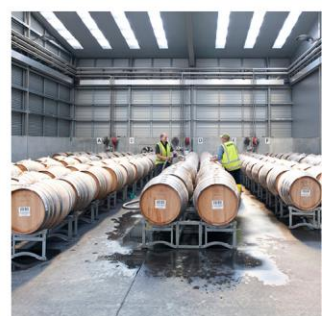


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Establishing a soil quality benchmark for the arable industry

Lawrence-Smith EJ, Beare MH, Tregurtha CS, Hu W

March 2019



Report for:

Foundation for Arable Research
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Report approved by:

Erin Lawrence-Smith
Scientist, Soil, Water & Environment
March 2019

Mike Beare
Science Group Leader, Soil, Water & Environment – Sustainable Production
March 2019

CONTENTS

Contents	2
Executive summary	4
1 Introduction	6
2 Datasets	8
2.1.1 Environment Canterbury Arable and Pastoral dataset	8
2.1.2 Land Management Index	9
3 Selection of sites for inclusion in benchmarks	10
4 Describing soil quality ‘Current state’ by region	12
4.1 Canterbury	15
4.1.1 Aggregate stability	17
4.1.2 Soil organic carbon	18
4.1.3 Penetration resistance	23
4.2 Southland.....	26
4.2.1 Aggregate stability	26
4.2.2 Soil organic carbon	27
4.2.3 Penetration resistance	29
4.3 Waikato.....	31
4.3.1 Aggregate stability	31
4.3.2 Soil organic carbon	32
4.3.3 Penetration resistance	35
4.4 Hawke’s Bay and Gisborne combined.....	36
4.4.1 Aggregate stability	37
4.4.2 Soil organic carbon	37
4.4.3 Penetration resistance	40
5 Next steps	41
6 References	43
Appendix	45
Field sampling methodology for Environment Canterbury Arable and Pastoral and Land Management Index monitoring programmes	45

EXECUTIVE SUMMARY

Establishing a soil quality benchmark for the arable industry

Lawrence-Smith EJ, Beare MH, Tregurtha CS, Hu W
Plant & Food Research Lincoln

March 2019

The Foundation for Arable Research (FAR) enlisted the help of Plant & Food Research (PFR) to establish a soil quality benchmark for the arable industry. In this context, establishing a 'benchmark' is the process of describing the 'current state' against either best practice or a known state. This report presents the benchmarks for three soil quality indicators, describes how they were derived, and concludes with comments on the next steps to improving the indicator target ranges for future comparisons.

- Two existing datasets for arable production systems in five regions of New Zealand were analysed to describe current soil quality, i.e. describe the benchmarks: the Land Management Index, and the Environment Canterbury Arable and Pastoral monitoring data sets.
- Benchmarks are provided for three soil quality indicators: aggregate stability, total soil organic carbon, and penetration resistance.
- Data are presented by region (Canterbury, Southland, Waikato, Gisborne and Hawke's Bay), recognising differences in production systems.
- Data for arable soils are presented for two cropping intensities (intensive and mixed cropping) alongside data for long-term extensive sheep/beef production systems as a reference land use. Paddocks were excluded from the analysis where their primary enterprise was vegetable cropping as opposed to a predominantly arable cropping. The one exception to this was in Hawke's Bay/Gisborne, where arable could not easily be separated from vegetable production. Moreover, sites where the primary land use was dairy were also excluded from the analysis.
- Benchmark data are compared with the 'national target range' published by the Land Monitoring Forum (where available), or alternative target ranges where these have been defined.
- The benchmarks will allow the industry to track changes in soil quality over time, thereby allowing a more transparent perspective on sustainable management of soils.

FAR has two intended outcomes from this benchmarking work. Firstly, the data provides a sector benchmark to track soil quality over time, and secondly, it provides an opportunity for individual farmers to compare their on-farm soil quality to the industry benchmark. Practical aspects of benchmarks being of use to individual farmers is beyond the scope of this report, although warrants further discussion given aggregate stability analyses are not currently offered by any commercial laboratory and penetrometers are not widely available to farmers. We suggest a review of PFR's Soil Quality Monitoring System test kits (promoted in the early 2000s) for on-farm monitoring and additional discussions in this space.

For further information please contact:

Erin Lawrence-Smith
Plant & Food Research Lincoln
Private Bag 4704
Christchurch Mail Centre
Christchurch 8140
NEW ZEALAND
Tel: +64 3 977 7340
DDI: +64 3 325 9364
Fax: +64 3 325 2074
Email: Erin.Lawrence-Smith@plantandfood.co.nz

1 INTRODUCTION

The last two decades have seen significant changes to the management of arable crop production systems in New Zealand. Some changes are likely to have led to an improvement in soil quality, while others may have had adverse effects. As noted by Horrocks (2018), *“Where best management practices are used, loss of soil quality under some forms of management is balanced by other management practices that restore soil quality. Where management practices are intensive and non-restorative, the loss of soil quality increases the risk that soil conditions will limit crop productivity and cause adverse environmental impacts”*.

Some commonly recognised changes in the management of arable crops over the last 20 years include:

- Greater diversity of crops grown: cereal, pulse, herbage, forage and vegetable seeds
- Duration of cropping phases has typically increased, while restorative phases have reduced in frequency and length. The frequency and duration of fallow periods have reduced
- Tillage intensity (number of passes, depth and degree of soil mixing) has decreased: Foundation for Arable Research (FAR) cropping practices surveys observed increased direct drilling and non-inversion cultivation, while ploughing has reduced (Fraser & Lawrence-Smith, 2011)
- The average yields of many key crops have continued to increase (wheat 6.5 t/ha in 2004 to 8.8 t/ha in 2012 (within Millner & Roskrug 2013)
- Stubble management practices have changed (e.g. less burning)
- Greater availability and uptake of technology enabling precision agriculture, e.g. variable-rate fertiliser and irrigation application technologies, GPS auto-steer
- Increased forage for the dairy industry/ dairy support crops.

These changes come within a wider context of greater consumer awareness (national and international) of environmental impacts and social responsibility. We are increasingly seeing regional authorities require environmental farm plans or permits/consents to farm, and nutrient budgets are becoming common place.

Such management change has led to varying opinions on whether soil quality has improved or deteriorated, and if change is ongoing or if a new equilibrium state has now been reached. Without the baseline datasets with which to make such evaluations, speculation is unhelpful.

Thus, to enable them to address their key research theme of ‘environmental responsibility’ (https://www.far.org.nz/research/research_and_extension_strategy_and_portfolio, accessed November 2018), and demonstrate commitment to sustainable production practices (both from an environmental and profitability perspective), FAR wish to establish some soil quality ‘benchmarks’ for arable systems. In this context, establishing a ‘benchmark’ is the process of describing ‘current state’ against either best practice or a known state. Following future assessments of soil quality, the benchmarks enable conclusions on soil quality improvement or decline to be drawn, thereby allowing a more transparent perspective of sustainability.

This report describes the process used to develop a soil quality benchmark, using two existing datasets for arable production systems in five regions of New Zealand. Data are compared with the 'national target range' published by the Land Monitoring Forum (where available), or alternative target ranges where they have been defined. The benchmark data for arable soil are presented alongside long-term extensive sheep/beef production systems as a reference land use. This land use is commonly used as reference because it is widely distributed across most agricultural soils and climates in New Zealand, and typically involves very little soil disturbance. This is not meant to imply soil quality under sheep/beef paddocks is 'optimal', but rather that it provides a well-known and dependable reference to account for inherent difference between soil types, independent of the management effects.

This report focuses on three soil quality indicators of interest to FAR: aggregate stability, total soil organic carbon, and penetration resistance. A brief description for each of these is provided in Table 1. Soil quality indicators and the issues they address. Details of soil quality programmes from where data were sourced are provided in Section 2 of this report.

Table 1. Soil quality indicators and the issues they address.

Indicator	Description	Importance to soil function	Contribution to ecosystem services
Aggregate Stability	Resistance of soil aggregates to breakdown in water	Forces arising from cultivation, compaction, raindrop impact, and wetting and drying cycles all exert stress on soil aggregates. Stable soil aggregates are more resistant to dispersion (slaking) and structural degradation, which can lead to run-off of sediment and nutrients into waterways and the formation of surface crusts (i.e. soil capping) that can create impediments to crop emergence and water infiltration.	Maintaining high stability soils is important for minimising the risk of run-off and avoiding impediments to crop establishment.
Total soil organic carbon	Soil organic carbon concentration and stock	Provides an index of the organic matter content of soil and can be coupled with bulk density to calculate the soil carbon stock to a defined depth. Soil organic C and organic matter play important roles in many aspects of soil function, including soil structure formation, nutrient cycling, soil water storage and soil biodiversity.	Organic matter depletion and carbon loss from soil can result in the loss of soil functions that are important to sustaining plant productivity (e.g. nutrient supply, soil water storage, suppression of soil-borne diseases) and filtering and buffering contaminants to mitigate adverse environmental impacts.
Penetration resistance	Soil strength (resistance to root penetration)	Soil with a high penetration resistance can impede root growth and restrict plant access to water and nutrients. Subsurface soil layers of high penetration resistance can also restrict drainage of water, creating anoxic conditions that enhance emissions of nitrous oxide, a potent greenhouse gas.	High penetration resistance can have adverse effects on plant production because of physical impediments to root growth and development.

2 DATASETS

This report describes results from two large on-farm soil quality monitoring programmes, and their use in defining soil quality benchmarks for the arable industry. The two datasets: Environment Canterbury Arable & Pastoral (ECan A & P) and Land Management Index (LMI), are large (i.e. number of sampled paddocks), include detailed management information (metadata) for each paddock, were sampled and analysed following very consistent methodologies to ensure comparability, and each sampling location was recorded using GPS navigation. The ECan A & P dataset is owned by Environment Canterbury, who granted permission to Plant & Food Research (PFR, data collectors) to use the data for the purposes of benchmarking arable soil quality and supplying the findings to FAR. The LMI dataset was collected as part of a Ministry of Agriculture and Forestry (now Ministry for Primary Industries (MPI)) Sustainable Farming Fund project. PFR are custodians of the data and MPI granted permission for the data to be used in this benchmarking analysis. Both datasets were collected using a survey approach (further information provided below). A subset of paddocks from these programmes were considered suitable for benchmarking based on the criteria outlined in Section 3.

2.1.1 Environment Canterbury Arable and Pastoral dataset

A subset of the ECan A & P monitoring dataset was analysed to provide a soil quality benchmark for the arable industry in Canterbury. The wider dataset is described below; however, for the benchmarking activity described here, the data from the most recent sampling date (between July 2013 and June 2018) for each paddock were analysed. There were 261 paddocks sampled during this timeframe, but after applying the guidelines to determine if each paddock's management history was suitable for benchmarking, the dataset was restricted to 187 paddocks, comprised of 79 intensive arable cropping, 86 mixed arable cropping, and 22 sheep/beef pastures.

The Arable and Pastoral Monitoring Programme was initiated in 1999–2000 to collect soil quality data for agricultural soils of the Canterbury plains and downs. To June 2018, a total of 261 paddocks had been sampled as part of the programme, with 86 of those paddocks having been sampled at three points in time, and a further 175 paddocks at two points in time (a total of 608 observations). Repeat monitoring typically occurred at 8-year intervals. Paddocks were resampled regardless of their management during the intervening time. Initially paddocks were selected to represent long-term arable, short-term arable/short-term sheep/beef pasture, and long-term sheep/beef pasture. Over time, the presence of dairying on the Canterbury plains has increased and paddocks with histories of long-term dairying were added to the dataset, while a number of short-term dairying paddocks have now been sampled because of land-use change of previously arable or sheep paddocks. Paddocks were also selected with consideration of soil type: those considered most important to agricultural production on the plains and downs of Canterbury. Sampled paddocks included soils from the Brown, Pallic, Gley and Recent soil orders. The number of paddocks sampled on each soil order or soil series was not proportional to the area represented by that soil, and not all soil orders or series were sampled. Up to fourteen indicators of soil quality were measured.

Field soil sampling, and laboratory analysis procedures are outlined in the Appendix.

2.1.2 Land Management Index

The LMI dataset comprises soil quality indicator measurements from 748 paddocks (each sampled at a single point in time between late 2002 and mid 2007) representing arable and vegetable cropping, dairy, intensive bull/beef and extensive sheep/beef pasture land uses. The paddocks were spread across seven New Zealand regions (Auckland, Waikato, Gisborne, Hawke's Bay, Manawatu, Canterbury and Southland), and represented a range of important agricultural soil orders (Allophanic, Brown, Gley, Granular, Melanic, Organic, Pallic, Recent). Fourteen different soil quality indicators were measured in each paddock.

The LMI dataset has been identified as an important nationally relevant source of soil quality information, particularly for cropped land. Many of the sampled sites/paddocks have been incorporated into New Zealand's Soil Carbon Monitoring System, which is used to prepare our national soil carbon inventory. An advantage of these data is that all samples collected were analysed at the same laboratory (PFR's Soil, Water & Environment laboratory in Lincoln), ensuring consistency in methodology. Detailed paddock management information was also collected for the ten-year period preceding sample collection.

Paddocks were selected for sampling to meet the specific objectives of the LMI project, which were to ensure that paddocks represented a range of common management practices for each of the dominant agricultural land uses and soil orders in the participating regions. In some cases, soils suspected of greater resilience or vulnerability to management change were specifically, but not exclusively, targeted for inclusion. The number of paddocks sampled on each soil order or soil series was not proportional to the area represented by that soil, and not all soil orders or series were sampled in each region. The selection of sites was somewhat opportunistic in that it relied on the goodwill of farmers to allow access to their paddocks and depended on the specific management practices available for comparison at a given location or on a given soil order (e.g. irrigated v. non-irrigated cereal cropping on brown soils, paddocks with a history of frequent grass leys compared with continual cropping).

A subset of 140 sites from the original LMI dataset were selected as suitable for inclusion in this benchmarking analysis, based on the criteria outlined in Section 3 of this report. This included sites from the Auckland/Waikato, Southland, and Hawke's Bay/Gisborne regions, and comprised 74 intensive arable cropping, five mixed arable cropping and 61 sheep/beef pastures. While much of the Canterbury region data were identified as suitable, the more recently collected ECan A & P dataset was preferred for this region, purely because it was more current (timewise).

Field soil sampling, and laboratory analysis procedures are outlined in the Appendix.

3 SELECTION OF SITES FOR INCLUSION IN BENCHMARKS

Categorising sites according to 'land use' can be challenging. The range of crops grown and the complexity and changeable nature of rotations means that land-use practices are essentially a continuum from long-term permanent pasture without renewal, to continuous annual cropping without any restorative phases.

The FAR brief to PFR for this report was to categorise arable cropping paddocks by cropping intensity, and compare soil quality data to sheep/beef pasture paddocks and national target ranges where applicable. Each paddock was assessed against the guidelines (Table 2) to determine suitability and assign cropping intensity. Categories were assigned based on land use for the 10-year period prior to sampling. Upon FAR's request, paddocks were excluded from the analysis where their primary enterprise was vegetable cropping as opposed to a predominantly arable focus. The one region where this was particularly difficult was in Hawke's Bay/Gisborne. The challenges encountered and compromise reached are discussed in Section 4.5. Sites where primary land use was dairy were also excluded from the analysis.

Because the ECan A & P and LMI datasets were collected to address other specific purposes, some of the sites did not meet the land use criteria established for this benchmarking analysis. As defined in Table 1, sites were excluded from analysis where primary land use changed <7 years prior to sampling. This was to increase the probability of the benchmark describing soil condition under relatively steady state conditions.

Mixed cropping paddocks in the LMI dataset were typically sampled in the 'cropped phase' as opposed to 'restorative phase' of the rotation, which may have biased results towards intensive cropping. This bias also applied to the ECan A & P data when each paddock was first monitored; however, the effects would be reduced in the dataset analysed in this report, as paddocks were resampled irrespective of management during the intervening time. This is in no way intended to imply that restorative phases of rotations are less important, or should be excluded from any benchmarking activity; however, we were restricted by the data available to us.

Table 2. Guidelines for determining site suitability for inclusion in the benchmarking dataset and for determination of specific land-use category.

Land use	Detailed management information for the 10-year period prior to sampling	Valid	Land-use category
Arable crop	Continuous annual cropping for >6 years immediately prior to sampling. Single year (up to ~18 months) grass or clover crops grown for the purpose of seed production were treated as any other crop (e.g. wheat or maize).	Yes	Intensive arable
	As above, except where a grass pasture or a grass (e.g. ryegrass seed, fescue) or clover seed crop was maintained (following initial seed harvest without any tillage (including direct drilling)) for a period of about 18 months or greater, i.e. the 'restorative crop' was present at two consecutive main harvests (or more) within the six-year period immediately prior to sampling, and the main enterprise was arable cropping (i.e. not a predominantly pastoral site with one or two forage crops grown during pasture renewal).	Yes	Mixed arable
	Currently in arable crop, but available management information suggests land use changed within the 10 years prior to sampling date, or there was insufficient information available to be confident of the land-use classification.	No	-
	Where the primary enterprise is considered fresh and process vegetable production (potatoes, onions, leafy greens etc.). This does not preclude the inclusion of some vegetable crops within a predominantly arable rotation.	No	-
Sheep/beef pasture	Continuous grass pasture for 10 consecutive years prior to sampling.	Yes	Sheep/beef pasture
	8 or 9 years in grass pasture, with one or two main crops (e.g. swedes or forage rape) grown as part of the pastoral system, providing these crops were not within 2 years of the sampling date.	Yes	Sheep/beef pasture
	Historically, a pastoral system with one or two crops (e.g. forage rape) grown within 2 years of the sampling date.	No	-
	Paddocks considered part of a dairy or sheep milking platform.	No	-
	A pastoral system with short rotation grasses (<6 years) and/or a pastoral system where 2–5 years of cropping was practised prior to re-grassing.	No	-
	Very intensive bull beef systems, characterised by high stocking densities such as the Techno grazing styles.	No	-
	Sheep/beef pasture at time of sampling, but not enough information was available to be certain of the land-use classification (i.e. less than 10 years' data or insufficient detail).	No	-

4 DESCRIBING SOIL QUALITY 'CURRENT STATE' BY REGION

The 'current state' of soil quality can be considered the 'benchmark' against which future assessments of soil quality can be compared. Within this report, benchmarks have been provided on a regional basis in recognition of the differing production systems, and soil series present in each region. The current benchmark values are compared with the 'national target range' published by the Land Monitoring Forum (LMF) (where available), or an alternative target range where it has been established (Table 3). Comment is included regarding whether the target range is applicable to all soils. Presenting the benchmark data alongside the 'national target range' allows these target ranges to be reviewed and updated in the future (as scientific advances further relate indicators to functional properties of soils, both from a production and an environmental perspective) without the benchmark at any point in time being altered. Arable data are also presented alongside long-term sheep/beef production systems. This is not meant to imply soil quality under sheep/beef paddocks is 'optimal', but rather that it provides a well-known and dependable reference to account for inherent differences between soil types, independent of any management effects.

The LMF typically reports soil quality data on a "by exception" basis (i.e. numbers or proportions of sites which do not meet the target). We believe it is more important to consider the overall distribution of data with respect to the target, not just the numbers/proportions of paddocks meeting the target. Where large proportions of paddocks are close to the target, seemingly small changes (e.g. to management practices or climate), could significantly change the proportion of paddocks meeting the target and conclusions drawn from the data. Thus, a more complete understanding of the distribution of data and changes with time provides more timely opportunity to identify soil quality responses to external (i.e. land-use) pressures.

An understanding of the distribution of data with respect to any benchmark allows discussion of why soil quality at an individual site may vary from the benchmark for any soil type and land-use combination, and an understanding of whether this deviation is important in a practical sense (e.g. if the difference is likely to result in reduced yield, root growth restriction, or reduced water holding capacity). It is important to appreciate:

- Soil quality is typically assessed by the measurement of indicators. Indicators are designed to measure a dynamic property or state of the soil that reflects its ability to support key functions (e.g. the supply of plant available nutrients, drainage of water, unrestricted root growth) and is responsive to changes in management. In some cases the relationship between an indicator and its associated soil function is well known, whereas in other cases the relationships are more qualitative. The state of this knowledge affects the degree of confidence that can be applied to setting a critical threshold or target range for a given indicator. In many cases, soil quality indicators (i.e. the properties they measure) are also affected by inherent properties (i.e. those that do not readily change) of the soil (e.g. soil texture and mineralogy), which affects the interpretation of results for a given site.
- Soil is inherently spatially variable. This continuum of soil properties means that some soils are more vulnerable to structural degradation than others, both within a single soil order and within single soil sibling categories. The New Zealand Soil Classification system (Hewitt 2010; Webb & Lillburne 2011) involves several levels of detail from the

most general level (Order) to the most specific (Siblings). The system considers soil properties such as the degree of weathering, drainage status, soil parent material and texture. In New Zealand we recognise 15 Orders, 74 Groups, 299 Subgroups, and an uncounted number of Families and Siblings (<https://soils.landcareresearch.co.nz/describing-soils/nzsc>).

- Within each of the land-use categories, there is a continuum of management practices: a wide range of crop types are grown and rotation compositions which influence organic matter returns, tillage practices from direct drilling to ploughing, and differing lengths of time under current management. Additionally, other practices such as irrigation and nutrient inputs can influence soil quality.

Cautious review of sample size for each comparison made is recommended. There are instances where sample numbers are low and therefore data should be treated as indicative only. The Land Monitoring Forum suggest a minimum sample size of 30 paddocks for making comparisons between land-use types within a region. The Land Use Type strata they use are broader than those applied within this report (e.g. they aggregate all annual cropping [arable and vegetable] with horticulture [orchards, vineyards and berry crops] and compare these with plantation forest, indigenous vegetation, intensive pastoral farming, and extensive pastoral farming). In addition, the LMF suggest samples within Land Use Type strata should be weighted according to the most common soil order (by area) for the particular land-use type. However, as one of FAR's intended outcomes is for individual farmers to be able to compare their soil quality to benchmarks to determine how they are tracking compared with the industry average, weighting of data by soil order for proportional land areas is not instructive, and has not been completed.

Benchmark data have been presented using box and whisker plots. The 'box' represents the 25th to 75th quartiles, while whiskers are the 10th and 90th quartiles, with dots representing influential data points <10th and >90th quartiles. The median (50th quartile) is depicted by the line within the box. A box and whisker has only been drawn where there are greater than seven observations (paddocks). If there are seven or fewer observations, individual data points are plotted. All quartiles and plots were calculated by Sigma Plot 12.5. The proportion of sites meeting the target range were calculated in Microsoft® Excel 2013 using direct counts (e.g. number of sites meeting the target, divided by total number of sites).

Table 3. National target range values applied to each soil quality indicator for comparison with the current state/benchmark.

Indicator	Target ranges, and associated evidence																																
Aggregate stability	<p>The target range applied within this report is >1.5 mm mean weight diameter (MWD, see Appendix), as soil with stabilities below this are at greater risk of producing crop yields below the regional average. Beare & Tregurtha (2004) linked aggregate stability to productivity, with lower aggregate stabilities more likely to be associated with lower crop yields. These relationships were derived from mineral soils from the Brown, Gley, Pallic and Recent soil orders. Relationships have not been independently assessed for Allophanic, Granular or Pumice soils.</p> <p>The LMF recommend seven key indicators of soil quality and two optional indicators, aggregate stability being one of the optional indicators recommended for intensively cultivated land. The LMF have not defined target ranges for the optional indicators.</p>																																
	<p>Total Carbon target ranges (% w/w) as reported in Hill & Sparling (2009). Soil quality monitoring. In: Land and Soil Monitoring: A guide for SoE and Regional Council Reporting. Land Monitoring Forum, New Zealand.</p> <table border="1" style="width: 100%; border-collapse: collapse; text-align: center;"> <thead> <tr> <th style="width: 30%;"></th> <th style="background-color: #808080; color: white;">Very depleted</th> <th style="background-color: #ffff00;">Depleted</th> <th style="background-color: #90ee90;">Normal</th> <th style="background-color: #008000; color: white;">Ample</th> </tr> </thead> <tbody> <tr> <td>Allophanic</td> <td>0.5</td> <td>3</td> <td>4</td> <td>9</td> <td>12</td> </tr> <tr> <td>Semi-arid, Pumice & Recent</td> <td>0</td> <td>2</td> <td>3</td> <td>5</td> <td>12</td> </tr> <tr> <td>Organic</td> <td colspan="5">exclusion</td> </tr> <tr> <td>All other soils</td> <td>0.5</td> <td>2.5</td> <td>3.5</td> <td>7</td> <td>12</td> </tr> </tbody> </table>						Very depleted	Depleted	Normal	Ample	Allophanic	0.5	3	4	9	12	Semi-arid, Pumice & Recent	0	2	3	5	12	Organic	exclusion					All other soils	0.5	2.5	3.5	7
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Total soil organic carbon (SOC)	<p>Total soil organic C target ranges adopted by the LMF (Hill & Sparling 2009) and applied within this report are soil order-dependent (a reflection that variations in soil organic matter and SOC are not only a result of management, but also of climate, soil acidity, parent material and drainage conditions), and applicable to all land uses. Organic soils do not have a target range, as they are defined as >15% SOC, and therefore C content is not a quality indicator for this order. The ranges were adopted following two workshops where expert opinion was sought (Sparling et al. 2008).</p> <p>The ranges are applicable to 0–10 cm sampling depth, although have been applied to 0–15 cm depth within this report. It is anticipated these ranges are a ‘reasonable approximation’ for cropped soils which are likely to have been mixed during cultivation. For pastoral soils, the larger sampling depth of 0–15 cm would dilute C concentration where vertical stratification is present. Thus, the target could be considered harder to achieve, although given the generally greater organic matter returns of continuous pasture compared with those of arable crops, and the wide range of Land Use Type Strata to which these are applied within the LMF guidelines, we do not believe the depth discrepancy to be an issue. Proportions of pastoral sites not reaching the target in this report also support this conclusion.</p> <p>The LMF report data on a “by exception” basis (i.e. numbers or proportions of sites which do not meet the target). For SOC, “by exception” is defined as</p>																																

Indicator	Target ranges, and associated evidence
	C concentrations below the 'depleted' category. No target ranges are available for soil C stocks t/ha, none has been defined for 15- to 30-cm depth. Reporting the numbers of sites with SOC values below the "depleted" target implies that SOC "depleted" soils maintain adequate levels of soil function. This requires further discussion.
Penetration Resistance (PR)	<p>A provisional target value of <2.5 MPa has been applied to the 0- to 15-cm depth. Critical resistance values are crop specific; however, adverse effects on plant root growth typically correspond to PR values above 2–3 MPa (Greacen & Sands 1980; Taylor & Ratliff 1969; Whalley et al. 2008). The provisional target range of <2.5 MPa is greater than that suggested by da Silva et al. (1994), who proposed <2 MPa for soils at field capacity (field capacity can differ significantly for each soil order, e.g. ~32% for a typical Canterbury Brown silt loam, and ~65% for an Auckland Allophanic silt loam). A higher target range may be more applicable to pastures.</p> <p>All PR data were normalised to a soil water content of 20 g g⁻¹ using a power model developed by Hu et al. 2019 (in preparation) prior to use within this report. This was required, as PR is inversely related to soil moisture at time of measurement (i.e. PR increases as soil moisture decreases), making raw field-recorded PR data less comparable. Details of the normalisation procedure are provided in the Appendix.</p>

4.1 Canterbury

The New Zealand arable industry is heavily concentrated in the Canterbury Region, with ~82% of all wheat and 68% of barley grown here in 2016 (Statistics NZ 2016). Typical arable crop rotations include wheat, barley, peas, ryegrass seed, clover seed, and small vegetable seed such as carrot. Many of the mixed cropping paddocks in Canterbury can still be considered relatively intensive, given that duration of restorative crops (e.g. grass pasture or perennial crops) is often relatively short (i.e. one year as a ryegrass seed crop, and one as pasture). Thus, there is sometimes little difference between paddocks classified as intensive crop v. mixed crop.

Data for this region came from the ECan A & P project, with paddocks sampled between July 2013 and June 2018. Numbers of paddocks used to set the benchmarks by soil order are provided in Table 4.

As previously mentioned, the mixed cropping sites may be slightly biased by predominant sampling within the cropping phase compared with the pastoral phase, although this is likely to be representative of cropping phases being longer than restorative phases. Of the 86 sampled paddocks, 52 paddocks were sampled following the second to sixth consecutive year of cropping following a restorative phase; 18 sites were sampled following the first crop since the pastoral phase, while 16 sites were sampled within the pastoral phase (Figure 1). This is partly a reflection of:

- The cropping phase being typically of greater duration than the pastoral phase
- A legacy of the original sampling selection criteria of the programme, e.g. comparison of shorter-duration cropping with longer-duration

- The land-use determination guidelines which dictate that paddocks cannot be in first year of pasture, as this would be considered a crop until the grass crop had been established for approx. 18 months or longer.

Table 4. Numbers of Canterbury paddocks in the benchmarking dataset by soil order.

Order	Intensive arable crop	Mixed arable crop	Sheep/beef pasture	Total
Brown	17	22	2	41
Gley	8	8	3	19
Pallic	50	51	16	117
Recent	4	5	1	10
Total	79	86	22	187

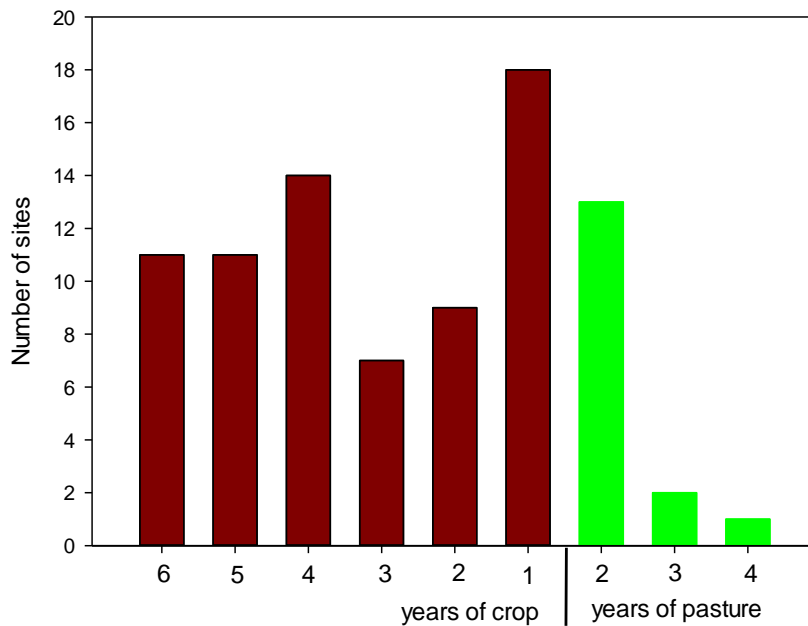


Figure 1. Canterbury sites categorised as Mixed Arable crop (n=86), depicted here by number of consecutive years in crop or pasture at time of sampling. Original data source: Environment Canterbury Arable & Pastoral monitoring dataset.

4.1.1 Aggregate stability

A very wide range of aggregate stability values were recorded for the cropping land uses in Canterbury: 0.8–2.3 mm MWD. The distribution of aggregate stability values for intensive arable (IA) and mixed arable (MA) covered a similar range (Figure 2), with values being approximately 0.2 mm MWD higher for MA than for IA. The similarities suggest little further structural decline from a MA to IA in this region. This is probably attributable to MA paddocks being sampled predominantly during their cropping phase and the typically short duration of grass leys in Canterbury (2–3 years) at the time of sampling (July 2013 and June 2018) resulting in an intensive form of MA. The distribution of values for sheep/beef pastures (LTP) were skewed towards higher aggregate stabilities, and the range of stabilities was narrower (1.9–2.8 mm MWD) than for cropping land uses. The proportion of paddocks meeting the recommended target range within each land use category were: IA = 61%, MA = 72%, and LTP = 100%.

The representation of soil orders within the land uses was unbalanced; given that soil properties can have a large influence on soil quality, we recommend data presented in Figure 2 are treated with some caution. Data summaries by land use and soil order are preferred where paddock replication is sufficient.

The differences in aggregate stability due to land use clearly differed between soil orders (Figure 3). The highest aggregate stability values were recorded under LTP for all orders. While replication of paddocks under LTP was lower than for cropping, the data suggest that Brown soils are generally more resistant to the effects of intensive cropping than the heavier Gley and Pallic soils (i.e. the difference between the median aggregate stability for LTP and cropping land uses was less for the Brown than for the Gley and Pallic soils).

Sample numbers for the Gley soils were low (for all land-use groups), so we must avoid over-interpretation, however, the distributions for both MA and IA suggested maximum stabilities of around 1.8 mm MWD, with stabilities very skewed towards these values. Additionally, the very different distributions for MA and IA suggest these soils may be particularly vulnerable to intensive cropping and careful management, with frequent restorative (ley) phases being highly beneficial for stability of these soils. This skew seen in Gley soils was not evident for the other soil orders sampled.

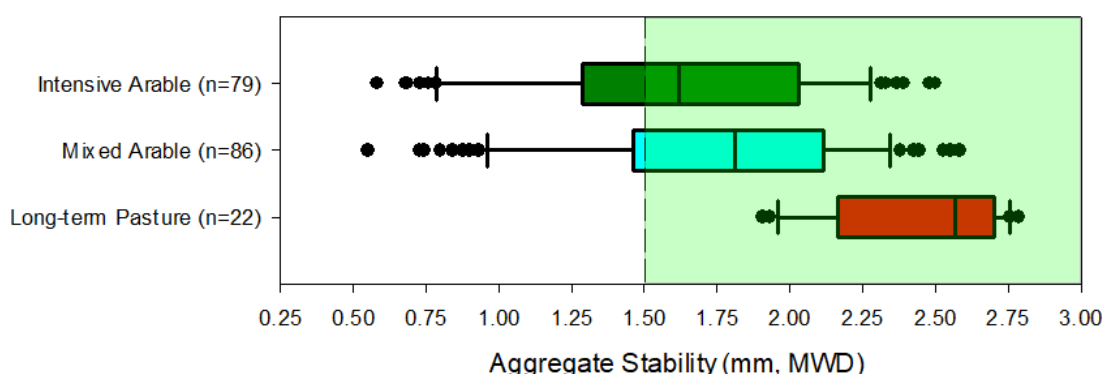


Figure 2. Aggregate stability for Canterbury sites sampled between 2013 and 2018 as part of the Environment Canterbury Arable & Pastoral monitoring programme. The box represents the middle 50% of stabilities, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. The recommended target range is shown with green shading (i.e. >1.5 mm mean weight diameter; MWD).

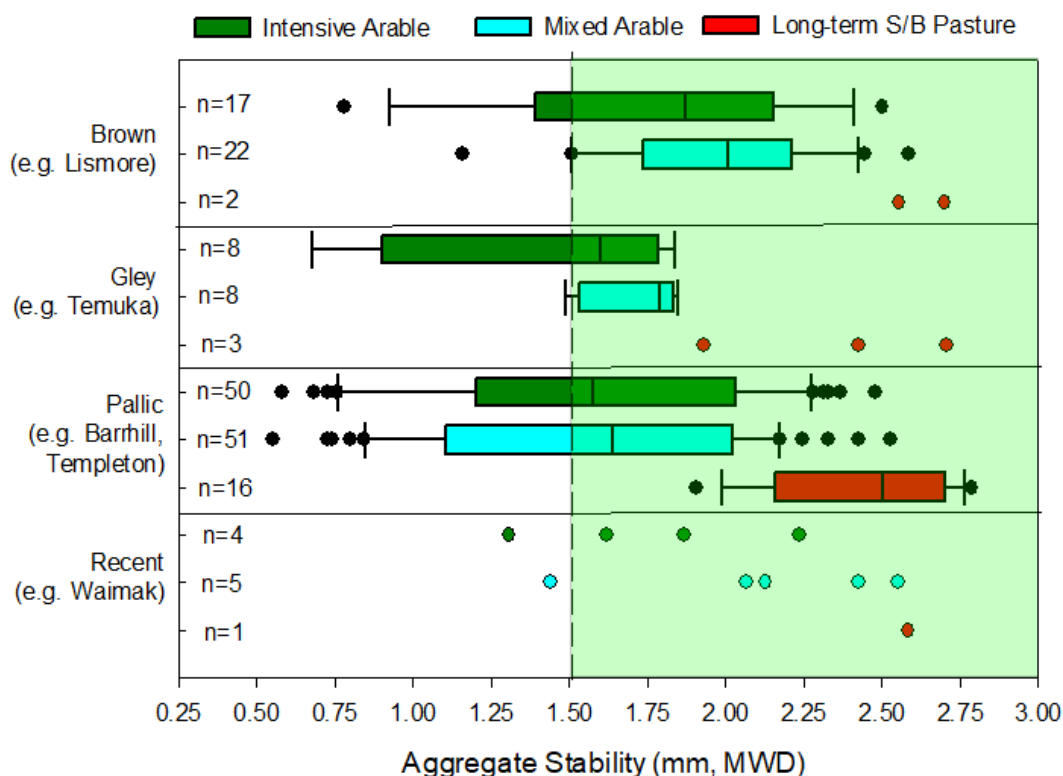


Figure 3. Aggregate stability for Canterbury sites sampled between 2013 and 2018 as part of the Environment Canterbury Arable & Pastoral monitoring programme. The box represents the middle 50% of stabilities, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. The recommended target range is shown with green shading (i.e. >1.5 mm mean weight diameter; MWD).

4.1.2 Soil organic carbon

Median total soil organic C (SOC) concentrations were greater at 0–15 cm than 15–30 cm for all land uses; furthermore, differences between land uses were only evident at 0–15 cm (Figure 4, Figure 5).

In the top 15 cm of soil (0–15cm), the distribution of SOC (on both a gravimetric [%] and volumetric [t/ha] basis) for IA and MA were very similar in shape and range (Figure 4). The median SOC concentration for MA and IA both round to 2.7 %, while differences between MA and IA at the 25th and 75th quartiles were 0.1%, which are unlikely to be significant from a production standpoint. The similarities suggest that typical short grass leys in Canterbury cropping systems are not resulting in increased C concentrations, although there may be other benefits of the leys. Long-term pastures had median SOC concentration of 3.6%, and the distribution covered a wider range of SOC concentrations than MA and IA.

The target range values for SOC (adopted from the LMF) are soil order-specific; the target depicted in Figure 4, >2.5%, is applicable to 95% of the paddocks represented (proportion remains consistent within the land uses). The proportion of paddocks meeting the recommended target by land use were: IA = 62%, MA = 76%, and LTP = 91%. This is an example where the absolute number of sites meeting the target gives the impression of MA

performing better than IA, however the distributions of SOC values are similar and differences are unlikely to be important.

The representation of orders within the land uses is unbalanced; given soil properties can have a large influence on soil quality, we recommend data presented in Figure 4 are treated with some caution. Data summaries by land use and order (Figure 6, Figure 7) are preferred where paddock replication is sufficient.

The highest SOC concentrations were recorded under LTP for all orders (Figure 6). Conclusions for the Pallic soils at 0–15 cm mirror those reported across all orders above; given Pallic soils make up 63% of the dataset, this is not surprising. Overall, for cropped soils, heavier Gley soils had the highest SOC concentrations, followed by lighter Pallic and Brown soils.

At 15–30 cm, land use and order effects (Figure 7) were less pronounced than for 0–15 cm. The IA paddocks on Gley soil had higher gravimetric SOC concentrations than paddocks in the other categories. There was no direct evidence this trend occurred when volumetric concentrations were presented, although low replication for Gley soils limits conclusions.

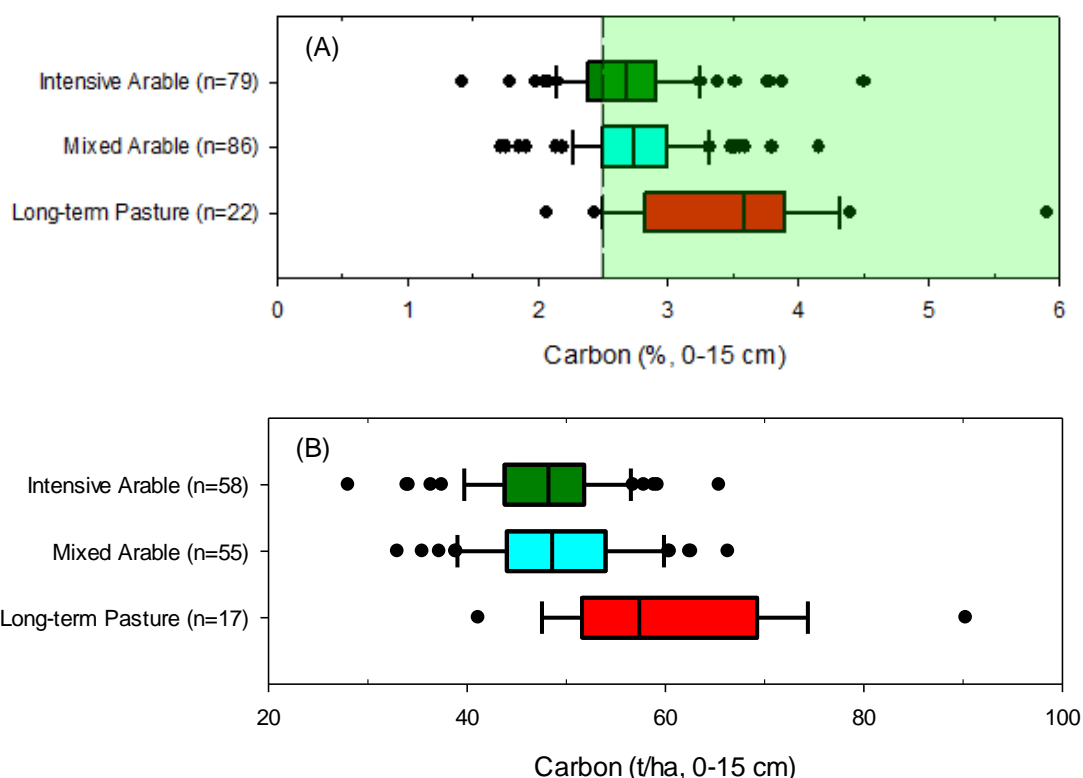


Figure 4. Total soil organic carbon concentration (0–15 cm) for Canterbury sites sampled between 2013 and 2018 as part of the Environment Canterbury Arable & Pastoral monitoring programme. The box represents the middle 50% of stabilities, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. (A) Gravimetric data with recommended target value (for 0–10 cm, Hill & Sparling 2009) depicted by the vertical dashed line (i.e., >2.5%) and green shading, and is applicable to the Brown, Pallic and Gley soil orders (95% of paddocks); remaining 5% of soils are Recent where >2% C applies; (B) volumetric data, tonnes of C per hectare.

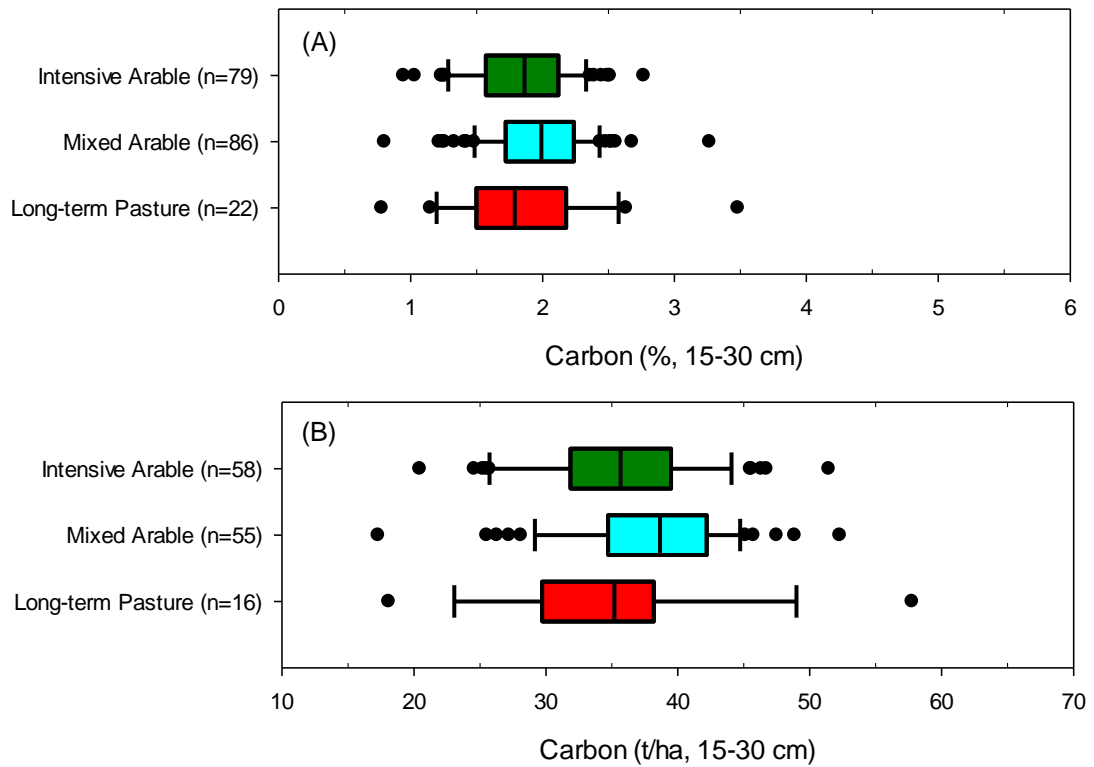


Figure 5. Total soil organic carbon concentration (15–30 cm) for Canterbury sites sampled between 2013 and 2018 as part of the Environment Canterbury Arable & Pastoral monitoring programme. The box represents the middle 50% of stabilities, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. (A) Gravimetric data, % C, and (B) volumetric data, tonnes of C per hectare.

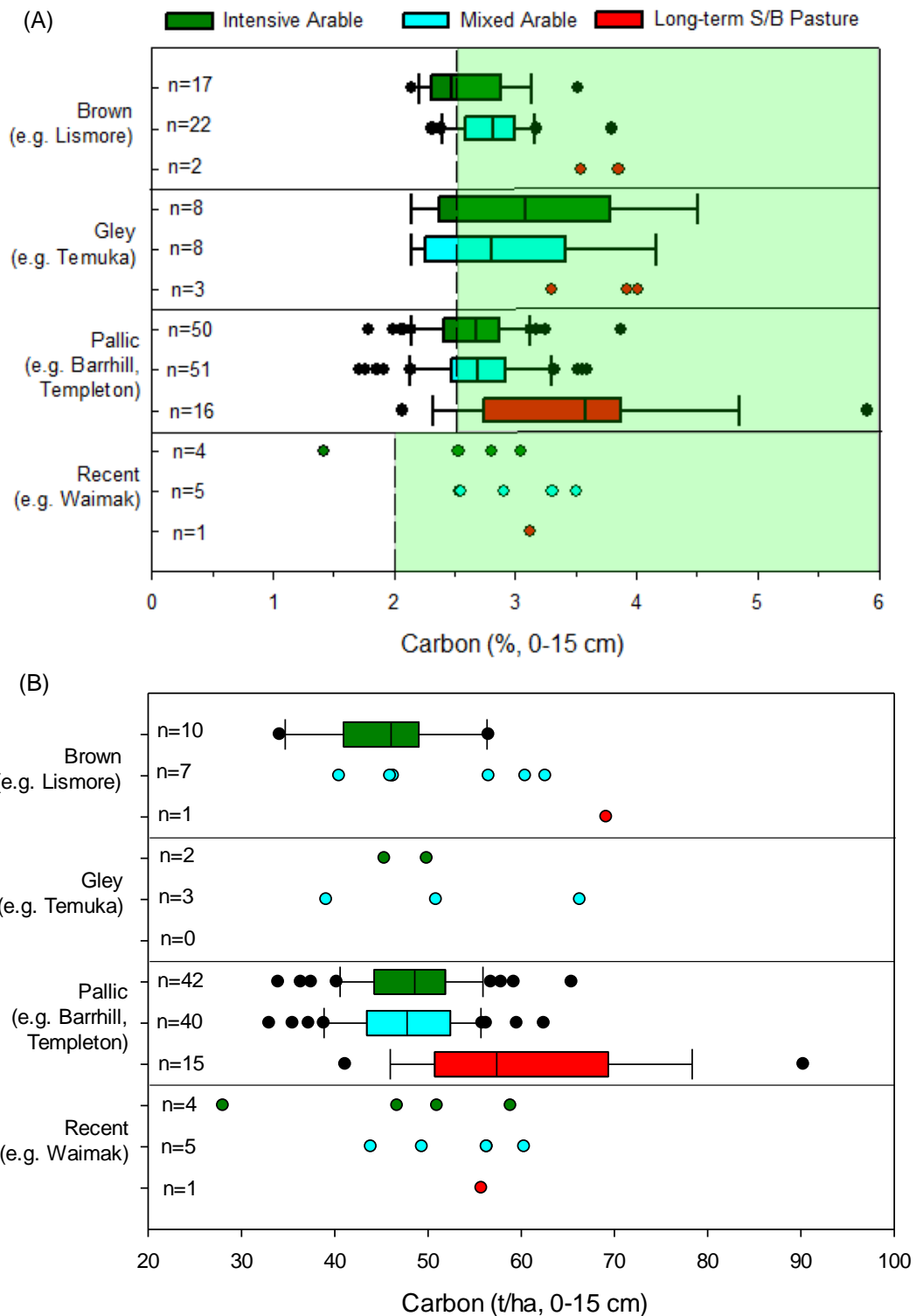


Figure 6. Total soil organic C concentration (0–15 cm) for Canterbury sites sampled between 2013 and 2018 as part of the Environment Canterbury Arable & Pastoral monitoring programme. The box represents the middle 50% of C concentrations, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. (A) Gravimetric data with recommended target value (for 0–10 cm, Hill & Sparling 2009) depicted by the green shading; and (B) volumetric data, tonnes of C per hectare.

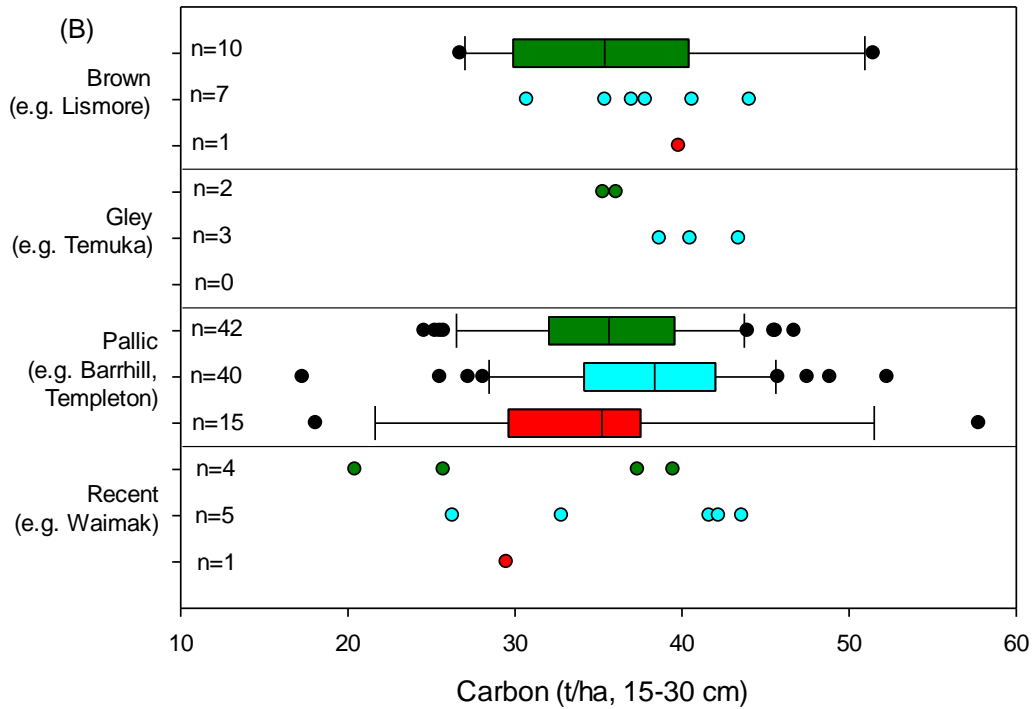
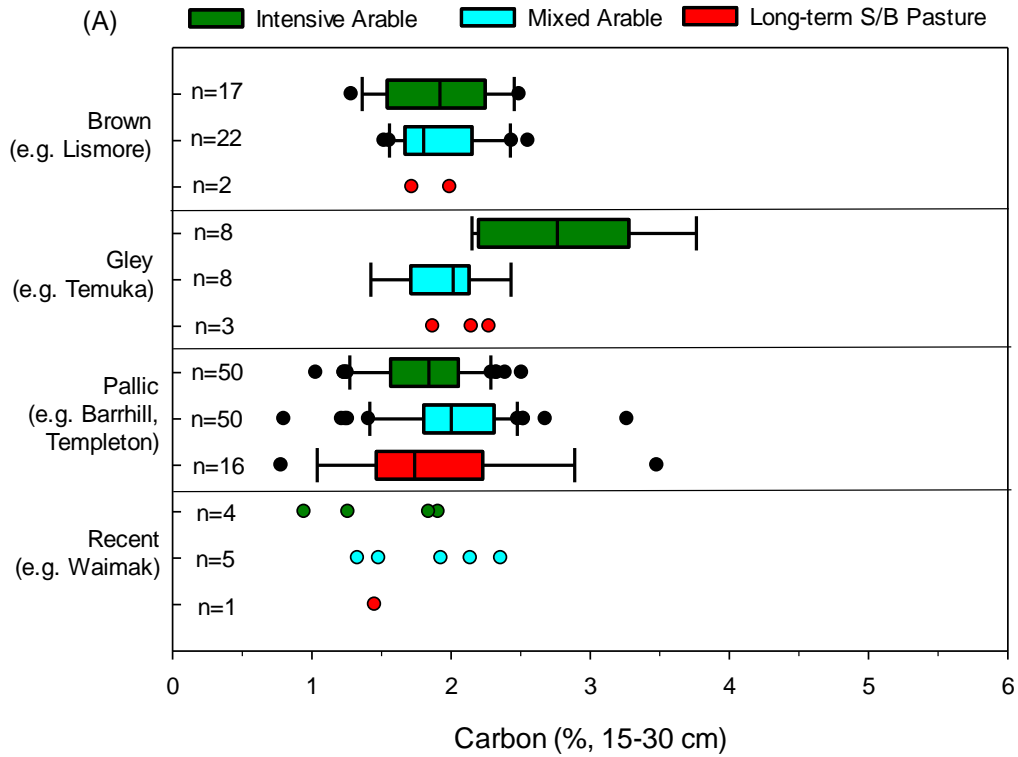


Figure 7. Total soil organic C concentration (15–30 cm) for Canterbury sites sampled between 2013 and 2018 as part of the Environment Canterbury Arable & Pastoral monitoring programme. The box represents the middle 50% of C concentrations, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. (A) Gravimetric data, % C, (B) volumetric data, tonnes of C per hectare.

4.1.3 Penetration resistance

In both the surface (0–15 cm) and subsurface (15–25 cm) soil, a wide range of penetration resistance (PR) values were recorded for the cropping land uses (Figure 8). The distributions covered a slightly higher range of PR values for the 15–25 cm depth than for the 0–15 cm depth; and covered a slightly wider range of values for IA than MA. The higher PR observed under LTP compared with that for cropped soils (both depths) was expected, given the reduced soil cultivation (i.e. loosening) under this land use and less compaction from stock treading. However, pasture root growth may also be less impeded by high PR, given its fine root architecture compared with the root architecture of many arable crops.

Median penetration resistance values were outside the recommended target range for all land uses at both depths, suggesting soil density may restrict root growth/proliferation, thus limiting the soil volume from which roots can access water and nutrients. This is especially so if soil moisture is low when roots are developing (penetration resistance and soil moisture are negatively correlated). Across all soil orders, the proportion of sites with 0–15 cm PR values within the recommended target range of below 2.5 MPa was 37% for IA, 34% for MA and 0% for LTP.

The representation of orders within the land uses was unbalanced; given soil properties can have a large influence on soil quality, we recommend data presented in Figure 8 are treated with some caution. Data summaries by land use and order (Figure 9) are preferred where paddock replication is sufficient.

For Brown soils, higher median PR for IA than for MA in the surface soil suggests greater surface soil (0–15 cm) consolidation that may be a result of structural degradation of soil over time without the presence of restorative grass leys. This trend was not observed in the Gley soils, where MA tended to have higher PR than IA. This result may have been due to Gley soils (which tend to remain waterlogged through winter and spring) being damaged by stock treading during the grass ley phase. This is not such an issue for the more freely draining soils. We advise caution in interpreting this result, given the relatively low sample numbers.

At 15–25 cm, land use differences within each soil order were less pronounced, although there is still evidence of higher PR under LTP than under the cropping land uses.

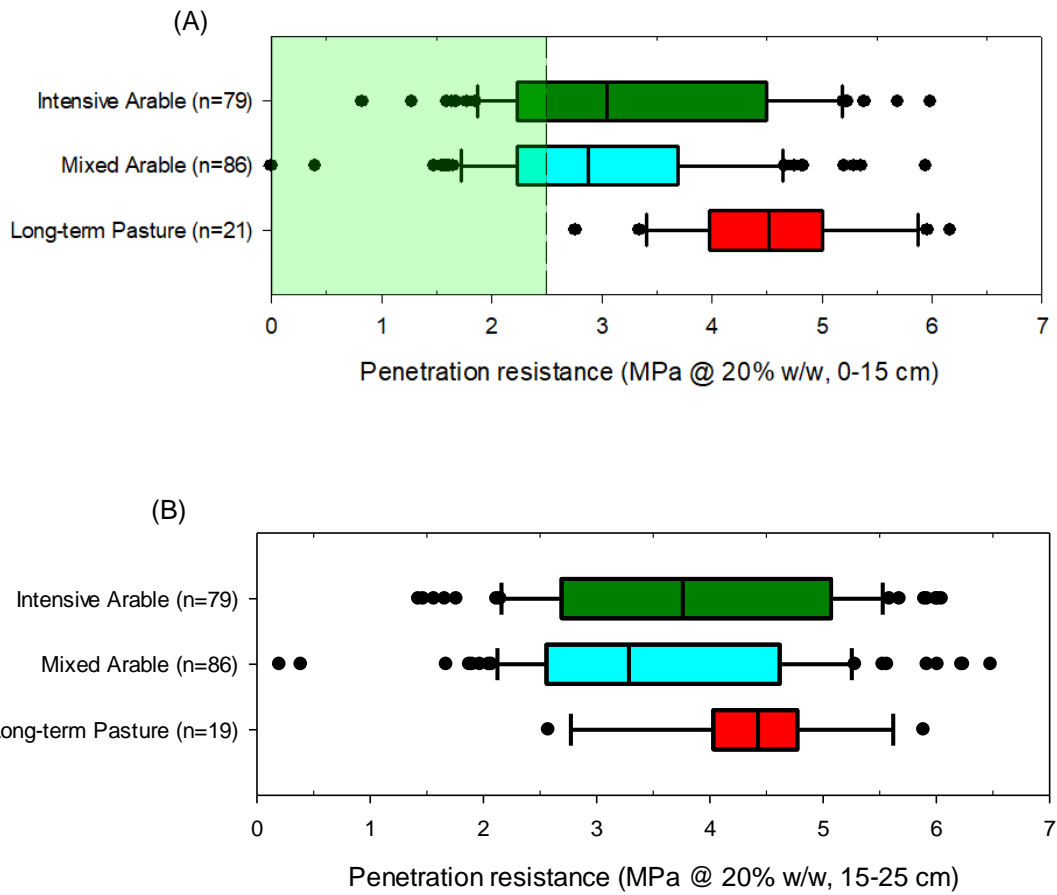


Figure 8. Penetration resistance for Canterbury sites sampled between 2013 and 2018 as part of the Environment Canterbury Arable & Pastoral monitoring programme; (A) 0–15 cm, (B) 15–25 cm. The box represents the middle 50% of stabilities, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. The recommended target (<2.5 MPa) is depicted by the green shading.

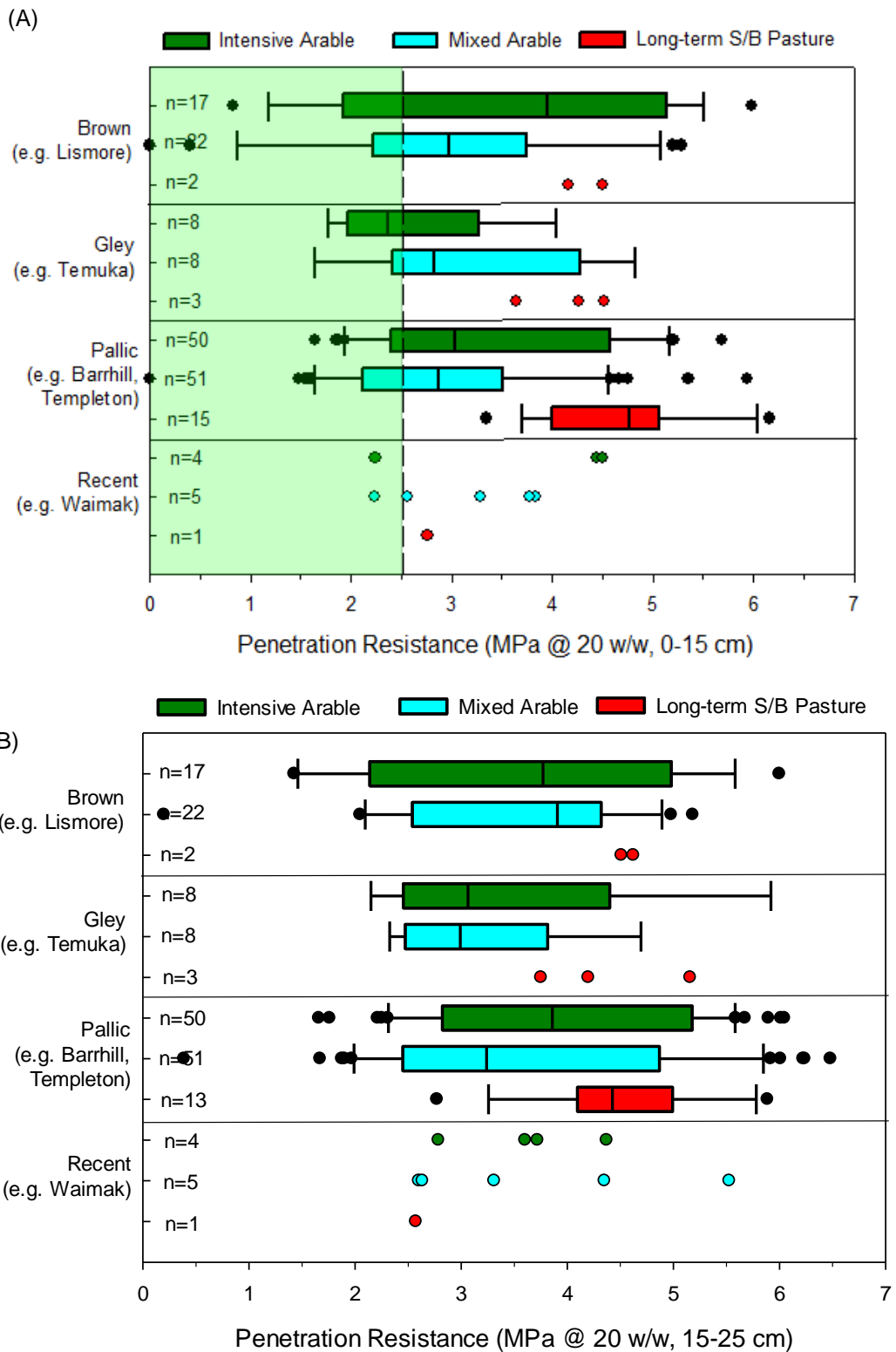


Figure 9. Penetration resistance for Canterbury sites sampled between 2013 and 2018 as part of the Environment Canterbury Arable & Pastoral monitoring programme. The box represents the middle 50% of stabilities, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. The recommended target (<2.5 MPa) is depicted by the green shading. (A) 0–15cm, (B) 15–25 cm.

4.2 Southland

Typical Southland crop rotations (at time of sampling) included frequent crops of wheat, barley and oats, often interspersed with peas and swedes. Mixed arable rotations typically included longer duration grass leys than other regions (e.g. Canterbury). Grass leys were often 4–10 years in duration, with equal or slightly shorter time in the intervening cropping phases. For the reported MA paddocks, the mean number of consecutive-years of cropping prior to sampling was 3.6 years (range 1–6 years, median 4 years).

Due to the common practice of including longer grass ley phases, it was difficult to determine (from the 10 years of management information available for each paddock) if some sites had recently undergone land-use change (from pastoral land use to cropping) or were in a crop phase following an extended grass ley phase of their rotation. At FAR's request, an inclusive approach was adopted for this region, whereby all paddocks sampled which meet the MA definition due to recent cropping were included, thereby assuming no land-use change had occurred.

Numbers of sites by soil order and land use in this region did not allow for more detailed investigation of soil order differences (Table 5).

Table 5. Numbers of Southland paddocks in the benchmarking dataset by soil order.

	Intensive arable crop	Mixed arable crop	Long-term pasture
Brown	12	10	3
Gley	3	6	3
Pallic	7	8	6
Recent	-	5	-
Total	22	29	12

4.2.1 Aggregate stability

The range of aggregate stabilities for both IA and LTP were near the higher end for the regions exemplified in this report. The data were reasonably normally distributed, with IA having a slightly extended tail towards higher aggregate stability values, and it was only this tail that overlapped with the LTP distribution (Figure 10). Median stabilities for LTP (2.5 mm MWD) were higher than for MA (2.1 mm MWD) and IA (1.4 mm MWD). The distribution of aggregate stabilities for MA partly overlapped both the IA and LTP categories.

In this region, the proportions of paddocks meeting the recommended target range within each land use category were: IA=41%, MA=93%, LTP=100%.

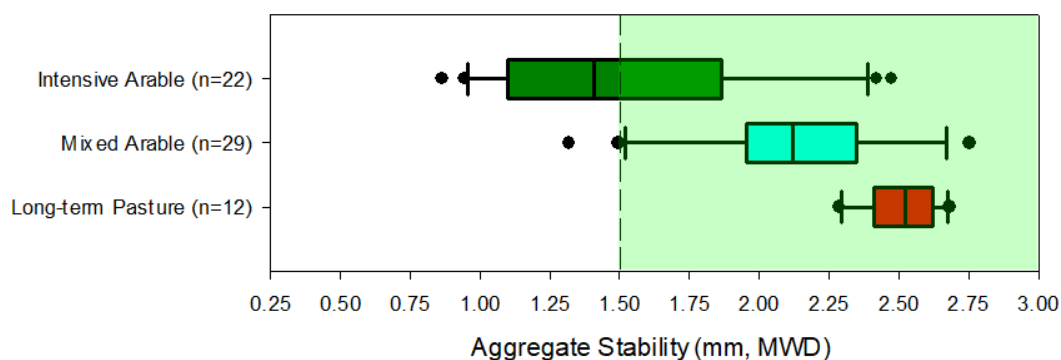


Figure 10. Aggregate stability for Southland sites sampled between 2002 and 2007 as part of the Land Management Index monitoring programme. The box represents the middle 50% of stabilities, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. The recommended target value to be above is the vertical dashed line with pale green shading showing desired aggregate stabilities (i.e. >1.5 mm mean weight diameter; MWD).

4.2.2 Soil organic carbon

For the surface soil (0–15 cm), LTP had a higher median SOC than IA (4.5 v. 3.0% C, Figure 11), with the distributions for both land uses being right skewed. The distribution of values for MA sites was centred between IA and LTP with median SOC of 3.8%. All the LTP and MA paddocks had C concentrations within the target range. Ninety-five percent of IA paddocks had SOC concentrations within the recommended target range, which is higher proportionally than in the other regions; however, the majority of paddocks were only just above the start of the target and therefore should be considered a priority for future monitoring. For example, the SOC at the 25th, 50th (median) and 75th percentiles was 2.7, 3.0, and 3.3% C, respectively. This means that if the recommended target range was lifted from 2.5 to 2.7% (i.e. an increase of 0.2% C), only 75% of the IA paddocks would have been within the target range. Variation of >0.2% C is often recorded within paddock replicates.

For the subsurface soil (15–30 cm), median C concentration for LTP (1.16%) was much lower than for IA (2.25%) and the distributions did not overlap (Figure 12). However, when data were presented on a volumetric basis, LTP still had greater C content than IA. This reflects tillage (and possibly stock treading) altering the bulk density of soil. It is for this reason that the preferred approach for assessing C stocks is via 'equivalent mass' (see Ellert & Bettany 1995 for details). While equivalent mass is beyond the scope of this report, and the data are not well suited to this purpose (because of the lack of depth increments), it is worth bearing this in mind.

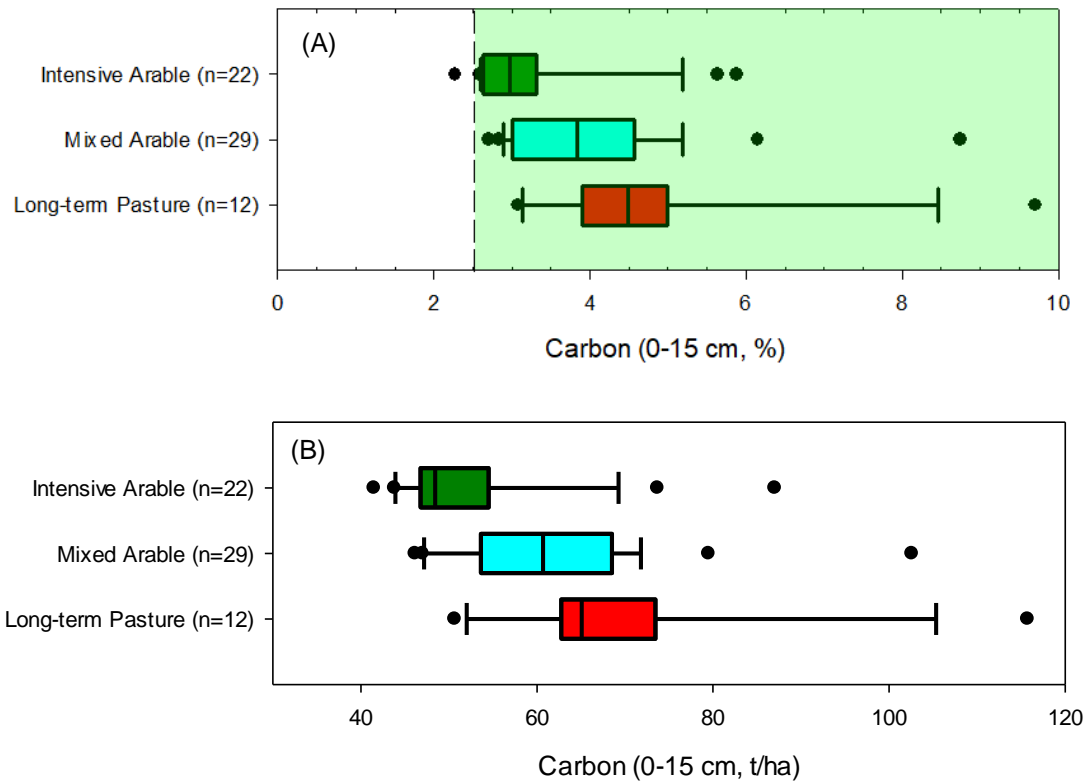


Figure 11. Total soil organic carbon concentration (0–15 cm) for Southland sites sampled between 2002 and 2007 as part of the Land Management Index monitoring programme. The box represents the middle 50% of carbon concentrations, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. A) Gravimetric data with recommended target value (for 0–10 cm, Hill & Sparling 2009) depicted by the vertical dashed line and green shading (i.e. >2.5% for the Brown, Gley, & Pallic soils); B) Volumetric data, tonnes of C per hectare.

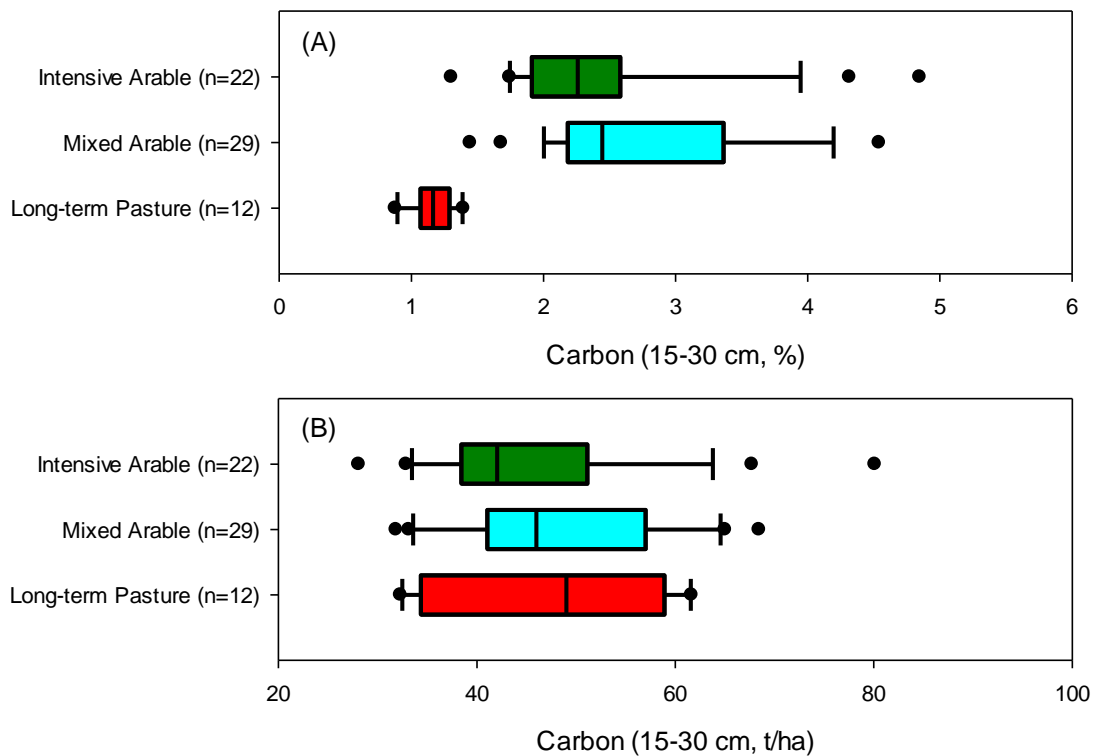


Figure 12. Total soil organic carbon concentration (15–30 cm) for Southland sites sampled between 2002 and 2007 as part of the Land Management Index monitoring programme. The box represents the middle 50% of carbon concentrations, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. A) Gravimetric data, % C, B) Volumetric data, tonnes of C per hectare.

4.2.3 Penetration resistance

The range of PR values recorded for the Southland region was similar to those in other regions; however, overall all land uses had lower PR values (Figure 13). This was unexpected, and despite investigation we cannot conclude why this is so. The distributions for all land use categories were right skewed for both 0–15 and 15–25 cm data.

For the surface soil (0–15 cm), 73% of IA, 62% of MA and 92% of LTP were within the target range. Low paddock replication and the heavy right-skewed nature of the distributions mean the addition of more paddocks to the dataset could have a large impact on the proportion of paddocks meeting the target.

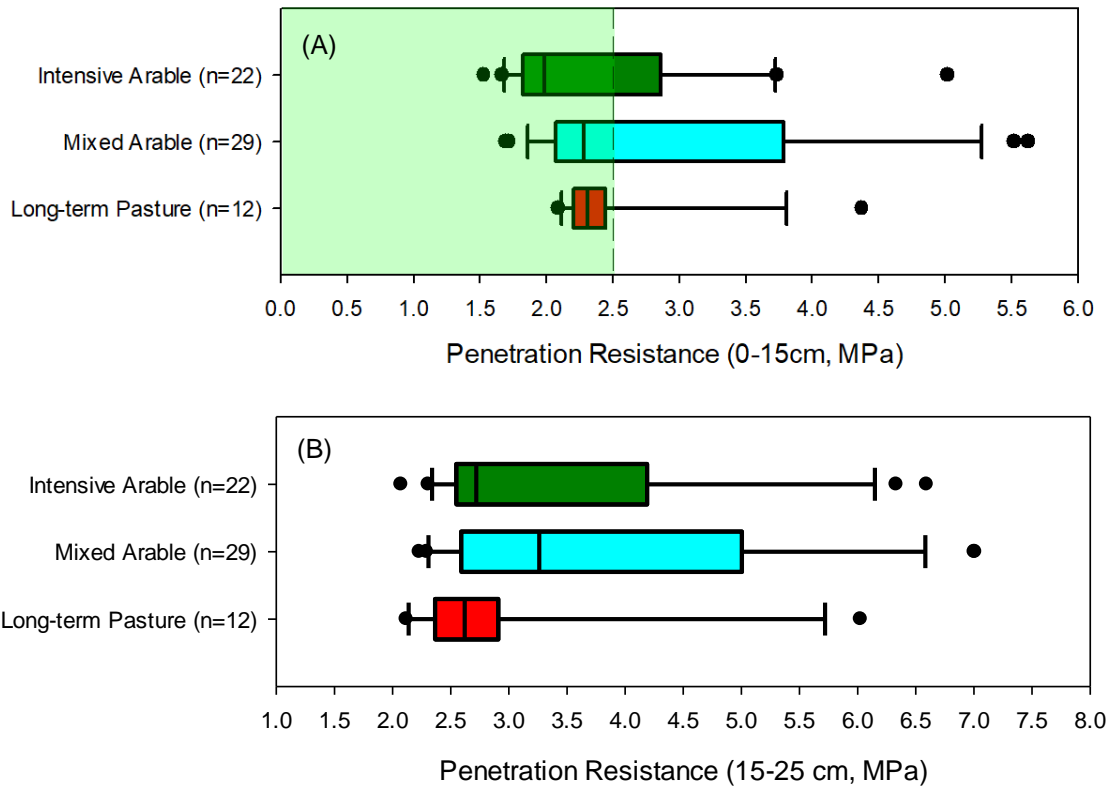


Figure 13. Penetration resistance for Southland sites sampled between 2002 and 2007 as part of the Land Management Index project; (A) 0–15 cm, (B) 15–25 cm. The box represents the middle 50% of stabilities, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. The recommended target (<math>< 2.5\text{ MPa}</math>) is depicted by the vertical dashed line and the green shading.

4.3 Waikato

Arable rotations in Waikato are generally not as diverse as in other regions. There are two main rotations: maize grown for grain, followed by winter fallow; and maize grown for silage, followed by a short-rotation grass over the winter. A small number of the LTP paddocks included here are actually located within the Auckland region; however, they were considered comparable to the Waikato cropping sites.

None of the MA paddocks sampled in this region were long-term cropping paddocks where grass leys were present. But rather, they were typically where the land use had recently changed from pastoral to maize production, and thus we were not confident they were under steady state conditions. As such, we excluded these paddocks from the benchmarking dataset.

Numbers of sites by soil order and land use in this region did not allow for more detailed investigation of soil order differences (Table 6).

Table 6. Numbers of Waikato paddocks in the benchmarking dataset by soil order.

Order	Intensive arable crop	Mixed arable crop	Sheep/beef pasture	Total
Allophanic	9	-	12	21
Brown	2	-	1	3
Gley	6	-	5	11
Granular		-	6	6
Total	17	-	24	41

4.3.1 Aggregate stability

Aggregate stabilities for IA paddocks in the Waikato region fit the pattern of a Normal distribution (Figure 14). The distribution did not overlap with that of LTP sites, which had much greater median stabilities: LTP median of 2.3 mm MWD, while IA median was 1.2 mm MWD. This indicates that the soil structure has been negatively affected by cultivation and that production under typical maize grain cropping rotations may be limited. However, the recommended target of >1.5 mm MWD has not been independently tested on Allophanic and Granular soils, or specifically tested for maize crops, so this statement must be treated with a high degree of caution. Compared with many small-grain cereal crops, the coarse root system of maize crops and the tendency for maize-grain crops to be followed a winter fallow period may contribute to a greater decline in aggregate stability values relative to that in pasture.

The proportion of paddocks meeting the recommend target range within each land-use category were: IA = 18%, LTP = 100%. It is prudent to acknowledge that proportions of paddocks from each order were not balanced within land uses.

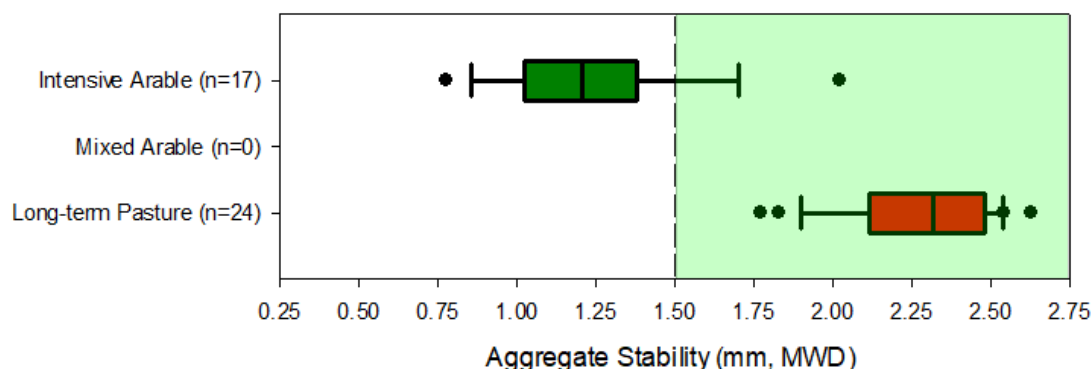


Figure 14. Aggregate stability for Waikato sites sampled between 2002 and 2007 as part of the Land Management Index monitoring programme. The box represents the middle 50% of stabilities, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. The recommended target value to be above is the vertical dashed line (i.e. >1.5 mm mean weight diameter; MWD).

4.3.2 Soil organic carbon

A very wide range of SOC (%) were measured in this region (Figure 15). This is a consequence of the diverseness of soil orders sampled. For example, Allophanic soils are dominated by allophane and are typically volcanic in origin, surface soils are normally 'light and fluffy' with low bulk densities, and they typically have higher C concentrations than the other soil orders sampled. Gley soils are heavier (than allophanic soils) and form beneath a high water table, are grey in colour due to reduction of iron caused from waterlogging, and typically have lower C concentrations than Allophanic soils. Allophanic soils made up 53% of the IA sites and 50% of the LTP. The distributions of C concentrations for IA and LTP pasture were bell shaped (i.e. Normal). While replication was insufficient to provide distributions and benchmarks for the individual soil orders, the SOC pattern for IA was Allophanic > Gley ≥ Brown, and for LTP pastures Allophanic = Granular > Gley = Brown. This pattern was applicable to both the 0–15 cm (Figure 15) and 15–30 cm (Figure 16) data.

For the surface (0–15 cm) soil, LTP had higher median C contents (% and t/ha) than IA paddocks. This trend was reversed for the 15–30 cm depth for gravimetric (%) data, although distributions overlapped and there was little difference between the land-use categories when presented on a volumetric (t/ha) basis.

Seventy-six percent of the IA, and 100% of the LTP met the recommended target range (applicable to the 0–15 cm sampling depth only). Four IA paddocks had C concentrations below the recommended target range: two Gley (out of six Gley IA paddocks sampled) and two Brown (two IA Brown soils sampled) soils. For comparison, all five Gley LTP pasture paddocks had C concentrations above the target range, as did the single Brown LTP pasture measured.

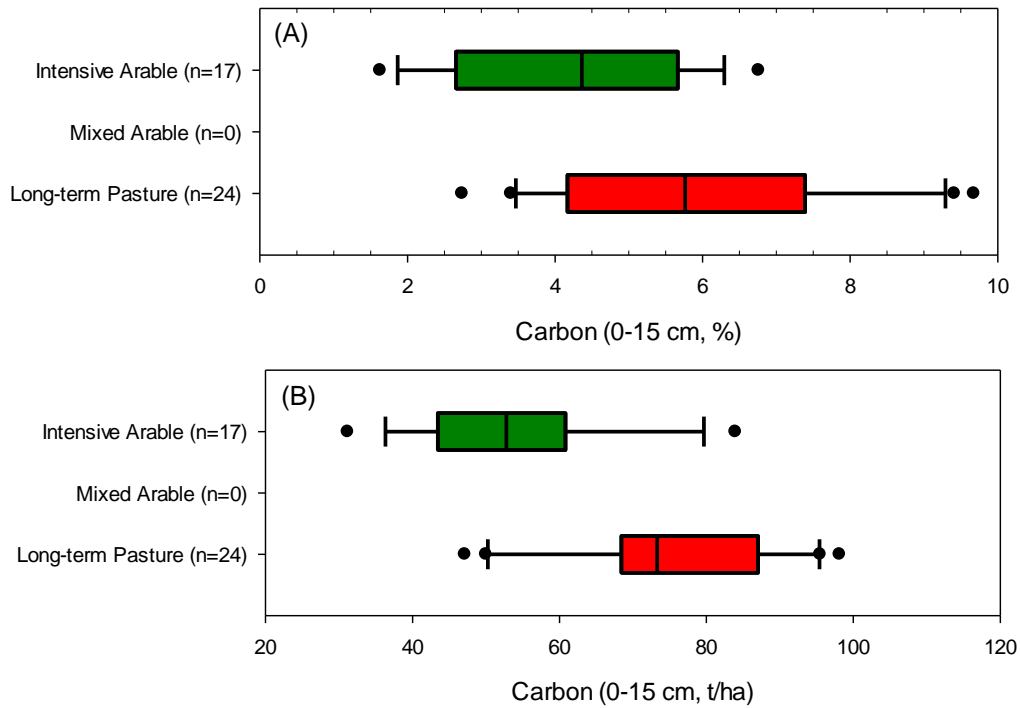


Figure 15. Total soil organic carbon concentration (0–15 cm) for Waikato sites sampled between 2002 and 2007 as part of the Land Management Index monitoring programme. The box represents the middle 50% of carbon concentrations, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. (A) gravimetric data, C % B) volumetric data, t C/ha. The recommended target range has not been presented on this figure, as two targets are applicable because of the diverse nature of the soil orders sampled.

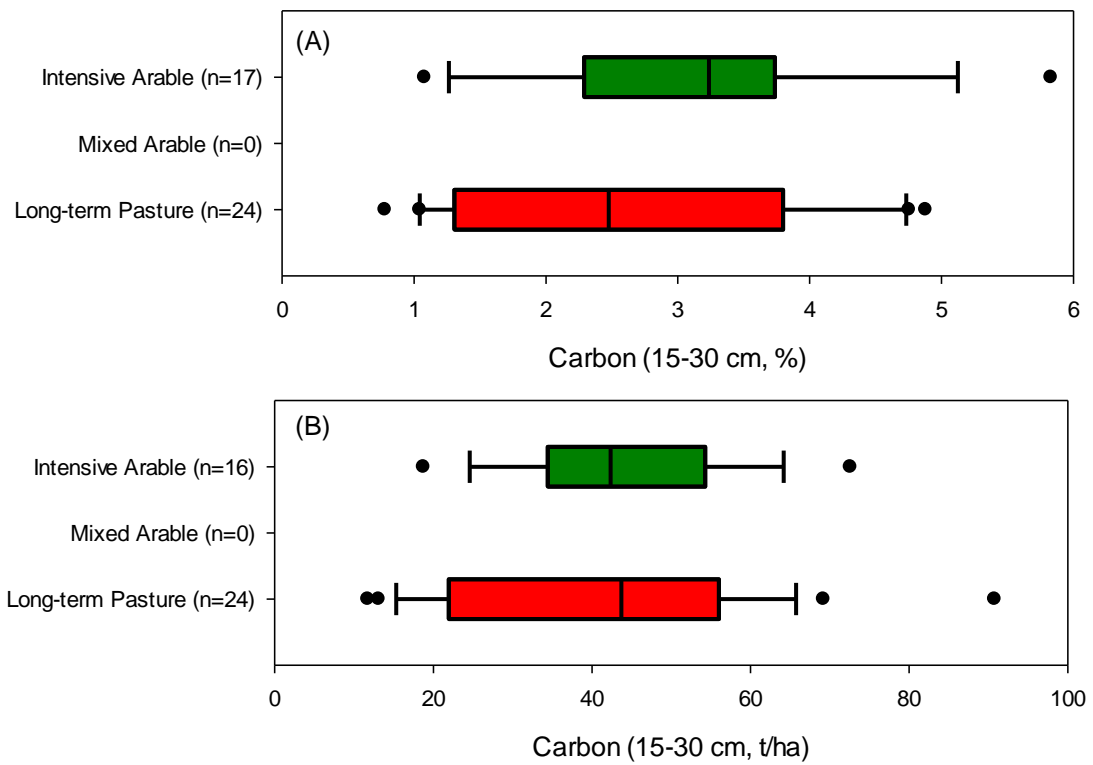


Figure 16. Total soil carbon concentration (15–30 cm) for Waikato sites sampled between 2002 and 2007 as part of the Land Management Index monitoring programme. The box represents the middle 50% of carbon concentration, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. (A) gravimetric data; (B) tonnes of C per hectare.

4.3.3 Penetration resistance

Frequent cultivation of the surface soil and lack of stock treading resulted in a lower PR under IA than LTP in the Waikato region, with median resistances of 2.6 and 3.3 MPa, respectively (Figure 17). Distribution shape was considered Normal for both land-use categories. Thirty-five percent of IA sites met the recommended target range for this indicator, while only 4% of LTP met the target.

There was little difference in PR values at the 15–25 cm depth.

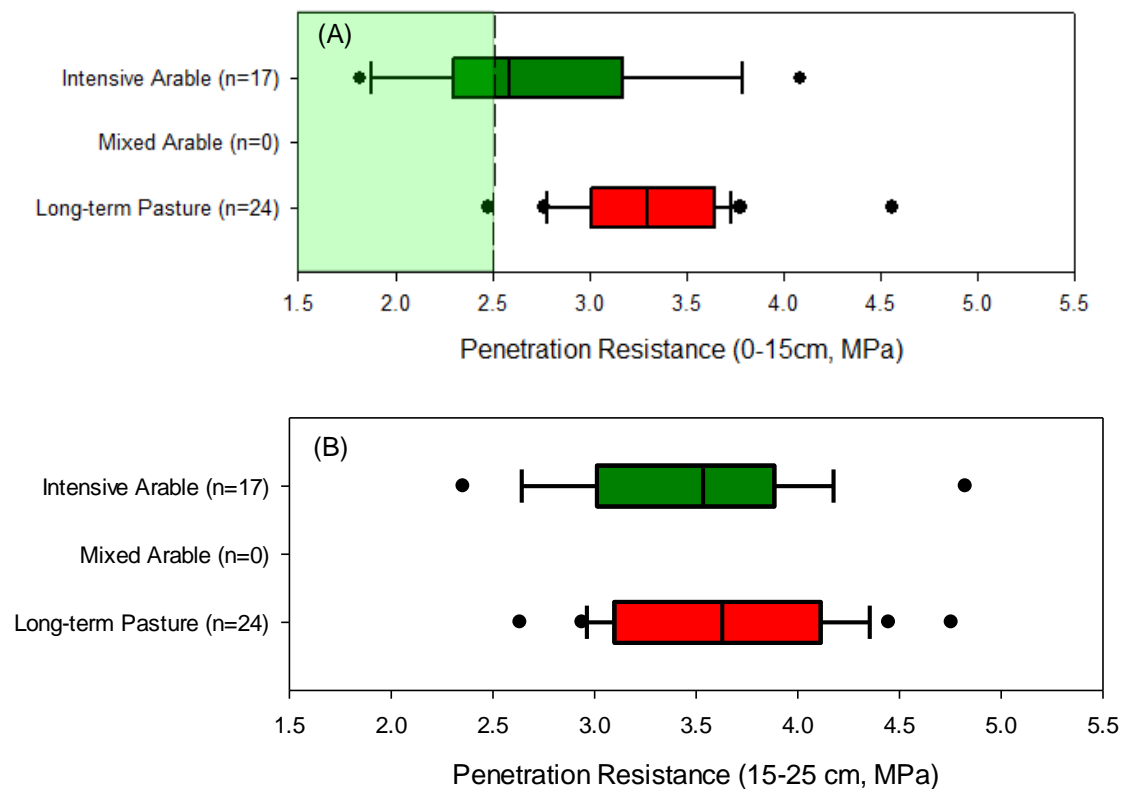


Figure 17. Penetration resistance for Waikato sites sampled between 2002 and 2007 as part of the Land Management Index project; (A) 0–15 cm, (B) 15–25 cm. The box represents the middle 50% of stabilities, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. The recommended target for 0–15 cm (<2.5 MPa) is depicted by the vertical dashed line.

4.4 Hawke's Bay and Gisborne combined

In the Hawke's Bay and Gisborne regions, both arable and vegetable crops are entwined into rotations, and there is often no clear 'main' enterprise other than cropping. The entwined nature of arable and vegetable cropping in these regions means arable soil quality is unable to be independently assessed in the absence of vegetable cropping. Given this, all cropping paddocks that met the other duration requirements have been included in the analysis for this region, regardless of the inclusion of frequent vegetable crops in the rotation, and are referred to as intensive crop (IC) (Table 7). Typical Hawke's Bay rotations include FAR levy crops such as barley, wheat, maize grain, ryegrass seed and open-pollinated vegetable seed crops (e.g. carrots): interspersed with non-levy crops such as process crops of peas, beans, carrots and sweetcorn and with fresh-market squash, greens, tomatoes and onions. The wide diversity of crops grown also means a wide range of tillage practices are employed, such as strip-tilling and the formation of flat beds for tomatoes.

Table 7. Numbers of Hawke's Bay and Gisborne paddocks in the benchmarking dataset by soil order.

Order	Intensive crop		Sheep/beef pasture		Total
	Gisborne	Hawke's Bay	Gisborne	Hawke's Bay	
Allophanic				3	3
Brown				1	1
Gley	11		1		12
Pallic				8	8
Recent	11	13	3	9	36
Total	22	13	4	21	60

4.4.1 Aggregate stability

The range of aggregate stability values measured in Hawke's Bay and Gisborne for the IC land-use category was the widest of all regions (Figure 18). We attribute this to the inclusion of both arable and vegetable crops, and the wide range of management practices undertaken within these regions. Distributions for IC and LTP overlapped, with median stabilities of 1.2 and 2.1 mm MWD, respectively. The distribution was left skewed for IC, indicating a few sites were skewing the distribution towards lower stabilities.

Twenty-six percent of IC and 92% of LTP met the target range.

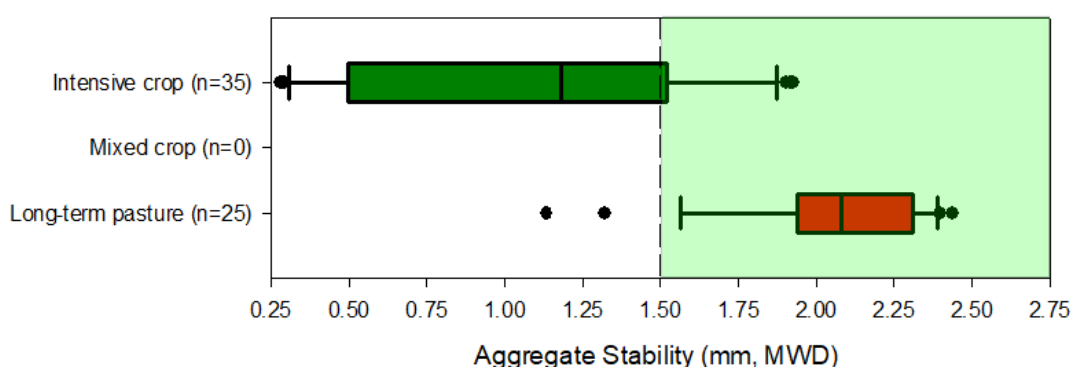


Figure 18. Aggregate stability for Hawke's Bay-Gisborne sites sampled between 2002 and 2007 as part of the Land Management Index monitoring programme. The box represents the middle 50% of stabilities, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. The recommended target range is shown with green shading (i.e. >1.5 mm mean weight diameter; MWD).

4.4.2 Soil organic carbon

Surface soil (0–15 cm) SOC distributions for IC and LTP pasture overlapped (Figure 19), with median concentrations of 2.4 and 3.4%, respectively. The distribution for IC was approximately Normal, while LTP was right skewed. The target range has not been plotted on the graph, as it is soil order-dependent, and three different recommended targets are applicable to the paddocks sampled (>2% for Recent soils; >2.5% for Brown, Gley and Pallic soils; and >3% for Allophanic soils). The proportion of paddocks meeting the appropriate recommended targets was 57% of IC and 77% of the LTP paddocks.

There was little difference in SOC between the land-use categories for the subsurface soil (15–30 cm) for both gravimetric and volumetric data (Figure 20).

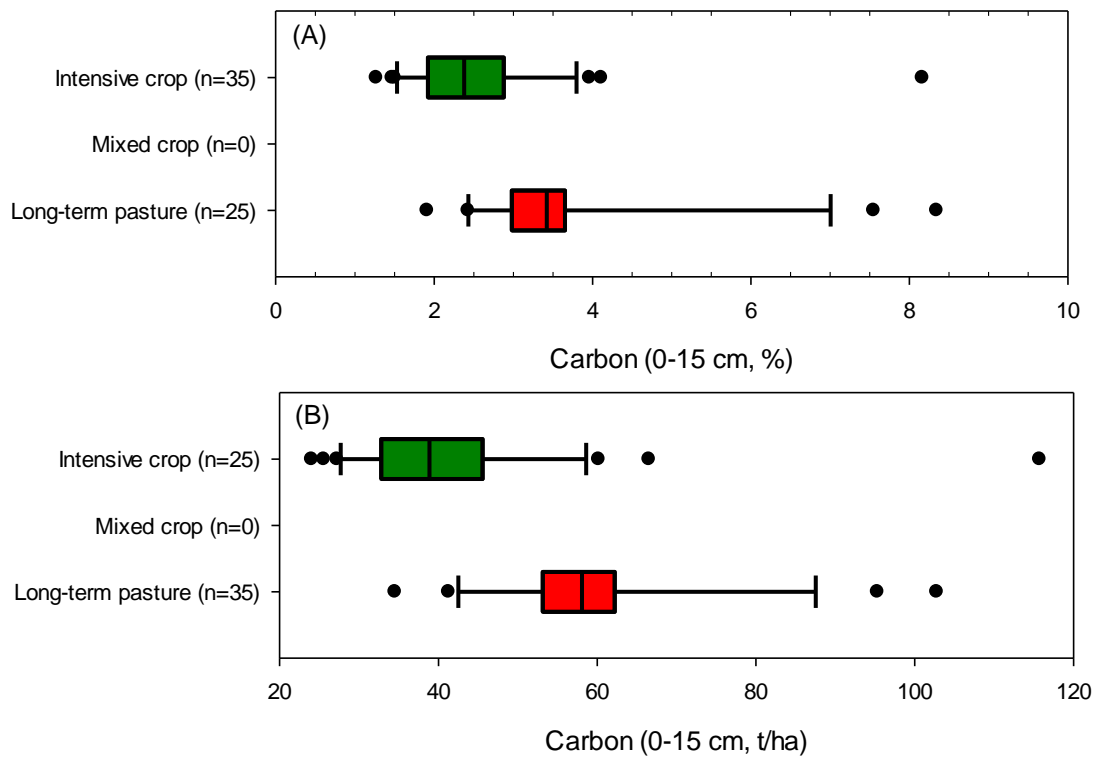


Figure 19. Total soil carbon concentration (0–15 cm) for Hawke’s Bay-Gisborne sites sampled between 2002 and 2007 as part of the Land Management Index monitoring programme. The box represents the middle 50% of carbon concentrations, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. (A) gravimetric data; (B) volumetric data (t C/ha).

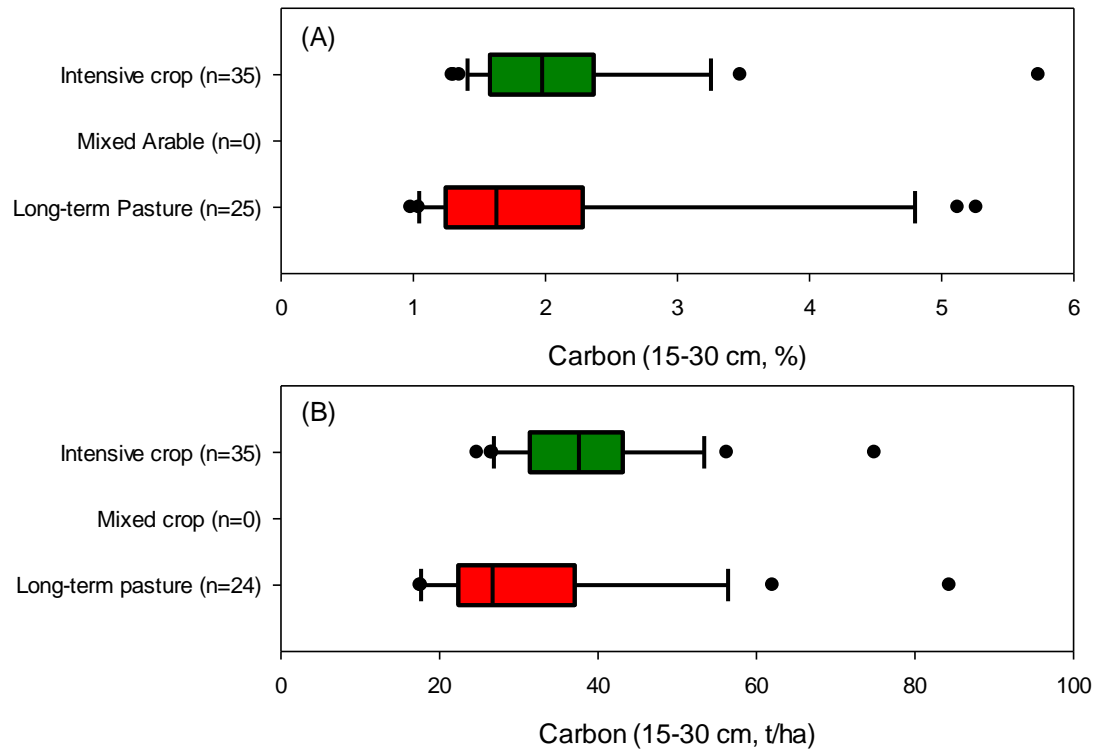


Figure 20. Total soil carbon concentration (15–30 cm) for Hawke’s Bay-Gisborne sites sampled between 2002 and 2007 as part of the Land Management Index monitoring programme. The box represents the middle 50% of carbon concentration, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. A) gravimetric data; B) tonnes of C per hectare.

4.4.3 Penetration resistance

For the surface soil (0–15 cm) there was little difference in median PR between the IC and LTP land-use categories (Figure 21); however, the distribution shape differed, with IC displaying a Normal/bell shaped curve, while the LTP distribution was right skewed.

Moreover, Gisborne sites tended to have higher PR values than Hawke’s Bay sites for both land-use categories. Overall, 36% of LTP met the target range (<2.5 MPa), all of which were from the Hawke’s Bay region (e.g. 42% of Hawke’s Bay sites). For IC sites, across both regions, 51% of sites met the target range; however, by region the statistics fall in Hawke’s Bay’s favour, with 71% of sites meeting the target while only 36% of the Gisborne IC sites met the target.

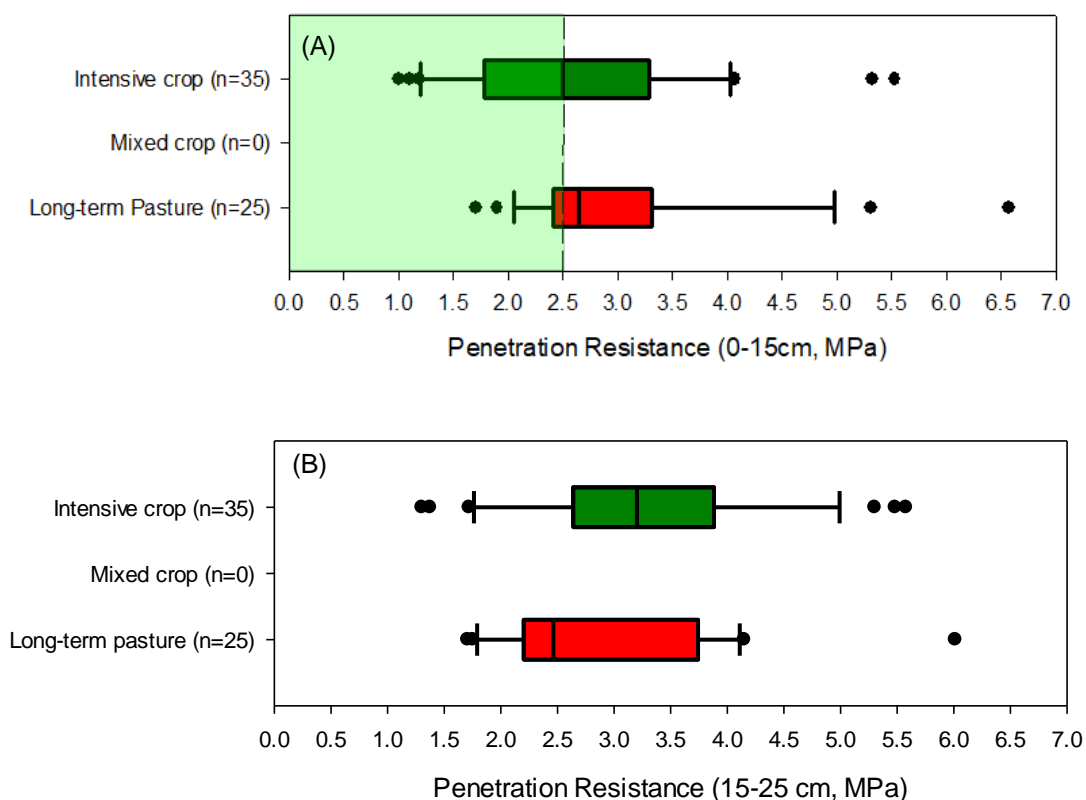


Figure 21. Penetration resistance for Hawke’s Bay-Gisborne sites sampled between 2002 and 2007 as part of the Land Management Index project; (A) 0–15 cm, (B) 15–25 cm. The box represents the middle 50% of stabilities, while whiskers represent the 10th and 90th quantiles. The line inside each box is the median value for this land use. The recommended target (<2.5 MPa) is depicted by green shading.

5 NEXT STEPS

The 'benchmarks' provided in this report describe the 'current state' of soil quality against a known state (i.e. the target range or sheep/beef pasture), thus providing a snapshot of soil health at a single point in time. The next step is to conduct future assessments of soil quality to monitor trends with time (i.e. improvement or degradation), allowing a more transparent perspective on the sustainable management of soils under arable cropping. To this end, FAR may wish to establish a soil quality monitoring programme for long-term tracking of quality for a range of management practices and soil types. Plant & Food Research would be able to assist with developing a structured approach to this, building on the success of the ECan A & P and LMI monitoring programmes. Furthermore, there may be opportunities for FAR to partner with PFR and Environment Canterbury to investigate soil quality changes with time more fully, using the repeat monitor data collected within the ECan A & P monitoring programme. We also suggest careful consideration be given to the duration of crop type history information collected for each site for any future monitoring.

The national target ranges applied within this report are useful guides to soil quality, but require further research to verify their impacts on critical soil functions. These include soil functions that affect both production and environmental outcomes, as well as understanding how they respond to changes in management. Some of these relationships are being explored in the MBIE-funded *Soil Health and Resilience* programme (led by Maanaki Whenua – Landcare Research) but further research is needed to define critical threshold and to quantify the impacts on both crop production and the environment (e.g. nitrate leaching risk). For example, soil organic matter provides functions such as increased water-holding capacity, nutrient supply, a food source for biota, and improves soil physical condition by contributing to soil structure formation (organic compounds that bind soil particles into aggregates). The wide range of functions provided by soil organic matter (of which SOC is an indicator) would be hard to capture in a single target. Thus more than one target per indicator may be required depending on the context of interpretation, and whether an environmental or production focus is desired. Regardless of any future changes to target ranges, the benchmark data report here provide a useful baseline against which future changes in these soil quality indicators can be assessed.

Furthermore, the SOC target range used in this report is from the LMF and highlights paddocks with SOC below "depleted", which implies that values in the "depleted" range of SOC are acceptable. Further research is needed to verify whether values in this range have any adverse effects on soil functions that may affect crop production or environmental outcomes (e.g. nitrous oxide emissions). This is an important point to consider when disseminating these results. Furthermore, target ranges should also be reviewed as scientific knowledge advances. In the case of SOC, the current targets are concentration based, dependent on soil order, and were adopted from a production focus. Recent work has shown these target ranges fail to recognise that soils have very different capacities to stabilise SOC. For example, the sequestration and loss of soil SOC on arable cropping farms could be evaluated by monitoring changes in soil C stocks relative to the capacity of soils to stabilise soil SOC. In simple terms, the concept is: an individual soil has a finite ability to store C, known as its stabilisation capacity, the amount of C present at any time can be expressed as a proportion of its stabilisation capacity. In a study of New Zealand soils (190 sites, including arable and horticultural cropping, and long-term pastures) Lawrence-Smith et al. (2018) demonstrated that over half the Brown, Gley and Pallic soils would not be able to reach the LMF SOC ample category even if current C was equal to the stabilisation capacity. However, for the Allophanic soil, all sites had the ability to reach the

ample category, and the depleted category was ineffective for identifying sites which had lost significant quantities of C. There were some limitations to the study, and further work is required to prove the concept, however this indicator has promise for future benchmarking activities.

Only a small proportion of the soil quality indicators measured in the LMI and ECan A & P monitoring programmes have been investigated in this report. A comprehensive review of soil quality indicators and data suitable for benchmarking is beyond the scope of this report; however, FAR may want to consider including the following additional indicators (which were measured in the LMI and/or ECan A & P programmes): macro-porosity, hot water-extractable carbon, total nitrogen, anaerobically mineralisable nitrogen, Olsen phosphorus, bulk density, and heavy metals.

Initially hot water-extractable C (HWC) was identified as an indicator of interest by the FAR for benchmarking; however, on further discussion the decision was made not to include it in this report. This was a reflection that methodologies applied in New Zealand differ between commercial and research laboratories. Methodology applied in the LMI and ECan A & P monitoring programmes was consistent, so relative differences in HWC between land use categories and regions could be reported. Samples analysed within these programmes were previously air-dried and analysed with sequential cold and hot water-extraction steps as per the published method of Ghani et al. (2003), with a 1:6 soil:water ratio. However, we understand that HWC method used by AgResearch involves a single hot-water extraction of air-dried soils using a 1:10 soil:water ratio (while a sequential cold and hot water-extraction is undertaken with field-moist soils). These methodological differences will give differing results; however, the magnitude of differences and whether relationships are consistent across a wide range of C concentrations and soil types is unknown. PFR is furthering work within this area, including optimising methodologies for determining hot water-extractable nitrogen (HWN). Recent studies have shown HWN to be a reliable indicator of a soil's ability to supply plant-available N in New Zealand's pasture and cropping soils (Curtin et al. 2017; Lawrence-Smith et al. 2018). In future, a methodology where both HWC and HWN can be determined on the sample extract would be preferable. The inclusion of HWC in future benchmarking activities should be reviewed as the research progresses.

Ultimately, FAR's intention is to establish benchmarks of soil quality that can be used by the industry and individual farmers to track changes in the sustainable management of their soils over time. Currently aggregate stability analyses are not offered by any New Zealand commercial laboratories. Additionally, penetrometers are not widely available to farmers. This presents a barrier to individual farmers finding these benchmarks helpful. While this practical aspect of benchmarks being of use to individual farmers is beyond the scope of this report, it certainly warrants further discussion. Previously PFR have developed soil quality test kits for use on-farm, which included a more rudimentary aggregate stability test than is presented in this report. These test kits were originally produced in the early 2000s, with limited uptake. The current environment, which includes greater awareness of soil quality issues and a greater focus on self-monitoring and compliance, may provide an appetite for revisiting the regular on-farm monitoring of soil quality and how to best to achieve this to support farmer and industry objectives.

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APPENDIX

Field sampling methodology for Environment Canterbury Arable and Pastoral and Land Management Index monitoring programmes

Within each paddock, soil samples were collected at three separate sample locations. These locations were selected to represent the main productive area of the paddocks and so excluded areas near fence lines, headlands, gates, troughs, etc. At each sampling position the following samples were collected:

- Three soil cores (70 mm diameter), to 15 cm depth, used for the majority of the analyses
- Three soil cores (25 mm diameter), 15–30 cm depth
- One intact soil core (100 mm diameter), to 7.5 cm depth, for macro-porosity determination (project and year dependent, data not relevant to this report)
- One sample (15 x 15 cm square), to 10 cm depth, for calculation of aggregate size distribution (data not relevant to this report)
- Five penetration resistance readings at each of two depths (0–15 and 15–25 cm).

Soil cores were sealed in plastic bags and immediately stored in a chilled environment until processing.

In cropped paddocks, or paddocks in pasture where drill lines were evident, cores were collected to represent the entire paddock. This was achieved by collecting one of the three cores from each of the following positions (albeit from different drill lines) at each replicate sample location:

- Directly over the drill line
- The centre point of two parallel drill lines
- Adjacent to the drill line (i.e. the zone between the two cores above).

Soil cores were collected using a recognised coring technique. Each 0–15 cm core was collected using a stainless steel corer of 23 cm in total length. The outside of the corer was carefully etched (by a precision engineer at manufacturing) at 15 cm. The corer was placed on the soil surface, a wooden block was then placed over the corer and the corer was tapped into the ground using a hammer until the 15-cm etch mark was level with the soil surface. A metal rod was then placed through the holes in the corer. Using the pin, the corer was twisted before it was lifted, to promote a smooth base to the core. To ensure the correct volume of soil was collected, if the base of the soil core was not level with the base of the corer, the sample was discarded and a different sample point was chosen. The 15–30 cm core was collected using a standard soil fertility corer that was placed into the 0–15 cm hole. An anvil was inserted into the top of the corer and hit with a hammer until the etched 30-cm mark on the corer was level with the soil surface. A metal rod was used to withdraw the corer, as for the 0–15 cm corer. This coring technique ensured the entire volume of soil from 0–15 and 15–30 cm was collected, regardless of whether soil shattered or compacted within the corer.

Soil sampling under most arable and vegetable cropping paddocks was carried out either between crop harvest and cultivation for the subsequent crop, or prior to crop harvest. For vegetable crops where the soil is disturbed during harvest (such as potato, carrot, and onion

crops), sampling was carried out prior to crop harvest. No sampling was carried out for at least 2 months following cultivation or any soil disturbance.

For each paddock, soil type information was determined using a combination of the most recent and accurate available soil maps and the knowledge of local farmers and regional council staff. The only exceptions to this were (1) where detailed profile descriptions were conducted for 13 paddocks in the Waikato region as part of the relevant regional council's annual soil quality monitoring project, and (2) where classifications were only made to the order level (55 paddocks). The soil order classification for each site (based on type/series information) was made with the expert knowledge of PFR, Maanaki Whenua – Landcare Research and the relevant regional council.

Laboratory analysis and data calculation

All samples were processed and analysed at PFR's Soil Water and Environment laboratory (PFR SWE laboratory) at Lincoln.

Initial sample processing

The laboratory procedure for 0–15 cm samples was as follows:

1. Each bagged sample was weighed and recorded. An average bag weight was used to correct these field-moist weights.
2. Sample was then sieved to <4 mm, homogenised, and a subsample taken for oven-dried water content (105°C). Any stones >4 mm were brushed free of soil and weighed.
3. A subsample of soil was then passed over a 2-mm sieve to separate aggregates 2- to 4-mm in size prior to air-drying at 25°C, and determination of aggregate stability via wet-sieving (Section 7.2.2).
4. Another subsample of soil was then sieved <2 mm and air-dried (~25°C) and retained for SOC determination (Section 7.2.3), as was used for additional indicators not described here in this report.

The laboratory procedure for 15–30 cm samples was the same except that step 3 was not undertaken, as aggregate stability was only determined at the 0–15 cm depth.

Aggregate stability

Aggregates 2- to 4-mm diameter were separated from the whole soil by gentle sieving as described above, and then air-dried at 25°C before aggregate stability determination using a wet-sieving method (Kemper & Rosenau 1986). The air-dried 2- to 4-mm aggregates (50 g) were sieved underwater for 20 min on a nest of sieves (2.0, 1.0 and 0.5 mm diameter). The soil remaining on each sieve was weighed after oven drying at 105°C. The weight of material remaining on the 2-mm sieve was corrected for stone content. The aggregate stability was expressed as a mean weight diameter (MWD):

$$MWD = \sum_{i=1}^n x_i w_i$$

where X_i is the mean diameter of adjacent sieves and W_i is the proportion of the total sample retained on a sieve.

Total soil organic carbon

Each <2 mm sieved sub-sample of soil for SOC analysis was mixed thoroughly and oven-dried overnight at 60°C. Total C (and N) determinations were made on single 0.4-g soil samples by an automated dry combustion (or Dumas) method using a LECO CNS-2000 analyser operating at 1050°C. Samples were weighed using Mettler balances (calibrations as described above) and read to 4 decimal places. For 0–15 cm samples, the total C and N (%) for each replicate sample location was applied in calculation of soil C stocks. The average C (%) for each paddock sampled was used to develop the benchmarks.

The C contents in t/ha for both sampling depths were calculated by multiplying the gravimetric C concentration by the 'factor for volume conversion' and the sample depth (i.e. 15 cm). Carbon stocks for each replicate 0–15 cm sample were calculated. These stocks were averaged for each paddock.

Penetration resistance

Penetration resistance was measured in the field using a cone penetrometer. For each depth, the five readings at each of the three locations within the paddock were averaged. To enable comparison of PR data across a wide range of soils, with differing moisture contents at field measurement, the three values of PR per paddock were then paired with their relevant soil water contents. Readings were then normalised to a fixed soil moisture content (20 g g⁻¹), using a power function, $PR = a \cdot \theta_g^b$ (Hu et al. in preparation). This single-equation model was sufficient to normalise PR for different soil textures and land uses; however, the parameters of a and b were different for each depth. Fitted values of parameters a and b were 0.825 and -0.785 for 0–15 cm and 0.857 and -0.878 for 15–25 cm, respectively. Once normalised, the three paddock replicate PR values were averaged, to give a single PR value for each depth and paddock, which was used to calculate the distributions and benchmarks. Further research is needed to test the assumption that normalising PR values to a fixed soil water content is preferable to normalising values to a soil-specific measure of soil water content, e.g. field capacity soil water content.



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