sparling & Schipper 2002), and with more recent SOE national soil quality monitoring data (StatsNZ 2019b). Sparling and Schipper (2002) found total C (and N) to be lower in topsoils (0-100 mm depth and excluding leaf litter layers) under cropping and exotic forestry than in topsoils under pastures (both dairy and sheep & beef) and indigenous vegetation. After eight years under arable cropping in Canterbury, soil C stocks (0–25 cm) were less than under pasture; the tillage type altered the vertical distribution of soil organic matter but not the total amount in the top 25 cm of soil (Curtin et al 2015).

Recent national monitoring data have shown that 26% of cropping sites monitored between 2014 and 2018 were below target values for total C (StatsNZ 2019b). This trend of depleted soil C in cropping systems is also evident in regional soil quality monitoring reports from multiple regional councils, including Canterbury (Lawrence-Smith et al. 2014) and Marlborough (Oliver 2022, 2023), and in multiple other research projects assessing soil C under agricultural land use in New Zealand (Sparling et al. 1992; Shepherd et al. 2001; McNally et al. 2017), including preliminary findings from the National Soil Carbon Monitoring (NSCM) programme (Mudge et al. 2022).

Shepherd et al. (2001) reported that the rate of decline of soil C immediately following conversion to cropping varied with soil type. Organic C was higher in soils with humic (organic-enriched) soil horizons and Allophanic Soils. However, compared to other soil types, Allophanic Soils appeared to retain more organic C after conversion to cropping in the medium to long term (11–20 years post-conversion) due to the allophane mineralogy of these soils slowing turnover of organic matter (Parfitt 2009).

The loss of soil C in cultivated soils has been attributed to erosion, lower C inputs in croplands, a reduced stabilisation of organic matter due to deteriorated aggregation, and subsequent mineralisation promoted by increased soil temperature and aeration (Weismeier et al. 2019). Shepherd et al. (2001) attribute the loss of C under cropping to repeated exposure to air and resultant oxidation of C during tillage and increasing mineralisation by microorganisms in the smaller aggregates created by tillage.

Wall et al. (2020) attributed the high biomass removal associated with harvesting of a periodic maize crop for supplemental feed, coupled with long establishment periods with no photosynthetic C inputs, as being the key factors in the much larger C losses from the maize system relative to pasture. The C balance in continuously cropped systems will depend on the extent of biomass removal or crop residue remaining on the ground, management practices (including tillage frequency), and nutrient supply (Wall et al. 2020).

While the loss of soil C stocks can be a direct impact of cropping systems on soils, the impacts of depleted soil C on primary production relate more to indirect effects on other soil properties that influence production outcomes than to direct effects on crop yield. As soil C is linearly correlated to aggregate stability, an indicator of soil structural quality (Shepherd et al. 2001), reduced C means reduced resilience of soil to water stress and drought – a feature enhanced by soil structure that allows fine roots to penetrate throughout soils (Saggar et al. 2001). Loss of soil C also results in reduced nutrient (primarily N and P) supply from organic matter (Saggar et al. 2001), meaning production becomes more reliant on inorganic fertilisers.

Cropping of Organic Soils has been shown to increase subsidence and C emissions. Cultivation is used to incorporate lime to improve pH and productivity, but lowering nutrient inputs to mitigate C emissions may reduce plant productivity (Pronger, Wyatt et al. 2022).

Perennial horticulture and forestry

In contrast to other land uses, limited information on soil C was found for perennial horticultural systems and plantation forestry, particularly at depth. The most readily available information was that from national SOE reporting, which shows that most forestry or perennial horticulture sites are above minimum 'target' levels of soil C for the 0–10 cm soil depth (MfE & StatsNZ 2021).

Perennial horticulture has potential to store C deeper in the soil profile than in other agricultural systems because of the long-lived and deep rooting systems (Gentile et al. 2021). For example, kiwifruit production had a modest increase in C and N stocks at 1.5–2.0 m depth compared with pasture, but cumulative C and N stocks to 2-m depth were not different between these land uses (Gentile et al. 2021). Changes in pine forest soil C chemical composition occur with increasing soil depth but further research is needed (Garrett, Byers, Chen et al. 2024).

As discussed in the next section, organic matter is suggested to be more effective in providing nutrients for forestry systems than inorganic fertilisers.

Soil carbon: key points related to primary sector land use

- Soil carbon is typically highest in pastoral land uses, although irrigation and periodic cropping (e.g. maize crops for supplementary feeding) consistently reduces soil carbon in pastoral systems.
- Cropping land consistently has lower carbon content.
- There are few studies on soil carbon in perennial horticultural land and forestry, and there is considerable uncertainty in C cycling for deep soils.
- Further information on soil carbon in agricultural soils will be available when the results of the National Soil Carbon Monitoring programme are released in mid-2024.

5.1.4 Nutrients

Agricultural production

New Zealand soils generally have low natural fertility. Efforts to 'improve' the land date back to the 1870s, when landowners were required by law to 'improve' the land (Hewitt et al. 2021). Improvement in the early stages focused on the use of phosphate fertilisers, and from the late 1940s to the early 1950s aerial topdressing, including in hill country, was widely used to increase agricultural production from New Zealand's soils (During 1984; Hewitt et al. 2021).

The initial focus was on major elements, including P, K, and S, with N largely provided through biological fixation using clover, particularly in pastoral systems (e.g. Edmeades et al. 1984; Sinclair et al. 1997; Edmeades et al. 2006; Roberts & White 2016). This research has included data from long-term field trials, including Ballantrae Hill Country Research Station (Mackay & Costall 2016) and Winchmore Research Station (Rickards & Moss 2012, McDowell & Condron 2012).

From the 1930s there was also recognition of trace element deficiencies, such as cobalt, which was discovered to be the cause of 'bush sickness' in livestock in the central North Island and elsewhere. Similarly, deficiencies of Cu and selenium in animals, boron for brassicas, clover seed crops and lucerne, and molybdenum in clover have been identified (Morton et al. 2019).

The most recent guidance is available from the Fertiliser Association of New Zealand, which includes general guidance on fertiliser application for pasture on dairy (Roberts & Morton 2023) and sheep & beef farms (Morton & Roberts 2018), forage crops (Morton 2020), and including trace elements in pastoral systems (Morton 2023), arable cropping

(Morton et al. 2012), and vegetable cropping (Reid & Morton 2019). These guides also include discussion on soil and foliar testing, which can be used to inform the fertiliser requirements of different species. Fertiliser representatives and agricultural consultants are also widely used to provide advice on fertiliser requirements, and commercial laboratories provide general guidance on tests and test results in relation to different crops.

Fertiliser is a major expense in farming systems, and economic considerations mean that fertiliser (and lime) is not applied as extensively in hill-country pastoral systems, with a corresponding lower level of pasture production observed (Roberts & White 2016; Morton & Roberts 2018). The influence of economic considerations on Olsen P levels in soil is partly reflected in results from Olsen P testing published on the Fertiliser Association of New Zealand website (https://www.fertiliser.org.nz/Site/about/soil-health-fertility/nz-soil-olsen-p-levels.aspx). The majority of these soil data are from pastoral farms, with much smaller numbers of samples from arable or horticulture land use, reflecting the relative areas of these different activities.

Figure 6 shows Olsen P levels for dairy and dry-stock farms on Ash and Sedimentary soils nationally (refer to Table 4 for the relationship between Ash and Sedimentary soils and soil order). For dairy, the best economic return is suggested to be provided by maintaining soil Olsen P levels in the target range. The best economic return is also dependent on the milk-solids production level, with higher application rates only justified where a response in pasture production is obtained. As can be seen in Figure 6a, the median Olsen P level is at the upper range of the target values, while for sedimentary soils the median and the majority of samples fall within the recommended range (Figure 6b). This contrasts with Olsen P levels in dry-stock systems (Figures 6c, d), which show median Olsen P concentrations to be at the lower end of the recommended range. On the website, the economically optimal soil fertility is indicated as being achieved at levels below the recommended ranges.

A smaller set of data is available through soil quality monitoring undertaken by regional councils and initiated in the late 1990s. Initial soil quality monitoring showed Olsen P to be high in soils under dairy pasture relative to other land uses (Sparling et al. 2000, 2001, 2002). Similarly, *Our Land 2024* (MfE & StatsNZ 2024) reported that Olsen P was above target ranges in 61% of monitored dairy pastures between 2014 and 2018. A similar proportion of cropping sites were also above the target ranges, while a smaller proportion of sites under the remaining land uses (including some forestry sites) were above the target ranges developed for SOE Reporting (StatsNZ 2019b, Cavanagh, Drewry et al. 2023) that are being updated in 2025. Other studies also support this evidence of elevated Olsen P, particularly in dairy and vegetable cropping land uses (e.g. Curran-Cournane 2015; Drewry, Cavanagh et al 2021).

Historically, ryegrass/clover pasture relied on N supplied by biological fixation by clover, but research over the late 1970s and 1980s established that even well-managed grass/clover pastures remain deficient in N for much of the time (Gray 2023). Since the 1990s, conversion to dairy and intensification of dairy land use has resulted in increasing use of N fertiliser (Gray 2023). StatsNZ data also shows that dairy soils received higher average per hectare applications of P and N fertilisers than other monitored land uses in New Zealand (StatsNZ 2021a, 2021b).

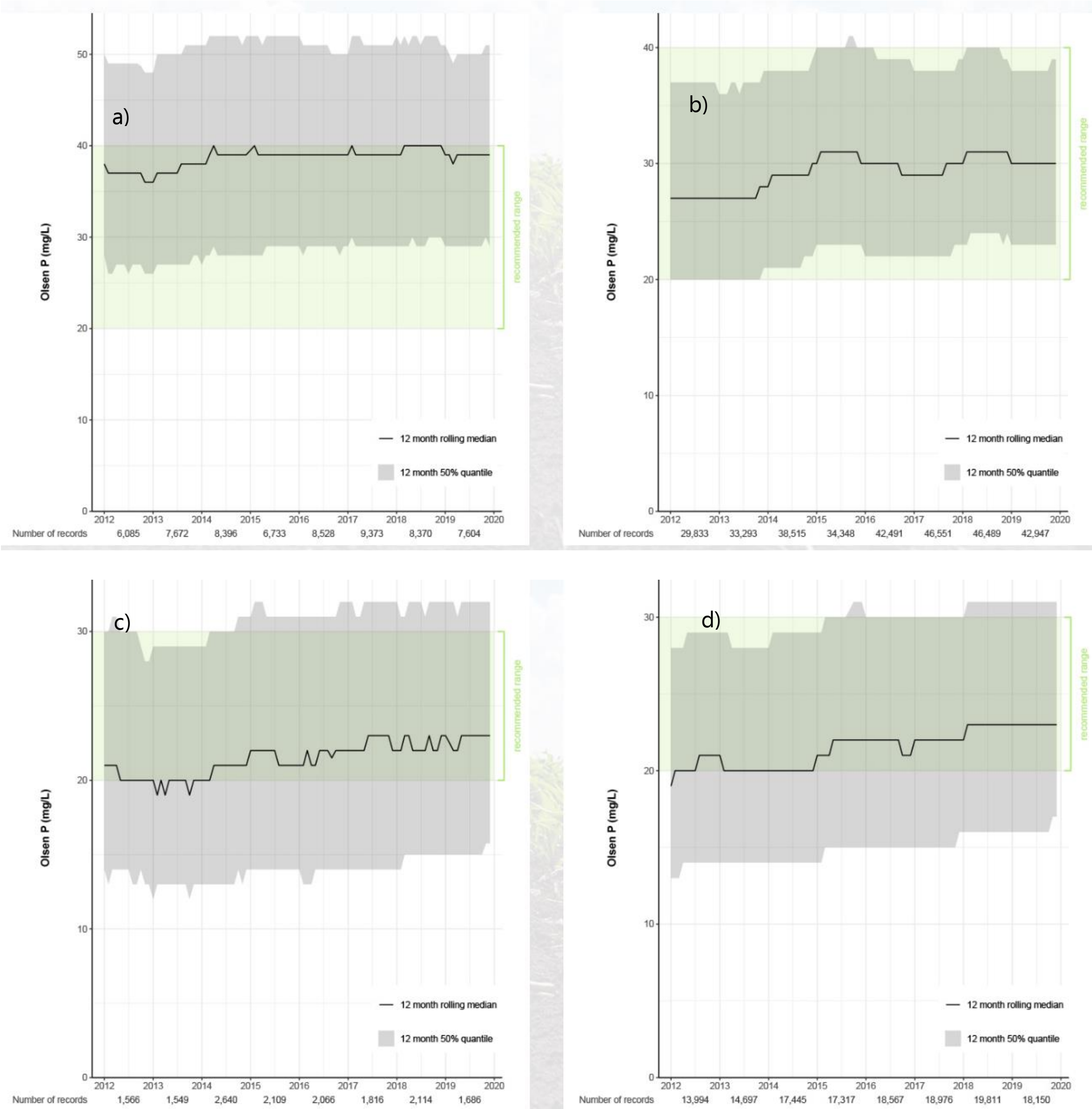

Figure 6. Yearly time series of the median level of Olsen P across (a) Ash soils for dairy farms nationally, (b) Sedimentary soils for dairy farms nationally, (c) Ash soils for dry-stock farms, and (d) Sedimentary soils for dry-stock farms.

Notes: The black line represents median levels of Olsen P, while the grey shaded area indicates the 25th to 75th percentile range. The recommended range, which provides for near-maximum pasture production, is shown in green. For dairy, the best economic return is provided by maintaining soil Olsen P levels in the target range, but is also dependent on the milk-solids production level.

Source: Reproduced with permission from the Fertiliser Association of New Zealand.

In combination with increased cow numbers/ha and fertiliser inputs, larger volumes of farm dairy effluent (FDE) are generated. Application of this effluent to land can offset the need for inorganic fertiliser, and there is guidance (e.g. DairyNZ 2015; Norris et al. 2019) and calculators (e.g. DairyNZ Farm Dairy Effluent Spreading Calculator) to help manage the application of effluent nutrients to land. One consideration when applying FDE is managing the high potassium concentrations which may lead to nutrient imbalances in dairy cows by decreasing calcium and magnesium intake, resulting in milk fever (hypocalcaemia) or ryegrass staggers (hypomagnesaemia) (Houlbrooke et al. 2004; Hawke & Summers 2006). Growing of summer forage crops that have a high K requirement (e.g. turnips) has also been suggested as a means to manage soils with a high K loading on dairy farm effluent blocks (Salazar et al. 2010). Summer turnip crops can take up large amounts of K, thus reducing soil K accumulation on the effluent blocks by re-distributing it to grazed pastures (Salazar et al. 2010).

In contrast to pasture species, arable crops, and perennial horticultural crops, vegetable crops typically have a short growing season and need to take up large quantities of nutrients quickly, although requirements vary considerably between vegetables. High concentrations of mineral nutrients in the soil are needed to maintain nutrient uptake and production (Reid & Morton 2019). Mineral nutrients are primarily provided by fertilisers, but the amount of nutrients needed is also determined by other factors, such as the capacity of the soil to naturally supply nutrients. Where applied in excess, some plants may take up more nutrients than is required for maximum yield (called 'luxury uptake'). Leafy vegetables and root crops are predisposed to luxury uptake (especially of N and K), but this can be associated with negative effects on crop quality or yield (Reid & Morton 2019).

In contrast to most other agricultural production, fertiliser use in viticulture is kept to a minimum in order to reduce vegetative vigour. An annual input of di-ammonium phosphate at 25 kg/ha (equivalent to 5 kg/ha N, 5 kg/ha P) is standard vineyard practice (Clothier & Green 2017). Additional nutrients may be applied as mineral or organic fertiliser, or to address or avoid deficiencies.

Different parameters are used to inform fertility requirements for agricultural production (e.g. quick-tests, cation storage and exchange, foliar testing; Roberts & Morton 2023; Reid & Morton 2019) compared to those often used for soil quality monitoring (total N, and anaerobically mineralisable N). As a result there are more limited data to provide an assessment of the state of other nutrients in soil in agricultural soils. Newer tests such as the Potentially Mineralisable Nitrogen (PMN) test (Curtin et al. 2017), based on measurements of hot water extractable organic nitrogen, gaining wider acceptance in some agricultural industries. Higher soil total N concentrations are typically observed in pastoral land uses (e.g. Sparling & Schipper 2002), with 27% of dairy sites monitored over 2014–2018 having total N concentrations above SOE target values. Sparling and Schipper (2002) noted lower C:N ratios (between 10:1 and 15:1) in pastures compared with plantation forests, tussock grasslands and indigenous forests (between 15:1 and 20:1), and concluded that this was due to the widespread coverage of ryegrass/white clover pastures.

Nutrient export via farm product (milk, vegetables, grain, etc.) removal off-farm occurs in all agricultural systems. However, despite this loss pathway there is no evidence for wide-spread or general nutrient deficiencies in soil arising from any agricultural production activity, most likely due to nutrient additions (e.g. Morton et al 2019, Reid & Morton 2019, Roberts & Morton 2023). However, addition of trace element fertilisers to address deficiencies for plant growth and animal health arising from naturally low concentrations present in some soils may be overlooked, resulting in soil reserves potentially becoming depleted. Excess nutrients in soil (e.g. Olsen P) and nutrient losses, particularly of the major nutrients N and P, to surface and groundwater are the greater concern (e.g. McDowell et al. 2009, 2019).

Forestry

In contrast to agricultural production systems, fertilisers are not applied to forests in a routine manner, and traditionally are only used to correct deficiencies (Davis et al. 2015; Garrett, Smaill, Beets, et al. 2021). Furthermore, early planted forests in New Zealand were almost exclusively established in locations that were considered either unsuitable or uneconomic for sustained agriculture, predominantly due to poor soil fertility (Will 1985, in Garrett, Smaill, Beets et al. 2021).

The use of fertilisers in planted forests in New Zealand began in the mid-1950s and was suggested to have peaked in the early 1980s (Will 1985, in Davis et al. 2013), with more recent fertiliser sales data to 2013 not available (Davis et al. 2013). More specifically, plantation forests have traditionally relied on the inherent fertility of soil, and the scavenging of N and P through associations of the tree roots with ectomycorrhiza (Payn & Clinton 2005). As noted in Table 3, some soil orders have naturally low levels of fertility, and low-nutrient soils are estimated to make up about a third of New Zealand's total planted forest area (Garrett et al. 2015). Increasingly more forests have been planted on land previously used for pastoral grazing with a fertiliser use history and therefore elevated fertility (Beets et al. 2019).

In a nationwide study of site quality under 31 plantation forestry sites, soil properties that were most strongly related to an annual increment in productivity 4 years after tree establishment included the C:N ratio, total P, and organic P, with total porosity the most important soil physical property, which is influenced by management – notably compaction during harvesting operations (Watt et al. 2008). In the same series of trials, C content, P retention, and soil physical properties were most strongly correlated to soil order under exotic forests (Ross et al. 2009). Subsequently, Beets et al. (2019) showed that the soil total N and organic P pools were the key drivers of productivity after accounting for the effects of the C:N ratio, and specifically noted the importance of organic matter as the source of both N and P.

The soil requirement for soil-derived nutrients is particularly strong during years 3 to 4 for commercial forestry operations (Cavanagh, Simcock et al. 2023); after canopy closure, litter-fall should be able to maintain nutrient supply. Biomass removal during harvesting reduces the pool of nutrients retained in the harvest residues, forcing the next rotation of trees to seek out more nutrients from soil rather than from the decomposition of residues of the previous tree crop (Garrett, Smaill, Addison et al. 2021; Garrett, Smaill, Beets et al. 2021).

The retention of harvest residues on-site can help mitigate the extent of this removal (for both current forests and in more intense future plantation systems). On steepland sites this may not always be achievable due to the hauler harvesting method, which often results in the concentration of woody debris in discrete locations (Garrett et al. 2015). Also, erosion and loss of topsoil on steepland sites can result in rapid changes in soil nutrient supply, reducing productivity (Heaphy et al. 2014).

The retention of the forest floor, in particular, and tree foliage/branches on-site post-harvest are beneficial to supplying nutrients to the following growing crop. The impact of harvest activities on soil fertility depends on the size of the initial soil nutrient pool, vulnerability to soil disturbance, and the number of harvesting events that have occurred over time (Garrett, Smaill, Beets et al. 2021). Sites at greatest risk of nutrient deficiencies are those that have soils already low in nutrients, although improvements in genetics and silvicultural management over decades have the potential to mask reductions in soil nutrient supply (Garrett et al. 2015).

Pastoral farmland previously treated with phosphatic fertilisers that has been converted to forestry contributed to an 18% gain in *P. radiata* productivity compared to land without an agricultural land-use history (Beets et al. 2019). This increase was suggested to be due to the accumulation of organic matter as a result of applying phosphatic fertilisers to clover/ryegrass pasture, as distinct from any elevation of mineral P. Increasingly, the New Zealand forestry sector is looking to develop nutrient management strategies that seek to use fertilisers to enhance forest productivity (Garrett, Smaill, Addison et al. 2021). Although wood density and stem form have been shown to be negatively correlated with soil N, value losses in quality may be less than the increase in volume growth; negative impacts on wood quality have only been associated with high N fertilisation throughout a rotation (Moore et al. 2021).

Nutrients: key points related to primary sector land use

- Other than hill- and high-country pastoral farming, there is no evidence for nutrient depletion on agricultural soils. Excess nutrients arising from a range of inputs, including fertiliser application, livestock excreta, and wastewater and effluent application, are the greater concern – largely from an environmental perspective rather than a yield or production perspective. Addition of trace element nutrients to address deficiencies for plant growth and animal health due to low concentrations naturally present in some soils may be overlooked, resulting in soil reserves potentially becoming depleted.
- Economic considerations constrain the extent to which lime and fertiliser are applied on hill- and high-country farms, which in turn limit pasture production on this land.
- Fertiliser application is not routine in exotic forestry systems, and early-planted forests were often located on low-fertility soils. The potential for nutrient deficiencies depends on the size of the initial soil nutrient pool, vulnerability to soil disturbance, and the extent of retention of the forest floor and harvest residue.
- Retention of the forest floor and harvest residue is more challenging on steepland sites, which may also be affected by erosion and loss of topsoil.
- Afforested pastoral land to which phosphatic fertilisers have been applied contributes to productivity gains for *P. radiata* compared to that grown on non-agricultural land.

5.1.5 pH

New Zealand's native unamended soil pH varies between different soil types, typically ranging from extremely acidic to moderately acidic, or a soil pH from <4.8 to 5.9 (Hewitt et al. 2021). For agricultural production purposes, lime is often applied to increase soil pH (capital addition) to that which is optimal for the growth of the desired crops, with smaller additions to maintain soil pH (maintenance applications) (Morton 2019). 'Liming' to deliver an optimal pH of 5.8 to 6.1 for mineral soils growing pasture is due to interactive or individual effects of improved clover nodulation, reduced Al toxicity, overcoming Mo deficiency, increasing mineralisation of organic N and encouraging earthworm activity (Morton & Moir 2018, Morton 2020). However, lime addition may not be economic in some hill- and high-country areas, so soil pH may be lower in these systems (Roberts & White 2016; Morton 2019).

In cropping and horticultural systems the pH for optimal yield, and thus the extent of liming, will depend on the species being grown (e.g. Reid & Morton 2019; Nicholls et al. 2012). Ongoing lime inputs are required to maintain desired soil pH, because some plant processes (e.g. the production of organic acids, and N fertilisers that contain urea or ammonium) can acidify soil (Morton 2019). Changing soil pH can also change the availability of both essential nutrients and non-essential contaminants to plants, and produce favourable or unfavourable conditions for soil microbes (Moebius-Clune et al. 2016).

In contrast to agricultural production soils, plantation forestry soils in New Zealand generally have lower pH than agricultural production uses (Sparling & Schipper 2002), and multiple studies have reported a relatively lower pH in exotic forestry soils than in pastoral soils (Parfitt et al. 1997; Giddens et al. 1997; Schon et al. 2022; Marshall et al. 2023). There is disagreement over how this difference is viewed, with Harnett (2019) stating that 'The widespread belief that pines lower soil pH is false', and that the lower pH is a result of natural reversion to a more acidic state.

The process of reverting to a more acidic state does require a mechanism. Parfitt et al. (1997) suggested that lower soil pH under forestry soils converted from pastoral land occurs as a result of the production of organic acids and biomass storage of cations in excess of anions by the *P. radiata* trees. They also suggest that enhanced organic matter decomposition may lead to nitrification and leaching of base cations, resulting in the production of protons and subsequently a decrease in pH, though the study did not measure these soil properties. Giddens et al. (1997) suggest similar mechanisms, but these mechanisms are not unique to forestry soils, instead being the reason that ongoing lime inputs are required for pastoral soils (Morton 2019).

The key point to note is that there is little difference in soil pH under indigenous vegetation and exotic forestry (Sparling et al. 2000; Sparling & Schipper 2002). In some cases indigenous forest sites may have lower soil pH than exotic forestry sites. For example, Beecroft (2016) found the soil pH in five indigenous forest sites in the Hawke's Bay region ranged from 4.7 to 6.4, which compared to a soil pH range of 5.4 to 6 in 10 exotic forestry sites. Thus, the soil pH in exotic forestry plantations is more likely to reflect the inherent pH of the soil on which it is being grown, and the absence of any ongoing lime additions, rather than any additional acidification. However, further studies using comparable soils would be required to fully verify this statement.

At a national level, soil pH rarely falls outside target ranges that have been established for SOE soil quality monitoring (MfE & StatsNZ 2021), although this may also reflect the relatively wide target ranges used (Cavanagh, Drewry et al. 2023).

Key points related to primary sector land use

- In most agricultural production systems lime is routinely applied to ensure soil pH is within a suitable range for optimal yield of the species being grown.
- Soil pH in exotic forestry soils is typically lower than for agricultural production systems, although is similar to that of indigenous forests. An apparent acidification of soils converted from pastoral land reflects a return to natural soil pH, probably through the generation of plant-derived organic acids and an absence of ongoing lime additions.

5.1.6 Soil physical characteristics – grazing land uses

Soil structure affects soil water, infiltration, drainage and water storage, root penetration, air movement, plant yield and environmental performance, including freshwater quality and greenhouse gas emissions (Hu et al. 2021; MfE 2023c). Well-structured soils have a good friable structure (Figure 7; right), whereas poorly structured soils typically have dense, firm soil, with few visible large cracks and pores (Figure 7; right). These features limit root penetration, water drainage and air movement. Large soil pores (macropores – visible pores) are responsible for air movement and drainage, but are the most susceptible to compaction from animal treading and vehicles. Such compaction is most severe when soil strength is weakened by wet conditions (high soil moisture) (Drewry et al. 2008; Houlbrooke et al. 2021) and when unprotected by a dense plant sward and/or unsupported by plant roots.

Figure 7. A very compacted Pallic soil (left) and a non-compacted Pallic soil (right).

Notes: Both photos are from the same paddock, but sampled from different areas to explicitly show contrasting differences. The very compacted soil has large, dense aggregates that are difficult to break apart. The non-compacted soil has many visible cracks and pores and more friable aggregates. (Photos: J. Drewry)

Issues associated with soil structural damage, pugging, and compaction typically include increased soil density, and reduced macroporosity, aeration, aggregate stability, soil water storage, and infiltration. Soil structural damage, pugging, and compaction affect pasture and crop yields and plant function, as described further below.

Cattle generally exert more severe physical damage to soil and to greater depths than sheep, as cattle pressures are much greater (Betteridge et al. 1999; Drewry et al. 2008), although some studies have found no differences in physical properties between stock classes (Houlbrooke et al. 2008). Grazing intensity and duration, or in combination, are also important for affecting soil physical and pasture damage, with greater effects on soil structural properties under higher grazing intensities/duration in wet conditions (Singleton & Addison 1999; Menneer et al. 2005; Drewry et al. 2008; MfE 2023c). Soils with a high clay content are also more vulnerable to pugging damage during wet conditions (Laurenson & Houlbrooke 2016).

The effects on soil structure and pasture yield from grazing sheep in winter have been recognised over a long period (Gradwell 1965; Brown & Evans 1973). Under intensive winter grazing by sheep, a poorly-drained Pallic Soil was more damaged than a well-drained Brown soil, and to nearly the full depth of topsoil (c. 30 cm) (Greenwood & McNamara 1992). Severe treading events by cattle on wet soils create greater surface contour change (terracing) than sheep when stocked at the same liveweight per hectare (Betteridge et al. 1999). This soil displacement contributes to reduced soil macroporosity and infiltration by exposing denser subsoils (Nguyen et al. 1998).

Surveys on Allophanic, Gley, Podzol and Ultic Soils in Waikato and Northland showed soil compaction under multiple treading regimes, including normal grazing practice and previously pugged areas (Singleton et al. 1999; Singleton & Addison 1999). Singleton et al. (2000) reported a decline in soil physical condition with increased treading, with previously pugged areas of soil not fully recovering 18 months after a pugging event. Even well drained Allophanic Soils which tend to be resilient to structural damage, also showed some decline in physical condition. In Waikato dairy farms pugging was having a long-term effect on soil physical properties of all three soil orders, including the well-drained Allophanic Soil that rarely pugged (Singleton & Addison 1999). For the Northland soils, hydraulic conductivity and aggregate size were greatly reduced in the previously pugged areas, and were the best indicators of this change. Singleton et al. (2000) reported despite a decline in soil physical values (particularly macroporosity), many values were within levels required for soil or plant health. The authors suggested an increase in pugging could mean a gradual decline in soil properties from levels now regarded as 'normal' to another less-favourable 'normal'. In a study of sheep and dairy farm sites on a range of soils in Southland and South Otago, soils on sheep farms had greater air permeability and hydraulic conductivity than soils on dairy farms (Drewry, Lowe, et al. 2000).

Soil compaction, as measured by macroporosity and bulk density, has been widely reported in regional and national soil quality reporting (Sparling & Schipper 2002; Taylor et al. 2010; Gray 2011; Curran-Cournane 2015; Taylor et al. 2017; Drewry, Cavanagh, et al. 2021; MfE & StatsNZ 2021). Houlbrooke et al. (2021) and Hu et al. (2021) review recent soil compaction results in regional soil quality assessments. They report soil compaction as a key issue in the Waikato, Auckland, Marlborough, and Wellington regions, with the greatest adverse effects in soils on dairy farms. For example, in the Marlborough region median macroporosity on dairy farms was 5.3% (Gray 2011; Houlbrooke et al. 2021), 4.7% lower than the level considered likely to limit pasture production (Drewry et al. 2008), and the 10–30% soil quality target value (Drewry, Cavanagh et al. 2021; Cavanagh, Drewry et al. 2023). Soil quality target ranges (limited to 0–10 cm soil depth) have been developed for SOE reporting (Cavanagh, Drewry et al. 2023) and are being updated in 2025.

Hu et al. (2021) also reported that dairy sites usually had the lowest macroporosity, and at a regional level, mean macroporosity was <6% in the Canterbury and Waikato regions, where dairy land use dominates. At a national level, 65% of dairy sites and 41% of drystock sites monitored were below the soil quality target for macroporosity for sites sampled between 2014 and 2018 (MfE & StatsNZ 2021). Further, there was no change in macroporosity in dry-stock farming or dairy farming from 1995 to 2018 (Stevenson & McNeill 2020; MfE & StatsNZ 2021), suggesting that reduced macroporosity is a persistent state. Although these monitoring results were at 0–7.5 cm depth, and sampled at a similar time of year. Soil compaction at this depth can recover between seasons e.g. summer, but can re-compact in other seasons e.g. spring in a cycle (Drewry, Paton, et al. 2004).

Additional indicators of soil structural degradation in New Zealand peer-reviewed studies were summarised by Hu et al. (2021). They reported relatively large average reductions in macroporosity and saturated hydraulic conductivity in Pallic, Gley and Allophanic soils under dairy and dry-stock grazing, with macroporosity reduction under dry stock generally about half that under dairy land use. Similar results were reported by Lawrence-Smith et al. (2014). On average Hu et al. (2021) reported that sheep/beef pastures tended to have a greater percentage of ideal aggregate size classes than dairy pastures, and that soil order was an important factor.

There were insufficient studies to make comparisons for the different primary industries for other soil orders except for Gley Soils under arable and vegetable cropping (Hu et al. 2021).

Soil compaction and pugging are associated with pasture damage, leaf burial in mud (reducing animal intake), reductions in pasture yield, and in functions of plants, such as N-fixation (Menneer et al. 2001; Menneer et al. 2005; Drewry et al. 2008). Pasture yields may be reduced over many months after a single pugging event. Drewry et al. (2008) report a 21–88% reduction in pasture yield and 8–31% reduction in a range of soil physical properties under dairy treaded treatments.

Pastoral grazing only results in visible pugging damage in very wet conditions when pasture cover is high (spring to autumn) (Drewry, Littlejohn, et al. 2004; Houlbrooke et al. 2009). Under these conditions, macroporosity is a useful indicator to assess the impacts of treading damage on dairy pasture yield (Drewry, Littlejohn, et al. 2004). For example, in New Zealand, spring pasture production was estimated to increase by 2.6% for a 1%

increase in macroporosity at 5–10 cm depth (Drewry, Littlejohn, et al. 2004). Hu et al. (2021) estimated if the dairy sector improved soil macroporosity values above a threshold value of 10%, pasture yield could increase by 6%.

One study suggests Olsen P concentrations above that generally recommended for pastoral soils may partially compensate for compaction (Mackay et al. 2010). These authors suggested a critical Olsen P value of >43 µg/ml, which was higher than the recommendations at the time (and currently) of 30-40 µg/ml for dairy farms that are operating at top 25% of a supply area (Roberts & Morton 2009, Roberts & Morton 2023).

Intensive winter grazing of animals on forage crops (e.g. swedes, kale, rape, fodder beets, oats, plantain, chicory) (Belliss et al. 2022; MfE 2023c) also damages soil structure through pugging (Drewry & Paton 2005), which can increase nutrients, sediment and bacteria in surface runoff (MfE 2023c) and winter erosion (Amies et al. 2024). Such grazing has been common in the southern South Island, with research often on Pallic Soils. Soil conditions between pre- and post-grazing of forage crops on poorly-drained Pallic Soils show visual soil deformation, pugging and a reduction in larger soil pores (Monaghan et al. 2017), erosion from hooves pushing soil downslope (Penny et al. 2016), and increased overland flow and ponding (MfE 2023c).

Intensive winter grazing of forage crops under beef cattle has also cause visible pugging and surface runoff on imperfectly and well-drained soils in hill country (Burkitt et al. 2017; MfE 2023c). This is similar to pugging effects observed for beef cattle on supplementary feed areas (Fransen et al. 2022). Little research has been done on Brown Soils in Southland, despite 63% of winter forage crops in the Gore-Mataura area being grown on these soils (Drewry et al. 2020).

A national map of intensive winter grazing showed 226,567 ha of intensively grazed forage in 2023; with no significant change in impacted area over the last three winters (Amies et al. 2024). However, research indicates impacts of intensive winter grazing of forage crops can be mitigated through improved grazing, tillage and re-sowing practices (Monaghan et al. 2017; Hu et al. 2018; Hu et al. 2020; Malcolm et al. 2022; MfE 2023a, b, c).

Another form of agricultural intensification is irrigation, which can lead to changes in soil compaction and reduced soil pore space, as well as available water capacity (Drewry, Carrick et al. 2021, Drewry, Carrick et al. 2022; Hu et al. 2021). Available water capacity and readily available water capacity are measures of the amount of water a soil can store that is potentially available for plant uptake. Irrigated soils grazed by dairy or beef cattle tend to have lower macropores than soils grazed by sheep grazing (Drewry, Carrick et al. 2021). Importantly, dairy and cattle grazing under irrigation degraded soil to about 30 cm depth, well beyond the 0–10 cm depth used in national soil quality monitoring (Drewry, Carrick et al. 2022).

The limited number of recent studies on the effects of spray irrigation on soil physical properties have focused on susceptible soils (Houlbrooke et al. 2008, 2011). Houlbrooke et al. (2011) reported compaction under both irrigation and cattle grazing, particularly in combination, but no evidence of decreased pasture growth attributable to soil physical condition. Houlbrooke and Laurenson (2013) showed that there was a reduction in readily available water capacity with cattle and spray irrigation compared with unirrigated cattle-grazed (dairy) and sheep-grazed plots, attributing this to soil compaction from treading. In a regional Canterbury study, readily available water also showed a reduction under irrigated and grazed pasture (Drewry, Carrick et al. 2022). Reduced soil water capacity may increase the frequency of irrigation (Houlbrooke and Laurenson 2013; Drewry, Carrick et al. 2022) potentially creating a negative feedback loop.

Highly localised compaction has also been reported along fence lines in paddocks with deer and soil structural degradation associated with 'wallows' (de Klein et al. 2003).

Subsidence of drained Organic soils is a different form of degradation of the soil structure, and can result in increased potential for flooding or water-logging, and increased cost to maintain drainage and pumping systems on farmland (Pronger et al. 2014; Pronger, Wyatt, et al. 2022). Drainage results in subsidence processes that include shrinkage, consolidation, and oxidation. Shrinkage and consolidation after drainage increase bulk density, whereas oxidation is a long-term process resulting in the loss of peat deposits (Pronger, Wyatt, et al. 2022). In the Waikato region, subsidence of Organic Soils on a dairy farm averaged 3.4 cm/yr, while C loss averaged 3.7 t/ha/yr, attributed to both consolidation and loss of organic matter through mineralisation (Schipper & McLeod 2002). At sites across Waikato, subsidence rates (2000s–2012) averaged 19 mm/yr, which was much less than the historical rates (26 mm/yr) between the 1920s and 2000s (Pronger et al. 2014). Productive performance after loss of peat has occurred is unknown; some areas in Waikato had 2 m depth of peat in the 1920s (Pronger, Wyatt, et al. 2022). In lower landscape positions continued drainage may become prohibitively expensive (e.g. Muggeridge's Catchment, Hauraki) (J. Pronger, MWLR, pers. comm.).

Soil physical characteristics: key points related to grazing land use

- Deeper soil physical damage tends to occur in soil when cattle rather than sheep are grazed. Previously pugged areas of soil from dairy cow grazing have typically not fully recovered 18 months after a pugging event. In Waikato dairy farms, pugging was found to be having a long-term effect on soil physical properties.
- Soil compaction, as measured by decreased macroporosity and increased bulk density, has been widely reported in regional and national soil quality reporting, showing it is a key issue in many regions.
- Short-term studies show that soil compaction and pugging in winter by animal treading are associated with pasture damage and reductions in pasture yield, nitrogen-fixation, etc. Soil compaction can affect pasture yield over the longer term, but there are fewer studies on this.
- Several studies show that dairy and beef cattle grazing under modern irrigation systems affects soil compaction down to about 30 cm depth.
- Many studies, including SOE soil quality monitoring, don't measure deeper (i.e. >15 cm) soil compaction.

5.1.7 Soil physical characteristics – non-grazing land uses

Short-rotation cropping

The impacts of arable/cropping land use on soil compaction were summarised in a recent review (Hu et al. 2021), which includes numerous New Zealand studies (Beare et al. 1999; McQueen & Shepherd 2002; Hu et al. 2018; Hu et al. 2022), and a key international study (Hamza & Anderson 2005). Soil structural degradation is common in cropping land, measured across a range of indicators. For example, 25% of Waikato region arable sites had aggregate stability below the target for average production (Taylor et al. 2010). In the Wellington region, 40% of cropping sites had topsoil (0-10 cm depth) macroporosity outside the target range (Drewry et al. 2021b).

In contrast, Hu et al 2021 report macroporosity at 0–10 cm and 10–20 cm depths was generally much greater in annual cropping than for other land uses (i.e. less compact), for a range of study treatments compared with control treatments. Soil macroporosity under cropping also had a wider range of values compared with other land uses, most likely due to the cropping cycle which includes cultivation and harvest (Hu et al. 2021). National environmental reporting showed that just over 25% of cropping sites topsoils were below the macroporosity target, while most remaining sites sampled between 2014 and 2018 were within the target range (MfE & StatsNZ 2021). No trend in macroporosity was found in cropping from 1995 to 2018 (Stevenson & McNeill 2020).

The impacts of land uses on indicators of soil structural degradation in New Zealand peer-reviewed studies were summarised by Hu et al. (2021). Indicators of arable cropping other than soil macroporosity had large reductions in aggregate stability and saturated hydraulic conductivity, compared with control treatments (Hu et al. 2021). The relative magnitude of these difference varied for Gley, Pallic, Allophanic and Melanic soils when arable and vegetable cropping was combined; there were insufficient studies on other soil orders to make comparisons between primary industries (Hu et al. 2021).

In general, a longer cropping history results in a greater increase in bulk density and a greater decline in aggregate stability and other soil physical properties, most likely to be related to repeated intensive cultivation and the loss of soil C (McLaren & Cameron 1996; Shepherd et al. 2001; Hu et al. 2021). A study in Canterbury reported aggregate stability was negatively correlated with the length of time under arable cropping, with lowest aggregate stabilities under long-term cropping (Lawrence-Smith et al. 2014).

Continued vehicle movement or ploughing in wet soil can lead to a compacted soil layer or a 'plough pan' below the ploughing depth, which can lead to reductions in crop yield (McLaren & Cameron 1996). Such pans are difficult to reverse, unless remedial techniques such as subsoiling (also called soil aeration) are used to break up the soil (Lawrence-Smith et al. 2014). Soil compaction in cropping systems generally reduces crop yields, and the optimal value of soil physical condition for yield varies with crop and soil (Drewry et al. 2008; Hu et al. 2021). Increases in bulk density have been associated with reduced crop yields in Southland (Beare & Tregurtha 2004). Compaction tends to reduce crop yield more in years with average or above average rainfall (because drainage is slower, resulting in longer periods of low aeration), and it may also increase yields in dry seasons where root volume and/or depth is limited by compaction (Drewry et al. 2008). However, few New Zealand studies show improved crop yield as a result of techniques such as subsoiling (but see Greenwood & Cameron 1990).

Perennial tree crops and vineyards

Soil compaction in orchards and vineyards can be caused by repeated passes of heavy machinery used for harvesting, pruning, mowing, and spraying. Gray (2013a) reported macroporosity of soils under Marlborough vines were 10.1% but 4.6% under the wheel tracks, estimating 29% of the vineyard could potentially be considered as compacted (excluding headlands). Similar results were also reported by Oliver (2023) and by Vogeler et al. (2006), in apple orchards. However, change in topsoil macroporosity or bulk density was observed in orchard/vineyard land use monitored nationally over 1995 to 2018 (Stevenson & McNeill 2020). Recontouring has occurred on some vineyards but no studies were found on the spatial extent or effects.

The application of winery wastewater to land can also degrade soil structure. Here, the cations sodium (Na^+) and potassium (K^+) increase dispersion of clay particles (Laurenson & Houlbrooke 2011; Nightingale-McMahon et al. 2024). Soil electrical conductivity, exchangeable sodium percentage and exchangeable potassium percentage (useful for estimating potential clay dispersion and structural instability) were higher from sites receiving winery wastewater compared to control sites (Gray 2012).

Forestry

Physical properties of soils in plantation forests may be physically altered during site preparation and harvesting (Murphy et al 2009; Watt et al. 2005; Watt et al. 2008). Ground-based logging equipment may travel over 60 to 90% of a site (Murphy and Firth 2004) causing soil displacement or mixing (of leaf litter and soils) and/or compaction. Trials established in the mid-1980s compared growth of seedlings over 14 years in areas of harvested Pallic and Brown Soils at sites ranging from undisturbed to major skid trails (Murphy and Firth 2004). The authors reported no clear relationship between soil disturbance and seedling mortality except in highly-disturbed areas without topsoil, on a Pallic Soil. Effects on early tree growth was influenced by weed growth with high competition at undisturbed sites supressing growth of pines up to age four despite favourable soil physical properties. Moderate and severe disturbance also resulted in supressed pine growth; higher bulk density and penetration resistance from the surface to 20 cm depth limited root growth. Impacts of compaction, which covered 14 to 20% of the sites, were present up to 8 years after logging and led to the authors recommending physical amelioration of such sites. At these sites, under poor weed control, an intermediate level of disturbance delivered the best tree growth. Murphy et al. (1997) reported similar levels of disturbance on an Ultic Soil, and severe topsoil disturbance reduced tree growth. A study of effects of compaction created by just 2 passes of a skidder on Ultic Soils reported survival of *Pinus radiata* seedlings was reduced due to reduction in macropore volume and shallower depth to perched water table decreasing root oxygen supply (Simcock et al 2006). In a study of 31 trial plots spanning the range of planted forest soils in New Zealand, moderate to severe compaction arising from harvest operations was evidenced by increased bulk density and penetration resistance, and reduced total porosity, air capacity, macroporosity, and void ratio. Air capacity and macroporosity were most strongly affected, followed by penetration resistance. Soil compaction can also contribute to increases in surface erosion.

Compaction during harvesting of plantation forests can be ameliorated to at least 50 cm depth using one-off mechanical loosening between harvests. This loosening, or 'site cultivation' generally also raises the soil surface and can be designed to enhance drainage. For example, the effects of deep ripping in forest on a Pumice Soil to 80 cm depth lasted 25 years (Ross et al. 2004). Deep ripping in pine forest soils reduced soil penetration resistance and increased the stem volume of *Pinus radiata* (Sands et al. 2007), with root systems proliferating in the loosened zones. In the short term, deep ripping and bedding increased seedling survival and height (Simcock et al. 2006). Ripping may also benefit tree establishment and growth in soils that are not compacted by ground-based harvesting if 'natural' soil conditions are unfavourable, and if ripping helps control weed competition (Sands et al. 2007).

Changes in soil compaction over long periods of time have been assessed in regional council SOE soil quality monitoring. For national environmental reporting, no decreasing trend or improvement in bulk density was found for exotic forestry from 1995 to 2018, although there was a slightly negative trend for macroporosity (Stevenson & McNeill 2020). As described above, the impacts of harvesting and site preparation can vary widely across individual compartments or trees stands, making it difficult to deliver to observe trends.

Soil physical characteristics: key points related to non-grazing land use

- Arable cropping studies show large reductions in aggregate stability, saturated hydraulic conductivity, and other physical degradation due to intensive cultivation and the loss of soil carbon, especially under long-term cropping. Soil compaction in cropping systems generally reduces crop yields.
- Soil compaction in orchards and vineyards can be caused by heavy machinery under the wheel tracks. Fewer data are available for orchards.
- Soil compaction occurs when ground-based forest harvesting is conducted. Remediation responses to compaction (ripping) to prepare sites for tree establishment last for many years.

5.2 Soil quantity – erosion

The main influence on soil quantity, and specifically soil loss, is erosion. Several reviews provide information on the state of erosion and erosion control in New Zealand (Hicks & Anthony 2001, Phillips et al. 2008; Basher et al. 2016; Mackay et al. 2012; McDowell et al. 2013; Phillips et al. 2020). Permanent soil loss occurs when eroded soils move into aquatic systems, while in other cases eroded soil may be redistributed within the farm landscape. There are four main types of erosion in New Zealand.

- ***Mass-movement erosion (shallow and deep landslides, slumps, earthflows)***. This occurs when heavy rain or earthquakes cause whole slopes to slump, slip or slide. Most hill slopes steeper than 15° are susceptible to mass movement, and those steeper than 28° generally have severe potential. Rainfall is the primary trigger. This is the most common form of erosion in the hill country
- ***Surface erosion (sheet, rill and wind)***. This occurs when wind, rain or frost detach soil particles from the surface, allowing them to be washed or blown off the paddock. Surface erosion can occur on any land that is exposed to wind and rain, but it occurs largely outside the hill country.
- ***Gully or fluvial erosion***. This occurs when running water gouges shallow channels or deeper gullies into the soil. On sloping land the gullies can cut deep into the subsoil or undermine surrounding soils.
- ***Streambank erosion***. This commonly occurs when fluvial and mass movement processes occur on river banks ranging from small banks to cliffs.

Because of the dominance of hilly and mountainous terrain in New Zealand, the most widespread type of erosion is mass movement, especially rainfall-triggered shallow landslides, with many being small and often occurring in adjacent areas due to inherent instability or high landslide susceptibility (Basher 2013) (Figure 9 & 10).

Other forms of mass movement erosion (earthflows, slumps, Figures 8, & 9), and gully (Figure 11), surface (sheet, rill, wind), and streambank erosion, are locally significant (Basher 2013). Surface erosion includes splash, sheet, and rill erosion. Sheet erosion is widely distributed and typically occurs on bare ground, such as cultivated slopes, forestry cutovers, stock tracks, and earthworks. Wind erosion occurs on small areas of coastal sand dunes on both islands, and in the Volcanic Plateau in the central North Island (Basher & Painter 1997). Historically, agricultural land on the Canterbury plains was susceptible to extensive wind erosion, leading to the need for shelter belts (Hicks & Anthony 2001). More recently, conversion to irrigated pasture has reduced the susceptibility of these agricultural soils to wind erosion.

Earthflow erosion is the slow movement of soil and is most extensive in the Gisborne, Wairarapa, and southern Hawke's Bay areas. Gully erosion can be channelised or have large, mass-movement features that are often amphitheatre-shaped (Marden et al. 2012) (Figure 11).

Streambank erosion is one of the least understood erosion processes in New Zealand but is common along rivers and streams throughout the country (Smith et al. 2019) (Figure 12). In the context of primary production, stream-bank erosion may also be exacerbated by a change in hydrological regime due to the artificial draining of land (Chris Phillips, MWLR, pers. comm.).

Information on and knowledge about erosion processes and control are reasonable, but New Zealand lacks quantitative data in many regions to ensure erosion control is targeted.

Figure 8. Mass movement erosion: rotational, deep-seated landslide (slump) near Apiti, Manawatu. (Photo: Andrew Neverman, MWLR)

Figure 9. Landslide erosion in the Kai Iwi area, Manawatū-Whanganui region. (Photo: Harley Betts, MWLR)

Figure 10. Shallow landslides initiated during Cyclone Bola (1988) in Tauwharepārae, Gisborne. (Photo source: unknown. Supplied by Mike Marden, MWLR)

Figure 11. Gully erosion in Bartons Gully in the Waiapu River, near Ruatoria, Gisborne. The area is too big (90 ha) and too steep, so is untreatable. (Photo: Mike Marden, MWLR)

Figure 12. Stream bank erosion in the Hikuwai River, near Tolaga Bay, post Cyclone Gabrielle. (Photo: Mike Marden, MWLR)

5.2.1 Forestry

Afforestation is a recommended erosion control practice for shallow mass movement and gully erosion (Basher 2013), stabilising slopes and soil through tree root reinforcement, as well as reducing soil moisture (Marden 2004; Phillips et al. 2012; Phillips, Bloomberg et al. 2023). Soils influence rooting depth through features such as pans, water tables, and depth to rock. Soils also influence toppling (and support), and biomass through nutrition (Phillips, Bloomberg et al. 2023). Exotic tree species generally out-perform indigenous tree species for soil reinforcement, especially over decadal time scales (Phillips, Bloomberg et al. 2023). Closed-canopy forest reduces erosion by 90% over 20 years and reduces catchment sediment yields relative to grassland (Fahey & Marden 2000; Basher 2013).

In the 1970s and 1980s large areas of erodible, soft-rock hill country across the eastern area of North Island were converted from pasture to *Pinus radiata* forests to control erosion. Many became production forests (Phillips et al. 2020) and have been or are currently being harvested, and the erosion problems that were evident under pasture or reverting scrublands are reoccurring, particularly following harvesting (Marden 2004; Phillips et al. 2012).

The impact of soil erosion by mass movement on forest production was investigated in the Pākuratahi River catchment, near Napier. The study showed that soil erosion affects production in planted forests, with decreased soil total N, total C, total P, and soil organic matter content in the eroded plots, which had a negative impact on tree volumes (Heaphy et al. 2014). In an assessment of log quality, trees in the eroded soil were forecast to produce 16% less volume from high-quality pruned logs than trees in non-eroded areas (Heaphy et al. 2014).

Most commercial forests in New Zealand are clear-fell harvested, with areas that were forested for decades becoming bare and susceptible to erosion until the next crop reaches canopy closure (about 8 years). The period following harvesting has been termed the 'window of vulnerability', when forests are more susceptible to erosion (Phillips et al. 2024). This period of 1 to 4 years is when shallow landslides are often triggered between tree rotations, and when the impacts of events such as Cyclone Gabrielle are at their greatest (Phillips et al. 2024).

This doesn't mean that landslides will happen in every window or the number of landslides will be large (C. Phillips, MWLR, pers. comm.). The period following harvesting is critical because the maximum effect of trees on soil stability does not occur until after canopy closure, at approximately 8–10 years after planting (Marden et al. 2004). This coincides with a loss of root structure from previous rotations (Phillips et al. 2012). In general terms, sediment yield from a forest rises as a result of harvesting (with or without storms causing landslides), and this then reduces to pre-harvest levels within a couple of years (C. Phillips, MWLR, pers. comm.).

In a changing climate, with increased severe storm events there is a need to consider the relative benefits of permanent afforestation versus commercial forestry in erosion-prone land. Factors to be considered include the likelihood and frequency of erosion given the relative benefits of maintaining erosion-prone land in pastoral land uses, and the transition from existing exotic forestry to indigenous forest.

5.2.2 Hill-country pastoral land

Several studies report that the recovery of pasture production on landslide erosion scars in hill country takes many decades, and is unlikely to fully recover compared with uneroded pasture sites (Rosser & Ross 2011, and references therein). The reduced productivity relates to the removal, or burial, of the thin, more nutrient-rich topsoil layer (by both landslide and surface erosion processes), with reduced water holding-capacity of the residual soil also identified as a factor limiting subsequent pasture growth (Lambert et al 1984). This exposes soil that is more dense than topsoil, with poorer physical and chemical characteristics. Rosser and Ross (2011) found that topsoil depths on eroded sites were a third of topsoil depths on uneroded sites, with reduced profile-available water capacity on eroded soils. They also found it was unlikely total C would recover to uneroded soil levels. Maximum pasture recovery occurred within about 20 years of landsliding, and further recovery beyond 80% of uneroded pasture growth level was unlikely (Rosser & Ross 2011); this has been confirmed by other studies (Lambert et al. 1984; Douglas et al. 1986; De Rose et al. 1995). These early studies (e.g. Lambert et al. 1984) also included evaluation of different activities (e.g. fertilisation, different pasture species) to aid recovery.

A wide variety of techniques have been developed for controlling erosion, and the New Zealand literature is extensive (e.g. Douglas et al. 2009; Phillips et al. 2023). Use of wide-spaced trees, in particular poplar and willow, is a common practice for mitigating shallow landslides and gully erosion, and therefore to help maintain pasture production on uneroded slopes. Space-planted trees can reduce erosion by up to 70%, but this is dependent on an optimal spacing of c. 10–15 m (Hawley & Dymond 1988; Schwarz et al. 2016). Density of planting is an important consideration because the effect of trees on soil stability decreases with distance from the trunk. However, some regional modelling of erosion and efficacy of control practices suggests that due to a changing climate it may be difficult to sufficiently protect some hill-country pastoral areas from erosion (Vale & Smith 2023). This highlights the need to consider the relative benefits of maintaining erosion-prone land in pastoral land uses.

5.2.3 Lowland pasture, cropping, and perennial horticulture

Surface erosion processes are the most dominant form of erosion on flatter land areas, where cropping and perennial horticultural land uses and lowland pastures dominate. Studies of soil loss from intensive winter grazing of dairy cows have primarily been undertaken on poorly drained Pallic Soils in South Otago (e.g. McDowell et al. 2003; Penny et al. 2016), so other regions and soils are less well represented. Improved practices such as 'strategic grazing' of dairy cows from the top of the slope and avoiding grazing critical source areas was found to reduce soil loss considerably (Monaghan et al. 2017; MfE 2023b). Stock exclusion from riparian areas and the use of land application of effluent were suggested as being the drivers for a decreasing trend in in-stream suspended solids in five dairy-dominated catchments around New Zealand over 2001 to 2011 (Wilcock & Wright-Stow 2012; Wilcock et al. 2013).

Vegetable production can result in soil erosion (e.g. Barber 2014; Basher et al. 1997; Basher & Ross 2001). Granular Soils around Pukekohe provide about one-third of New Zealand's fresh vegetable production (Hewitt et al. 2021). One study estimated net soil loss in paddocks on Granular soils around Pukekohe to be 7–30 t/ha/yr (Basher & Ross 2002), with much higher rates of surface erosion and deposition within the paddocks (and some farmers transport the eroded soils back upslope). Granular Soils are very resilient to frequent cultivation and are inherently productive soils, with very deep topsoil meaning the loss of soil from surface erosion has less impact compared to erosion in areas with a shallow topsoil layer (Hewitt et al 2021; C. Phillips, MWLR, pers. comm.). On Allophanic Soils near Ohakune mean erosion rates were low in paddocks, but there was a wide range of erosion and deposition within the paddocks (Basher et al. 2004). The study reported that water erosion was the dominant mechanism, and no wind erosion was observed. Compacted areas in paddocks from wheel tracks and headlands are major sources of runoff and soil erosion (Phillips et al. 2020).

Finally, on the plains and downlands and in cultivated areas wind erosion can be a local problem, although the contribution of wind erosion to total soil loss, or annual sediment budget loads is tiny (C. Phillips, MWLR, pers. comm.). The most severe wind erosion occurs on small areas of coastal sand dunes and on the Volcanic Plateau in the central North Island with slight wind erosion mapped over large areas of the South Island (Basher & Painter 1997). The study by Basher & Painter (1997) was conducted prior to the significant conversions to irrigated dairy pasture that is now widespread across the South Island, reducing the risk of wind erosion. Where vegetation has been removed or soils have been cultivated, Allophanic topsoils (e.g. near Ohakune), Sandy Soils (e.g. Gley, Recent, dunes), Pallic, and Semi-arid Soils may be at risk of wind erosion (Hewitt et al. 2021).

5.2.4 Soil loss estimates

There are some estimates of the extent of soil loss via erosion from primary production land. Many studies show increases in soil loss directly associated with an increased percentage of bare ground, associated with treading damage of pastures during winter in hill country (Russell et al. 2001; Elliott & Carlson 2004; Belliss et al. 2019; Dymond & Herzig 2015). Intensive winter grazing of cropping land is also associated with large areas of bare ground and high rates of modelled soil loss (Belliss et al. 2019; Donovan 2022; North et al. 2022). For intensive winter grazing in hill country, Belliss et al. (2019) estimated 689,900 tonnes of sediment is eroded. Surface soil erosion from grazed winter forage crops in lowland and hill country is typically much greater than for pasture (McDowell et al. 2003; MfE 2023b).

Donovan (2022) provided the first national-scale soil surface erosion model based on the Revised Universal Soil Loss Equation (RUSLE), which calculates the mean annual soil erosion rates on slopes as a function of various factors (e.g. precipitation, slope, vegetation, tillage, erodibility, and erosion protection). Across a range of land uses, modelled surface erosion rates for winter forage paddocks (11 t/ha/yr) were substantially higher than for pastoral grasslands (0.83 t/ha/yr), woody grasslands (0.098 t/ha/yr), and forests (0.103 t/ha/yr). Annual and perennial cropland were combined and were estimated to have similar loss rates to pastoral grasslands, although due to their smaller area soil loss from these land uses was estimated to be <5%. In total, modelled soil losses via surface erosion across New Zealand could range between 16.5 and 29.2 Mt/yr (Donovan 2022). This compares to an estimate of 182 million tonnes of eroded soil from all erosion processes across New Zealand entering rivers in 2022 (MfE & StatsNZ 2024). This estimate used the New Zealand Empirical Erosion Model (Dymond et al. 2010).

Other models have encompassed all New Zealand erosion processes (especially shallow landslides and earth flows), with the SedNetNZ sediment budget model developed by Dymond et al. (2016) used in many regions to quantify erosion (e.g. Mueller & Dymond 2015; Vale & Smith 2023). In SedNetNZ, outputs of sediment loads (quantity) are not available for different land uses, because there are too many other factors influencing the outcome (erosion process, climate, slope, soil properties, etc.). These factors vary to such an extent that it is difficult to discuss erosion rates by land use in the absence of other detailed contextual information (H. Smith, MWLR, pers. comm.). National erosion models, including the Highly Erodible Land model and the New Zealand Empirical Erosion Model (Dymond et al. 2010), include all erosion processes.

Key points in relation to primary sector land use

- Shallow landslides in New Zealand are the most significant in terms of total soil erosion. Much hill-country pastoral land and exotic forestry are located on erosion-prone land.
- For forestry and pastoral land located on erosion-prone land, tree growth and pasture production on eroded soil can be reduced for many decades.
- Surface erosion processes are more dominant in flatter land (pastoral land and cropping land uses), and are more locally visible and significant. The highest soil losses arise from winter forage cropping.
- Information on and knowledge about erosion processes and control are reasonable, but New Zealand lacks quantitative data to ensure erosion control is targeted.

5.3 Summary of land-use impacts on the soil resource

A summary of the impacts of the different land uses on soil properties, drawing on the information provided in sections 5.1 and 5.2, is given in Table 6.

Table 6. Summary of the impacts of primary sector land use on soil properties

	Dairy	Dry-stock[a] flat–rolling	Dry-stock hill- & high-country	Arable cropping	Short-rotation horticulture	Perennial horticulture	Forestry
Soil pH	Ongoing inputs of lime are required to maintain pH within an optimal range for pastoral systems.		Due to economic constraints, lime may be minimally applied.	Ongoing inputs of lime may be required to maintain pH within an optimal range for crop species.			Lime is not applied; soil pH is more similar to pH under indigenous vegetation.
Soil carbon	Elevated C compared to other land uses. Irrigation is consistently shown to decrease soil C. Fertilisation has limited or no effect. Periodic cropping reduces soil C		Variable influence of slope, aspect and livestock movement.	Lower soil C than other land uses.		Minimal information available.	Minimal information available.
Nutrients	Ongoing inputs of major and micronutrients are required to maintain optimal yield. Excess N and P is more an issue, primarily for environmental (water quality) reasons.		Due to economic constraints, there may be minimal application, at low rates of application.	Ongoing inputs to meet crop requirements. Excess Olsen P a greater observed issue for wider environment than nutrient deficiency.		Ongoing but usually low inputs as required by most crops.	Limited fertiliser application, may only be at establishment. Deficiencies driven by climate, extent of biomass and leaf litter removal during harvest, underlying soil fertility and number of rotations.
Contaminants	Cd, with elevated Cd primarily a legacy effect. Pesticide residues associated with legacy DDT usage, Zn for facial eczema treatment, herbicide use during pasture renewal, and insecticide use for control of pasture-browsing pest species.		Minimal inputs of contaminants.	Some input of fertiliser-derived contaminants, and pesticide residues.	Wider range of pesticides applied, and therefore residues expected.	Evidence of elevated Cu in some soils.	Deficiencies of nutrients more likely than accumulation of trace elements or other contaminants.
Biology	Most information available is for exotic earthworms. Patchy distribution – more dependent on likelihood of introduction than anything else. Limited information on the state of other soil fauna and microbes.		Limited information on state; some indication of bacterial composition changes associated with land use, but it is unclear whether this impacts soil functions. Patchy information on soil fauna in all land uses.				

	Dairy	Dry-stock[a] flat–rolling	Dry-stock hill- & high-country	Arable cropping	Short-rotation horticulture	Perennial horticulture	Forestry
Physical structure	Compaction and pugging, particularly in winter forage crops, wet conditions, or grazing during irrigation.		Less compaction associated with sheep compared to cattle.	Compaction associated with use of heavy machinery for cultivation, harvesting, or spraying. Decreased aggregate stability associated with intensity and frequency of tillage and loss of organic matter.		Compaction associated with use of machinery, harvesting, or spraying.	Compaction associated with harvesting activities; relief of compaction with site preparation (cultivation, ripping, spot mounding).
Soil loss	Surface erosion loss dominant.		Shallow landslide loss dominant.	Surface erosion loss dominant.			Shallow landslide loss dominant.

[a] A wider range in the intensity of land use may be observed on flat-rolling hill used for beef cattle and sheep grazing on flat-rolling as compared to that used for grazing dairy cows, including wintering dairy cows.

6 Implications of the impact of each key primary sector land use on the productive capacity of New Zealand soils

The preceding section discusses the impact of various land management activities on specific soil properties, with section 5.3 providing a summary of these changes in relation to different land uses. However, while land uses and land management activities may result in changed soil properties, these changes are infrequently evaluated in the context of the significance of these changes.

In the context of the productive capacity of soils, this can be judged directly by the yield (and quality) associated with the crop being grown and/or the resources (water, fertiliser) that may be required to attain this or an improved yield. A further consideration in the context of changes in soil properties, and their subsequent impact, is the extent to which the observed changes are *reversible*.

Finally, as discussed in section 4.1, there is a tension between the classic description of land uses and the alignment of those activities with industry sectors. Notably, the full impacts of the dairy sector are a combination of the impacts associated with dairy land use, plus that of dairy support – which may comprise cropping land used for supplementary feed, or grazing of non-lactating dry stock off the dairy farm.

6.1 Reversibility of changes in soil properties

6.1.1 Soil quality changes

Soil pH and nutrient changes are fundamentally reversible through the adjustment of lime and fertiliser applications to change soil pH and nutrient concentrations. Soil pH is usually increased, reducing pH is a slow and/or more difficult process. However, the accumulation of trace elements is, arguably, essentially irreversible. This is the case even for essential elements such as Cu and Zn, which can slowly be used by plants and soil organisms, as the rate of input is generally greater than the rate of uptake.

Cadmium is arguably the most significant trace element due to the potential for non-compliance of food crops with food standards. This is a well-known issue that is not necessarily related to the accumulation of Cd associated with ongoing inputs, but rather to the combined influence of crop species, cultivar, soil type, state (e.g. pH, soil Cd concentrations) and management activities. The management of this issue is dependent on an understanding of the associated risks in relation to soil and food crops. There is evidence of markedly elevated Cu and Zn concentrations in some soils, although the broader significance of this for an individual sector is unknown.

The impacts and magnitude of pesticide residues and microplastic contamination in New Zealand primary production soils are largely unknown, as is the reversibility of these issues.

Soil C loss is theoretically reversible, either through direct inputs of organic materials or plant growth increasing soil C. However, in practice it is much harder to gain C due to the complex nature of interactions that influence the amount of C that is sequestered over the longer term versus decomposed to provide nutrients. Further, different soil types have different levels at which the soil C becomes 'saturated'. For example, Allophanic Soils tend to have the highest absolute amounts of C. The amount that can be sequestered by a soil also depends on its starting point, with cropping soils, which typically have lower soil C, typically being able to sequester the greatest relative amount. Allophanic and Gley soils have high C saturation deficits, but their potential to sequester C nationally is limited by the areal coverage of these soils (McNally et al. 2017). Further, the depth to which C is sequestered is also relevant and is enabled by deep-rooted species.

Soil compaction is to some extent reversible, especially for shallow soil depths, but this depends on ongoing farm and grazing management, and is much more difficult to reverse when compaction extends to the depth of the topsoil (Greenwood et al. 1998; Drewry et al. 2004a). Several agricultural and forestry studies indicate long-term impacts from soil compaction, which is backed up by many soil quality monitoring studies. Natural amelioration, such as cracking and biological activity (i.e. worms, roots), may ameliorate compaction given sufficient time (months), but rejuvenation typically only occurs at shallow depths (Drewry et al. 2004a).

As an example of compaction and recovery cycles, rejuvenation of compacted soil on a Southland dairy farm over 3 years showing compaction occurring in spring, with some recovery during summer and winter periods (Drewry, Paton, et al. 2004). Management practices such as mechanical aeration for alleviating compaction at deeper depths may be required (Laurenson & Houlbrooke 2014; Laurenson et al. 2015).

Compaction issues are particularly prevalent on Pallic, Ultic and Gley Soils. In forestry, compaction associated with ground-based harvesting can be mitigated between harvests using deep cultivation (ripping, spot mounding) to at least 50 cm depth, with naturally compacted soil horizons also remediated to improve plantation establishment, growth, and resistance to toppling. Whole compartments may be treated where soils are vulnerable to compaction (e.g. Ultic Soils, Podzols) or cultivation may be restricted to the most physically compromised areas (e.g. skid sites and main tracks in Pumice Soils).

Subsidence associated with draining and cultivation of Organic Soils is essentially irreversible (without rewetting of soils) and at the extreme end can lead to the retirement of land from agricultural production activities. This issue of subsidence with Organic soils also highlights the changes caused by drainage of land for agricultural purposes.

There is insufficient knowledge to gauge the extent of reversibility of changes in soil biology, and requirements for maintaining soil functions. Some studies suggest there is a legacy effect arising from changes (i.e. permanent changes in composition and abundance). Native species that require deep, stable, moist leaf litter layers and coarse wood are absent from cultivated areas and pasture but may be found in plantation forests. Non-native earthworms dominate pasture ecosystems while native species dominate native forests (Schon et al 2017); reversibility has not been demonstrated.

6.1.2 Soil loss

Soil loss is essentially irreversible when eroded soil is delivered to waterways, as soil formation and replacement is a very slow geological process. Some eroded soil may be redistributed within the agricultural landscape and therefore is not lost. However, as discussed in section 4.3.2, pasture yield and tree growth on eroded soils in hill country may never return to the levels achieved on uneroded soil.

There is considerable guidance available on land management practices that can minimise or avoid soil loss on flat to gently sloping land through surface erosion processes. It is largely a matter of those practices being implemented.

Similarly, there is guidance on and awareness of various techniques that can mitigate erosion, including shallow landslides, in hill country (e.g. Phillips et al. 2020). However, with an increasing frequency of severe weather events, and thus increasing likelihood of erosion events in these erosion-prone areas, soil loss through shallow landslides on hill-country pastoral land may only be avoided by removing this erosion-prone land from pastoral production.

Afforestation is one method that can be used to reduce the susceptibility of the land to erosion. Whether this land, and other erosion-prone land is used for commercial forestry which provides some level of resistance to erosion while forested), or retired to permanent forests, depends on a number of factors. These factors include the susceptibility of that land to erosion, the likelihood, severity, and extent of erosion following harvest and early plantation growth, and the social and economic benefits associated with pastoral or forestry production. Under a changed climate with an increasing frequency of severe weather events, this is an increasingly urgent conversation for affected communities to be having.

Under changed climate conditions, changed hydrological processes associated with artificially drainage can also change erosion processes e.g. drainage can result in faster removal of water from the landscape resulting in faster stream flows leading to stream bank erosion.

6.2 Impacts of primary sector land use on the productive capacity of New Zealand soils

As highlighted above, there is a distinction between changes in soil properties associated with land management activities and the impact of those observed changes on the productive capacity of soils. Although numerous studies identify changes in various soil properties, often associated with different land uses, the significance of those changes, particularly in relation to productive capacity, is rarely identified.

This is particularly evident for studies on soil C. While there is a considerable focus on understanding the influence of different land management practices on soil C stocks or content, and general recognition of the importance of soil C (or, more correctly, organic matter) on nutrient cycling, soil structure, and soil water storage, there are few studies that attempt to quantify the significance of any changes (with the exception on climate change and greenhouse gas inventories). This is particularly evident for cropping soils, despite the recognised low C content of these soils.

Sparling et al. (2006) arguably provide the best attempt at doing this by monetising the value of organic matter based on modelling pasture yield in terms of C loss and the associated impact on productive capacity. Similarly, Dodd et al. (undated) used modelling to assess the impact of increases in organic matter on the yield of wheat, and also used pedotransfer models to relate changes in organic matter content to soil physical properties. Finally, there is a tension between whether the desired outcome of management is C sequestration or decomposition of organic matter to release nutrients. This point is emphasised by Moinet et al. (2021), who argue for a shift away from a sole focus on C sequestration and climate-smart soils, to soil-smart agriculture, whereby multiple soil functions are quantified concurrently.

Thus, for soil C, while there is some knowledge about different land management practices that lead to changes in C, it is not possible to say whether these changes are significant enough to have an impact on the productive capacity of the soil. It is also important to note that potential yield decreases due to loss of organic matter may be masked by fertiliser use, and any potential yield impacts from reduced water-holding capacity may be masked by use of irrigation. In relation to specific primary sector land uses, lower soil C content and stocks are typically associated with cropping (arable and horticultural), and higher C content and stock with pastoral land uses.

For pH and nutrients, there is well-established guidance on pasture and crop needs, and on soil and foliage testing, which may be used to fine-tune requirements to optimise yield and quality. This is typically achieved through the addition of lime (to raise pH, or, rarely, sulphur to reduce pH), mineral fertilisers or organic materials. Crop rotations and cover crops are another means to provide soil nutrients. Nutrients may also be elevated through the application of waste products (e.g. animal excreta, effluent, wastewater) to land.

Significant knowledge has been gained over many decades to increase the productive capacity of New Zealand soils through use of lime and fertiliser, particularly many studies associated with soil nutrient concentrations and plant yield relationships. Similarly, research has also shown that irrigation significantly increases the productive capacity of soils, particularly those on the dry east coast. Drainage of soils has also contributed greatly to improving productive capacity of soils.

Insufficient nutrients can constrain productivity, while there is rarely a production 'penalty' associated with excess nutrients. There may, however, be an economic penalty associated with excess fertiliser application, and/or a regulatory penalty when excess nutrients (and soil) move into waterways. Excess nutrients are primarily associated with intensive pastoral use, and occasionally horticultural cropping; less so arable cropping and perennial horticulture. Our experience with farmers and growers is that some are more attuned to the resources (fertiliser and water) required to provide optimal yields and to minimise impacts on the soil resource (and the surrounding environment) than others. For hill- and high-country pastoral farming, the economic cost of lime and fertiliser application can be such that no or minimal amounts are applied, which constrains the growth of exotic pasture species.

In contrast to agricultural production, fertiliser application is not routine in forestry operations. Thus, there has been a reliance on the existing soil nutrient pool, with the main attention placed on addressing deficiencies rather than enhancing productivity. Low nutrient pools, and biomass and forest-floor removal at harvest, can lead to nutrient deficiencies in soil following harvest. This issue is particularly pertinent for early-planted forests (forests planted before 1960), which were typically planted in low-fertility soils. Conversely, there have been observed productivity gains converting pastoral land to forestry, arising from legacy nutrients present in the soil. Recent research has also suggested that inorganic fertilisers are not as effective as retained organic matter in providing nutrients for subsequent harvests.

Decreased pasture yields are evident from short-term studies on compaction and pugging, but the extent to which natural recovery or routine management (e.g. cultivation during pasture renewal or sowing of forage crops) redresses this decreased yield in the longer term is unclear. Optimal soil physical condition varies with crop and soil, and Pallic, Gley, Ultic, and Organic soils are most susceptible to compaction and pugging issues. Compaction tends to reduce crop yield more in years with average or above-average rainfall, but it may also increase yields in dry seasons – but this is less clear for pastures.

Trace element contaminant accumulation, primarily Cu in perennial horticulture and Zn in pastoral systems, is arguably the greatest threat to the future productive capacity of soils. Accumulation of trace elements is essentially irreversible, even though Cu and Zn are also essential elements required by plants and animals for growth. At elevated concentrations trace elements can have an impact on yield or quality, and on soil function, including reducing the ability of microbial populations to degrade pesticide residues. While higher concentrations of Cd are observed in some land used for dairying, the concentrations found don’t pose an issue in relation to the productive capacity of the soil. However, ongoing vigilance is required in relation to the management of uptake of Cd in soils by food crops to ensure compliance with food standards, particularly when food crops are exported. For both Cu and Cd, there are primary sector programmes in place to help manage accumulation and associated risks of the contaminant impacts.

A summary of the state of knowledge associated with the different key impacts and qualitative assessment of the amount and robustness of evidence associated with influence of productive capacity is provided in Table 7. This table addresses those impacts that can’t easily be mitigated; for example, pH and nutrient issues can be remedied with lime or fertilisers and so are not considered here. Conversely, given the general lack of information about soil biota and nature of change across different land use, soil biota are also not included in Table 7.

Table 7. Qualitative uncertainty assessment of the character and magnitude of key primary sector impacts on the productive capacity of soils[a]

Industry sector	Character of impact	Assessment of character (evidence and agreement)	Magnitude of impact	Assessment of magnitude (evidence and agreement)	Narrative assessment
Dairy[b]	Trace element accumulation and productivity (pasture growth, nutrient cycling, soil biology).	Medium evidence and medium agreement on accumulation.	None observed.	Limited evidence and high agreement.	Zn: there can be elevations in soil concentrations, but they are not at a point of concern. Cd: the highest concentrations occur under dairy pasture with a long history of fertiliser application; no impact on productive capacity.
	Pesticide residues.	Limited evidence and medium agreement on the presence of residues.	Unknown.	No studies.	No studies.
	Soil structural impacts on pasture production	Robust evidence and high agreement for soil structure impacts (compaction and pugging).	Short-term impacts (2–3 seasons) on pasture growth from pugging (high magnitude). Compaction affects pasture in the longer term (lower magnitude but over a longer period).	Robust evidence and high agreement for pugging impacts on pasture yield. Limited evidence and medium agreement for compaction on yield.	Compaction affects primary production by changing soil structure, restricting roots and tillering, reducing available water capacity, nutrient access, and consequently reducing pasture yield.
	Compaction in soil >15 cm depth	Medium evidence and medium agreement for deeper soil structure degradation (compaction and pugging).	Limited evidence for impacts on pasture production.	Limited evidence and medium agreement.	Many studies do not measure soil depths >15 cm.

Industry sector	Character of impact	Assessment of character (evidence and agreement)	Magnitude of impact	Assessment of magnitude (evidence and agreement)	Narrative assessment
Dairy[b] (cont.)	Soil carbon loss.[c]	Robust evidence and medium agreement on loss of soil C from irrigation. Medium evidence and low agreement on loss of soil C under pasture. Medium evidence and medium agreement on loss of soil C under pasture renewal and periodic cropping.	Unknown.[c]		
Meat, fibre, breeding[d]	Trace element accumulation and productivity (pasture growth, nutrient cycling).	Medium evidence and medium agreement on accumulation.	None observed.	Limited evidence and high agreement.	Zn: some elevation in soil concentrations, but generally not at a point of concern for productive capacity. Cd: present in some soils at elevated concentrations, but not at point of concern for productive capacity.
	Erosion soil loss (hill- and high-country, specifically).	Robust evidence and high agreement for occurrence of erosion.	Evidence of reduced yield on eroded soils: 80% of uneroded soil.	Limited evidence and high agreement.	Erosion reduces pasture yield and productivity.
	Soil C loss.[c]	For more intensive land use, refer to 'Dairy'. For hill- and high-country, medium evidence and low agreement of soil C loss (highly variable).	Unknown.[c]		

Industry sector	Character of impact	Assessment of character (evidence and agreement)	Magnitude of impact	Assessment of magnitude (evidence and agreement)	Narrative assessment
Arable cropping	Trace element accumulation and productivity (yield, compliance with food standards).	Medium evidence and medium agreement on accumulation.	Some food crops at or near food standards (Cd).	Medium evidence and high agreement.	Cd in soils can result in non-compliance with food standards if not properly managed.
	Soil structure impacts on productivity (yield).	Robust evidence and high agreement on structural degradation (compaction, aggregate stability).	Compaction often reduces yield, although magnitude is unclear.	Medium evidence and high agreement.	Soil structural impacts reduce yield.
	Soil C loss.[c]	Robust evidence and high agreement on loss of soil C (combined tillage, biomass removal, fallow periods); high agreement on low soil C.	Unknown.[c]	Limited evidence.	
	Pesticide residues.	Limited evidence and high agreement on the presence of pesticide residues.	Unknown.		
Horticulture – short-rotation	Trace element accumulation and productivity (yield, compliance with food standards)	Limited evidence and medium agreement on accumulation.	Some food crops at or near food standards (Cd).	High agreement and medium evidence.	Plant uptake of Cd in soils in food crops requires management to ensure compliance with food standards.
	Soil structure impacts on productivity (yield).	Strong evidence and high agreement on soil structure impacts (compaction).	Medium evidence, high agreement on impacts on soil structure.	Limited evidence and medium agreement.	
	Soil C loss.[c]	Robust evidence and high agreement on loss of soil C (combined tillage, biomass removal, fallow periods); high agreement on low soil C.	Unknown.[c]	Limited evidence.	
	Pesticide residues	Limited evidence and high agreement on the presence of pesticide residues.	Unknown.	No studies.	

Industry sector	Character of impact	Assessment of character (evidence and agreement)	Magnitude of impact	Assessment of magnitude (evidence and agreement)	Narrative assessment
Horticulture – perennial	Trace element accumulation and productivity (pasture growth, nutrient cycling).	Medium evidence and high agreement on accumulation (Cu).	Medium agreement on magnitude.	Medium agreement and medium evidence.	Cu: has accumulated to concentrations that may cause negative impacts in some areas.
	Soil structure impacts on productivity (yield).	Limited evidence and medium agreement on soil structure impacts (compaction, vehicle tracks).	Unknown.		
	Pesticide residues.	Limited evidence and high agreement on the presence of pesticide residues.	Unknown.		
	Soil carbon loss.[c]	No information found.			
Forestry	Erosion impacts on productivity.	Robust evidence and high agreement of erosion in steepland forests.	Evidence of reduced yield on eroded soils: 80% of uneroded soil.	Limited evidence and high agreement.	Forestry is often located in erosion-prone areas.
	Soil carbon loss.[c]	No studies found, but recognition of biomass and leaf litter removal during harvesting.			

[a] This table addresses those impacts that can't easily be mitigated; for example, pH and nutrient issues can be remedied with lime or fertilisers and so are not considered here.

[b] Dairy sector includes non-milking dairy stock.

[c] There are many studies on soil C loss, and the relative magnitude of this loss but no studies on the significance, i.e. the impact, of this loss on the productive capacity of soils were found. Knowledge of the impact associated with loss or low soil C content, is understood from general understanding of the role of organic matter in soils, rather than quantitative assessment.

[d]Meat, fibre, breeding includes all other non-milking stock.

6.3 Knowledge gaps and next steps

6.3.1 Knowledge gaps

The key knowledge gaps that arise from our assessment are:

1. quantitative assessments of the impact of changes in various soil properties, notably soil C (and its impacts on nutrient provision and cycling, soil biology, water-holding capacity, soil porosity/aggregate stability, and crop or pasture yield) and compaction (and its impacts on infiltration and yield) (all land uses)
2. knowledge of the distribution and role of microbes and soil invertebrates in primary production soils, and their relationship to the productive capacity of soils for all land uses
3. the efficacy of management activities for addressing issues; in particular, reduced pasture or crop yield associated with pugging and compaction (pastoral land uses, cropping land uses)
4. better understanding of the extent to which land management practices that prevent or mitigate known impacts are being adopted across New Zealand (predominantly agricultural land-uses)
5. methods and approaches for supporting decision-making on retiring land from primary production where current land use is not sustainable (e.g. erosion prone pastoral and forestry land and drained Organic Soils)
6. the extent and impacts of Cu and Zn accumulation (agricultural land uses)
7. the extent and impacts of pesticides residues and microplastics in agricultural soils.

We consider that existing knowledge is adequate, and systems are largely in place, to manage pH and nutrients in the context of productive capacity. For example, there is ongoing research and extension to manage nutrients for production in forestry, and there is considerable guidance available for agricultural production. Arguably there is a gap in demonstrating the absence of yield reductions by withholding phosphate fertiliser application where Olsen P is elevated, and assessing the time it takes for these elevated concentrations to reduce to agronomically optimal levels. This is more limited knowledge on micronutrient concentration in soil, and in food and forage crops, in relation to yield and nutritional quality.

6.3.2 Addressing the knowledge gaps

Knowledge gap 1

The limited number of studies that provide an assessment of the significance of changes (i.e. impact) in soil properties was a surprise to us. The current project was constrained in time and budget so we may have missed some studies. This limitation will be addressed, to some extent, in a recently commenced Ministry for the Environment-funded project on 'Revising soil quality target value ranges', which is focused on eight soil quality indicators (pH, total C, total N, anaerobically mineralisable N, Olsen P, macroporosity, bulk density, and hot-water extractable carbon). This project will undertake a more in-depth review of the studies and data available to link 'target' values with outcomes, with the greatest focus being on environmental outcomes (e.g. soil biodiversity, water quality). Nonetheless, we consider it likely the identified knowledge gap is real.

This knowledge gap fundamentally requires additional research. In some instances this might be achieved by including additional measures in existing research (e.g. the collection of water-holding capacity alongside studies on C content, and the collection of infiltration data in studies on compaction). In other cases, more specific research programmes might be appropriate. We highlight, in particular, the need to connect research to building a greater understanding of the multifunctionality of soils. This is particularly so for organic matter and soil C, including the provision of nutrients from organic matter decomposition and the extent to which it can feasibly be used to offset, or be better than, inorganic nutrient addition. The ongoing subsidence and loss of C from drained Organic Soils also requires further research to test approaches to slow or stop these losses.

Knowledge gap 2

There is a dearth of knowledge on the distribution and role of soil invertebrates, other than for pest species, in the functioning of New Zealand agricultural soils, and limited knowledge on the role of bacteria and fungi. Yet, as shown in Table 8, they can have many roles to support the functioning of soils. An across-the-board increase in studies to provide base-level understanding is required. These studies should explicitly include measures of soil function alongside compositional information.

Table 8. Essential functions performed by different soil organisms

Function	Organisms involved
Maintenance of soil structure	Bioturbating invertebrates and plant roots, mycorrhizae, and some other microorganisms
Regulation of soil hydrological processes	Most bioturbating invertebrates and plant roots
Gas exchange and C sequestration (accumulation in soil)	Mostly microorganisms and plant roots; some C is protected in large, compact, biogenic invertebrate aggregates
Soil detoxification	Mostly microorganisms
Nutrient cycling	Mostly microorganisms and plant roots; some soil- and litter-feeding invertebrates
Decomposition of organic matter	Various saprophytic and litter-feeding invertebrates (detritivores), fungi, bacteria, actinomycetes, and other microorganisms
Suppression of pests, parasites and diseases	Plants, mycorrhizae and other fungi, nematodes, bacteria and various other microorganisms, collembola, earthworms, various predators
Sources of food and medicines	Plant roots, various insects (crickets, beetle larvae, ants, termites), earthworms, vertebrates, microorganisms and their by-products
Symbiotic and asymbiotic relationships with plants and their roots	Rhizobia, mycorrhizae, actinomycetes, diazotrophic bacteria and various other rhizosphere micro-organisms, ants

Function	Organisms involved
Plant growth control (positive and negative)	Direct effects: plant roots, rhizobia, mycorrhizae, actinomycetes, pathogens, phytoparasitic nematodes, rhizophagous insects, plant-growth promoting rhizosphere micro-organisms, biocontrol agents Indirect effects: most soil biota

Source: Bot & Benites 2005.

Knowledge gap 3

We note that many studies on pugging associated with winter grazing of forage crops have been undertaken on Pallic Soils in Otago, presumably because wintering on forage crops is common in the southern South Island and this is where effects have been most visible. An evaluation of the extent to which pugging and compaction occur on other soil orders, the significance of this on pasture yield (and also sediment and nutrient loss), and the efficacy and adoption of mitigation strategies is required. Gley, Ultic, and Organic Soils, would be expected to be similarly susceptible to pugging and compaction issues. Some insight into the efficacy of mitigation strategies, and the longer-term effect of soil compaction, could be obtained by simply documenting what activities have or haven't occurred at study sites over the course of any current research, and by extending the duration of the study and/or revisiting previously studied sites. This is relevant for pastoral and cropping land uses.

Knowledge gap 4

This knowledge gap fundamentally relates to obtaining more detailed information on the management practices being used by farmers and growers at a scale that is useful to be able to meaningfully be able to scale-up the impacts of different land management practices across regions, sectors or nationally. This could be through surveys such as the Survey of Rural Decision Makers, or related research. Addressing this knowledge gap effectively i.e. to be able to relate information on the management practices used with efficacy of mitigation, or improved state, requires the knowledge gained through addressing knowledge gap 2. (We acknowledge that more detailed information on farm management practices can be challenging to obtain.)

Knowledge gap 5

Suggestions on the way forward for this knowledge gap are largely outside the authors' expertise. Instead, we aimed to highlight the broader current context of the productive capacity of soils associated with forestry and pastoral farming in erosion-prone hill country and drained Organic Soils. This former issue is sharply in focus for the forestry sector following the recent governmental Ministerial Inquiry into land uses associated with the mobilisation of woody debris (including woody residues left after harvesting operations) and sediment in the Gisborne and Wairoa districts (MfE 2023d). As noted by Phillips et al. 2024 in their introductory statements, knowledge such as how to determine when a steepland forest is most susceptible to rainfall-induced landslides (together with other information) would both inform both forestry operations in these locations, and enable forestry companies and regional councils to improve their ability to manage such hazards and future risk to downstream communities. Research is required to test land management approaches to (i) reduce loses under current land use, (ii) explore alternative wet productive land uses, (iii) and retirement and restoration to stop losses (linked to knowledge gap 4).

Knowledge gap 6

In the first instance, addressing this knowledge gap simply involves undertaking a greater level of surveillance of Cu and Zn concentrations in key land uses (perennial horticulture, pastoral land use susceptible to facial eczema). Currently, regional council SOE soil quality monitoring appears to be the primary means for assessment of soil concentrations. It may be that some industry programmes for soil testing already exist, and we note that the Fertiliser Association of New Zealand has a formal arrangement to receive sub-samples from the National Soil Carbon Monitoring programme for the analysis of some basic soil properties and certain trace elements, including Cu and Zn. This will be a useful data set if it becomes available.

Knowledge gap 7

There is also a dearth of knowledge on the extent and impact of pesticide residues and microplastics in New Zealand agricultural soils. However, for pesticide residues in particular, it is debateable as to how simply knowing more about the concentrations present is useful, particularly when there can be broad range of pesticides and metabolites present. There is also arguably an equal, if not greater need to identify whether there are any negative effects associated with residue concentrations that could inform whether some greater level of intervention is required.

One alternative approach, which could be adopted alongside campaigns to promote the minimisation of pesticide use, is to assess the degradative potential of the soil, given that bacteria and fungi are the key organisms that can degrade pesticide residues (see Table 8). Research is required both to develop an appropriate approach to assessing degradative potential and to undertake the assessment. This approach is less dependent on knowing how much pesticide is there, and affords insight into the potential for ongoing degradation of the residues.

If knowing more about concentrations present is useful, targeted sampling – based on knowledge of usage patterns and an understanding of the potential toxicity and persistence of key ingredients – across agricultural production in New Zealand would be the most useful approach. Chemical analysis could be undertaken, which would provide an understanding of the concentrations present, and/or a range of biological tests could be undertaken to assess potential effects. This approach would be most useful if biological response is considered alongside that of changes associated with gross soil properties (i.e. pH, organic matter content) to isolate the effects associated with chemical residues.

7 Conclusions

We found that there are numerous studies that identify changes in a wide range of soil properties often associated with different land uses, but the significance and impact of those changes in relation to productive capacity of soil are rarely identified and quantified.

In relation to soil impacts on the future productive capacity of the dairy industry, soil pugging and compaction affect pasture yield although the reversibility of this impact is unclear. For hill-country pastoral land used for meat and fibre production, and for exotic forestry located in erosion-prone areas, landslides contribute most to soil erosion and in these areas productivity on eroded soil can be reduced for decades. For arable cropping and short-rotation horticulture, plant uptake of Cd in soils requires management to ensure compliance with food standards, while decline in soil structure associated with cultivation and/or compaction by heavy machinery may affect crop yield. Although there is agreement about the loss of soil C under some aspects of dairying operations, and low soil C present in cropping soils, the magnitude, and type of impact on productive capacity are largely unknown. Copper has accumulated in some perennial horticultural soils, and occasionally to soil concentrations that may cause negative impacts to productive capacity. The accumulation of trace elements is largely irreversible, including for essential elements when input exceed uptake.

For pH and nutrients (primarily major nutrients, N, P K, S), there is considerable knowledge about requirements for production and we consider that existing knowledge is adequate, and systems are largely in place, to manage pH and nutrients in the context of productive capacity for most land uses; hill country pastoral land and some forestry land may be nutrient limited. There is more limited knowledge about micronutrients in the context of productive capacity, particularly with respect to the nutrient content of food products.

There is largely a dearth of knowledge around the distribution and role of soil fauna on productive capacity of soils used for primary production land uses. There is a dearth of knowledge about the extent and impact of pesticide residues and other contaminants, including microplastics.

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Appendix 1 – Soil order description

Description of the characteristics of all soil orders, and assessment of the suitability or unsuitability of those orders for primary production.

Table A1. Summary of the characteristics of different soil orders, and generalised suitability/unsuitability for primary industries

Soil order	Characteristics	Suitability for primary industries
Allophanic (5% of New Zealand)	Low BD, high macroporosity, weak ped strength, topsoils resistant to compaction when wet, low penetration resistance, high P retention, low natural fertility, A horizons contain large populations of soil organisms, usually well drained with high permeability.	Highly productive soils for many primary industries. Physical properties appropriate for supporting plant growth. Wheel trafficking and handling should be minimised, and rejuvenated through cultivation, to retain permeability. High water-holding capacity. Natural drainage is predominantly moderately (32%) to well drained (66%).
Brown (43% of New Zealand)	Well-developed structure, moderate-high bulk density, moderate-high water-holding capacity, low-moderate natural base saturation, large populations of soil organisms.	Highly productive soils for many primary industries. Favourable topsoil structure and good physical properties. Moderate phosphate retention. Often requires fertiliser P for agricultural production. Natural drainage is predominantly moderately well drained (43%) to well drained (40%).
Gley (3% of New Zealand)	Chemically reduced, affected by waterlogging, anaerobic conditions restrict soil organisms, shallow potential rooting depth, high BD, high OM, high subsoil CEC, low-med P retention.	Formed where soils are saturated for long periods. Where drainage is installed they can be highly productive for pastoral and cropping. Trafficability limited when wet. Generally fertile. Natural drainage is predominantly poorly drained
Granular (1% of New Zealand)	Dominated by clay minerals, high penetration resistance – limited rooting depth, moderately permeable, well-developed fine structure, friable, low plasticity, low nutrient reserves, low P and SO_4^{2-} in B horizons.	Important for vegetable production. Highly productive, limited workability and trafficability when wet, resistant to degradation by ploughing. Naturally low reserves of nutrients such as P, K, Mg. Wheel trafficking should be minimised and rejuvenated through cultivation, to retain permeability. Natural drainage is predominantly imperfectly drained (36%), moderately well drained (47%) to well drained (17%).
Melanic (1% of New Zealand)	Naturally fertile, biologically active, high BS, exchangeable Ca, Mg, and CEC, high OM content, stable topsoil, clay fraction dominated by smectite – soil shrinks on drying and swells on wetting, sticky and plastic, sensitive to water content.	Resistant to structural degradation (e.g. from continuous cultivation), versatile and sought after for grape and truffle production.
Organic (1% of New Zealand)	Very low BD, low bearing strength, high shrinkage when dried, very low thermal conductivity, high available-water capacity, high CEC, acidic, common nutrient deficiencies, high C:N ratios, soil organisms restricted by anaerobic conditions.	Drainage and high inputs of lime and fertiliser applied to establish productive farming. Suitable for effluent irrigation when not saturated. Prone to subsidence. Cultivation greatly increases the rate of shrinkage and biodegradation. High fire risk. Natural drainage is very poorly drained.

Soil order	Characteristics	Suitability for primary industries
Oxidic (<1% of New Zealand)	Limited rooting depth, moderate-rapid infiltration rates, soil water deficits common in summer, clay content 50–90%, low CEC (at natural pH), high P retention, friable, low plasticity, fine stable structure, low K, Mg, Ca and P reserves, acidic	Challenging soil for plant growth without amendments. Sheet erosion risk without vegetation cover, rill and gully erosion risk when topsoil is removed.
Pallic (12% of New Zealand)	Weak structure, med-high BD, slow permeability, limited rooting depth, high BS, low OM, med-high nutrient content (except S), low P retention, biological activity and plant root growth often limited by anaerobic conditions in winter, often high silt content.	Some have deep-rooting potential, with high available water capacity to support plants. Highly versatile and may support a range of productive uses. High potential for erosion due to slaking and dispersion. Susceptible to gully erosion. Lower North Island areas particularly prone to landslide erosion. Can be unsuitable for wastewater application. Natural drainage is a mix of poorly drained (20%), imperfectly drained (34%), moderately well drained (17%), and well drained (29%).
Podzol (13% of New Zealand)	B and E horizons, cemented/compacted B horizon, slow permeability, limited rooting depth, low fertility, low BS, strongly acidic, low biological activity.	Limited nutrient availability and Al toxicity to plants is common without lime. Fertilisers and ripping generally required for agricultural production.
Pumice (7% of New Zealand)	Sandy/gravelly, earthy to single grain, rapid drainage, clay content <10% and dominated by allophane, imogolite, ferrihydrite, weak ped strength, sensitive, low BD, high macroporosity, deep rooting depth, low major nutrient and race element reserves, medium P retention, low soil macroinvertebrate populations.	Low nutrient and trace element reserves mean additions are required for most production. Potential for erosion in pasture, and susceptible to gully erosion, particularly when soil is left exposed. Resistant to light compaction. Natural drainage is predominantly moderately well drained (29%) to well drained (70%).
Raw (3% of New Zealand)	Very young soils. No distinct topsoil, no B horizon, may be very fluid with high water-table, lack OM, N.	Greenspace: Sandy Raw topsoils are susceptible to erosion. Fertility limited by lack of OM and N, generally not suitable for food production. Some invasive weeds will readily establish on Raw Soils and need to be managed. Geotech: Fluid Gley Raw Soils may be drained and reclaimed for agricultural use, though there is a risk they will form acid sulphate soils. Gley Raw Soils have very low bearing strength and are not suitable for heavy traffic.
Recent (6% of New Zealand)	Weakly developed, spatially variable, absent or weakly expressed B horizon, deep rooting, high plant-available water capacity, variable texture, high natural fertility, high BS, low P retention.	Productive and versatile soils. Risk of wind erosion on Sandy Recent Soils – particularly with ploughing and vegetation removal.

Soil order	Characteristics	Suitability for primary industries
Semi-arid (1% of New Zealand)	Dry for most of the growing season, lime and salt accumulation in lower subsoil, high nutrient levels, high slaking and dispersion potential, moderate-high BD, weakly developed structure, low P retention, low OM, low CEC, weakly buffered, low biological activity.	Solonetzic Semi-arid Soils are an endangered habitat to specialist native plants adapted to grow on these soils (e.g., *Lepidium kirkii*). Topsoil structure degraded with heavy machinery and tillage, particularly when wet. Erodible, high slaking and dispersion potential. Require irrigation for crop production, though flood irrigation leads to bypass flow.
Ultic (3% of New Zealand)	Clayey subsoil (includes swelling clays), low permeability, dispersible surface horizons, strongly acidic, low nutrient reserves, biological active topsoil.	Slow permeability, low soil fertility, and low water-holding capacity, along with winter wetness and summer drought, means the soils are usually challenging to use productively. Drainage and physical properties are highly spatially variable. Impermeable when compacted meaning perched water tables can form on compacted subsoil and run-off can occur. Not suited to wastewater discharge. Failure can occur on slopes of 15–20°. Slopes are prone to earthflows and landslides. Topsoils are susceptible to livestock treading damage and erosion, especially when left bare. Natural drainage is predominantly imperfectly drained (79%).

BD – bulk density; BS – base saturation; CEC – cation exchange capacity; OM – organic matter.

Source: Adapted from Cavanagh, Harmsworth et al. (2023) and includes information from Hewitt 2010, Hewitt et al. 2021, McLaren & Cameron 1996, Molloy 1993, and Simcock 2009.

Appendix 2 – Soil order drainage classes per soil order

Table A2. Drainage class area (km^2) per soil order for the five natural drainage classifications available from FSL and S-map.

Soil order	Well drained	Moderately well drained	Imperfectly drained	Poorly drained	Very poorly drained	Total area (km^2)
Anthropic	40	105	0			**146**
Brown	41768	44821	17455	829		**104875**
Melanic	1338	1272	595	248		**3452**
Gley	0	0	1	9521	525	**10047**
Allophanic	12019	5739	239	179		**18176**
Pumice	11285	4702	84	24	0	**16096**
Granular	489	1349	1035	15		**2888**
Organic				34	2140	**2174**
Pallic	7358	4384	8596	5141	25	**25504**
Recent	15659	8252	3120	4		**27036**
Semiarid	1033	855	185			**2072**
Ultic	157	1331	5937	52		**7476**
Raw	1831	2149	8	50	42	**4081**
Oxidic	126	303	40			**469**
Podzol	11350	12069	2527	1691	553	**28189**
Total area	**104454**	**87333**	**39820**	**17790**	**3285**	**252682**