7.9 Soil compaction

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Preamble: There are multiple measures for soil compaction. These indicators for soil compaction can be measured at a single points in time or multiple points in time to determine the degree to which soil is compact when comparing against established target values. Soil compaction is responsive to physical actions, including biological activity – this means multiple points in time are more robust; near-surface compaction can change seasonally. Indicators of compaction include:

- Macroporosity (typically volumetric percentage of soil pores greater than 30 or 60 microns, or other as specified in the literature) [1, 2]. The definition using pores greater than 30 microns tends to be used by AgResearch and the Land Monitoring Forum[1], with pores greater than 60 microns used in studies by Manaaki Whenua – Landcare Research (MWLR) [2], and the MWLR laboratory [3]. Compaction is indicated by low macroporosity.
- Bulk density – well used in the literature and by the Land Monitoring Forum but is useful within similar soils, and a poor measure across different soils (e.g., Organic and Pumice Soils intrinsically much lower than Pallic and Ultic Soils)
- Aggregate stability – well used as an indicator under cropping, in the literature for cropping land use and by the Land Monitoring Forum particularly for cropping land use, and in some reviews, studies [4, 5]. It could be used as an indicator of compaction (compact soil has more ‘massive/blocky’ aggregates), but more commonly used as indicator of structural degradation.
- Penetration resistance – well-used in the literature particularly to indicate restrictions to root growth but is responsive to moisture content, can be subject to operator influence (so not a good indicator in my opinion)
- Infiltration and other measures of water flow through pores e.g., saturated or unsaturated hydraulic conductivity.

State of knowledge of the “Soil Compaction” attribute: Excellent / well established – comprehensive analysis/syntheses; multiple studies agree. There is a comprehensive body of knowledge on how soil compaction through animal treading and machinery for arable cropping affects soil physical properties, with good knowledge on crop yields.

Part A—Attribute and method

A1. How does the attribute relate to ecological integrity or human health?

The attribute relates to ecological integrity (not human health). Soil compaction usually occurs in unsaturated soil (moderately wet or below field capacity) [1]. Soils can only be compacted when air is present (otherwise they are deformed); the response of a soil to compaction is related to soil moisture (soils being more resistant when dry). Typically, some large air-filled pores in soil get compressed when soil is compacted by various means e.g., stock-treading, machinery trafficking. The resulting soil structure can restrict air, gas and water movement in soil, thus affecting plant root and shoot growth, arrangement of pores, and therefore a range of ecosystem services such as storage and filtering of water, biomass production, nutrient cycling, carbon storage, soil biodiversity, and physical stability [1, 5]. Soil compaction can also affect gas exchanges, and biological processes such as C and N mineralisation, nitrification and denitrification [6]. Soil function underpins key ecosystem services such as pasture and crop production, nutrient cycling and contaminant losses [5, 6], so soil compaction affects soil function. Compact soils limit root growth through loss of aeration and/or resistance to root penetration – this can limit plant establishment e.g., pine trees [7], crops, and plant succession (favouring species tolerant of compaction), drought resistance and vulnerability to pathogens [8]. For urban areas and perennial species impacts of compaction are greater in non-irrigated areas and undrained areas. Over-compaction of the soil when heavy machinery is used in urban areas impacts on drainage capacity and the ability of roots to penetrate the subsoil [9].

A2. What is the evidence of impact on (a) ecological integrity or (b) human health? What is the spatial extent and magnitude of degradation?

There is a good body of evidence on how compacted soil affects pasture and crop yields, plant root growth; as soil becomes more compact, plant yield and root growth generally decline [1, 10, 11]. There is some evidence on the impact of soil compaction on macrofauna, such as worms where compaction limits earthworm abundance and activity [5, 10]. There are only a few recent studies on the impact of soil compaction on soil bacterial communities and their diversity [13, 14] and the mycorrhizal community.

The weight of evidence and state of knowledge is very strong on how soil compaction affects soil properties from as shown by multiple literature reviews [1, 5, 6], and from New Zealand regional and national reporting [19-25]. Macroporosity, bulk density and aggregate stability are commonly used indicators [1, 5, 6], [19-25]. Spatial extent is clearly linked to soil management practices and moisture variation at the time soils are vulnerable.

A3. What has been the pace and trajectory of change in this attribute, and what do we expect in the future 10 - 30 years under the status quo? Are impacts reversible or irreversible (within a generation)?

Considerable research on soil compaction has been conducted in New Zealand, primarily in the context of agricultural, and plantation forestry [7, 28], and to a lesser extent in horticultural production [27]. Such studies evaluate how soil compaction is affected by different grazing practices, soils or mitigations [6, 30-34], crop management and practices [5, 35], and farm system modelling of the impact of pugging on pasture yield across a farm system [36, 37], and plantation harvesting and site preparation [7, 28]. Pugging primarily occurs when the soil is very wet, causing visual soil deformation, whereas compaction is more 'hidden' i.e., below the surface. A very few studies have studied soil compaction associated with large-scale infrastructure (dams, mines, roads and urbanisation) [38, 39].

Changes in soil compaction over long periods of time have primarily been assessed in regional council state of the environment soil quality monitoring but few trends have been observed over the long-term [19, 22, 40]. No trend in macroporosity was found in drystock farming, dairy farming, orchard/vineyard land use, or cropping from 1995 to 2018 [20, 40]. Similarly, no trend in bulk density was found for drystock farming land use from 1995 to 2018 [40]. An exception is changes in compaction following remediation actions to prepare sites for establishment of plantation forests – these studies show responses last >20 years, being 'locked in' as root systems proliferate in loosened zones.

Most experimental research studies that have examined changes in soil compaction over time, have typically been up to about three years duration, or up to five years duration [41,42]. Most studies have tended to be short term changes over time (< several years) following treatments to make the soil compact. However studies examining recovery/rejuvenation of compaction are much fewer, e.g., in cropping [43] or pasture [41].

Compaction is reversible (through natural process and active management for remediation) to some extent especially at shallow soil depths, e.g., 0–10 cm, but is much more difficult to reverse at deeper depths to 20 or 30 cm under dairy cattle grazing especially with irrigation [46,47]. Recent evidence indicates from several indicators e.g., macroporosity, bulk density, available water capacity etc, soil compaction under dairy farming is occurring to depths of about 30 cm, i.e., typical depth of topsoil [46, 47]. Some reversibility can be from natural processes (e.g., cracking, shrink/swell, frosting, worm activity etc) given sufficient time [41] in shallow depths, or from management practices including mechanical subsoiling/aeration equipment using a tractor for deeper soil e.g., subsoil depths [48-50]. Cultivation is not generally practical for pasture except at pasture renewal.

On cropping farms, continued vehicle movement or ploughing on wet soil, can lead to soil compaction sometimes called a 'plough pan' or a 'pan' i.e., not a natural feature. But a pan can occur at deeper depths caused by ploughing, and so is more difficult to reverse, unless something like subsoiling or soil aeration is used. Soil compaction on cropping farms in also reviewed by [5], and there are numerous New Zealand studies [46], and international studies [47] (if more detail is needed). Vineyard compaction mitigation is through compost application, managing vegetation cover, changing machinery ground-pressure, etc [96].

Compaction caused by ground-based harvest of plantation forests is ameliorated to at least 50 cm depth using one-off mechanical loosening between harvests that also raise the soil surface and can be designed to also enhance drainage. For example, the effects of deep ripping in forest, on a Pumice soil to 80 cm depth lasted 25 years [53]. These techniques are also used to ameliorate deep compaction associated with infrastructure developments (R Simcock pers comm). Deep ripping in pine forest soils reduced penetration resistance and increased the stem volume of *Pinus radiata* [54], and increased seedling height and survival [55].

New Zealand has experienced significant land use intensification such as expansion of the dairy industry and irrigated land, and both in combination, over the last 20–30 years [2, 5, 47]. The change of land use to irrigated dairying or irrigated beef cattle grazing has resulted in more soil compaction than under non-irrigated land [15, 47].

A4-(i) What monitoring is currently done and how is it reported? (e.g., is there a standard, and how consistently is it used, who is monitoring for what purpose)? Is there a consensus on the most appropriate measurement method?

Regional council SoE soil quality monitoring includes macroporosity and bulk density at 0–10 cm depth across New Zealand [24, 56, 57], with methods specified in the NEMS for soil quality and trace elements. Data are usually compared to provisional target values for these soil quality indicators [41]. Many councils undertake monitoring yearly and report per year, e.g., Wellington region, whereas others undertake monitoring and reporting 5-yearly e.g., Taranaki region. Several studies provide an assessment of regional soil quality monitoring over time [19, 21, 22, 40], with some additional targeted studies on aspects of compaction also available [25, 58, 59]. At the time of writing, most councils have undertaken monitoring and have published results through reports. There appears to be few details or reports published from some councils (e.g., Horizons, Gisborne), while other councils have recently commenced monitoring (Otago) or have undertaken monitoring intermittently (Southland). No soil quality monitoring has been undertaken in the West Coast region.

In Canterbury, under long-term arable production, aggregate stability (used a lot in cropping due to aggregate break-down), macroporosity, bulk density, penetration resistance etc are used to monitor soil quality [58].

There are variable terms used, and variable ways in which macroporosity can be measured, which has led to confusion and inconsistency in the reporting of macroporosity in previous studies [60]. The NEMS specifies uses the term air-filled porosity, for macro-porosity measured at -10 kPa.

A4-(ii) Are there any implementation issues such as accessing privately owned land to collect repeat samples for regulatory informing purposes?

For direct soil measurements, there is a need to access privately owned land to collect repeat samples for monitoring of this attribute. Landowners may be more, or less, willing to provide access to land for sampling and to have data from their land used for regulatory informing purposes.

A4-(iii) What are the costs associated with monitoring the attribute? This includes up-front costs to set up for monitoring (e.g., purchase of equipment) and on-going operational costs (e.g., analysis of samples).

A key cost is staff time to undertake sampling of about an hour plus travel, with additional staff required for interpretation and reporting etc.

Bulk density and macroporosity are sampled using undisturbed cores (not sieved) using stainless steel rings. The Land Monitoring Forum/NEMS recommends 3 samples per site (0-10cm depth only is monitored, but this is a limitation for perennial deeper-rooted plants), each of which get analysed in the laboratory. Topsoil and upper subsoils should be measured in non-pastoral sites with deeper rooting species to better inform implications for resilience and production. The Manaaki Whenua – Landcare Research physics laboratory routinely does bulk density and macroporosity testing, along with aggregate stability, and a range of other tests. Further information is available from:

https://www.landcareresearch.co.nz/partner-with-us/laboratories-and-diagnostics/soil-physics-laboratory/

Current costs for bulk density and macroporosity measurements combined are approximately $60+GST/sample, but noting that 3 samples per site are needed (total ~$180).

A5. Are there examples of this being monitored by Iwi/Māori? If so, by who and how?

Yes. Ngāi Tahu Farming is involved in a soil health project with AgResearch, where soil macroporosity (air-filled porosity at −10 kPa) and bulk density were measured [60]. More broadly, soil health is of high interest to Māori, and soil macroporosity is just one attribute within a suite of holistic measures that can be used to assess health status.

A6. Are there known correlations or relationships between this attribute and other attribute(s), and what are the nature of these relationships?

Surface runoff of nutrients and other contaminants (P, sediment, *E. coli*) (and hence impacts on freshwater quality) are more likely from compacted soils [5, 61]. Some correlations of compaction measures with changes in the composition of soil bacteria have been observed based on NZ soil quality monitoring data [13,14].

Part B—Current state and allocation options

B1. What is the current state of the attribute?

Macroporosity and bulk density, have been reported in several regional and national studies, and numerous other studies have assessed soil compaction using a wider range of soil physical properties e.g., [59]. In national reporting of state of the environment soil quality monitoring [60] and other review [5, 6] Soil compaction (as measured by macroporosity) has been reported as a key issue in the Waikato, Auckland, Marlborough and Wellington regions [5] – primarily associated with land used for dairy [6, 21].

However, no trend in macroporosity over time were observed in soils used for drystock, dairy, orchard/vineyard, cropping land use, or other land uses, 1995 to 2018 [40, 63]. Similarly, no decreasing trend or improvement in bulk density was found for drystock farming land use from 1995 to 2018 [40].

B2. Are there known natural reference states described for New Zealand that could inform management or allocation options?

No. Compaction primarily occurs on land which is disturbed though human activity, i.e., primary production land, urban land development [39], but is also recorded in native forests from wild ungulates (deer) [61]. Comparison of measures used to assess compaction (macroporosity, bulk density) in undisturbed fence line areas may help to identify typical ranges associated with undisturbed agricultural land. However, indigenous forest soil sampling to compare agricultural land may not be useful for monitoring. In just a few studies, soil compaction has been measured under farm paddock fence lines [65] to compare with paddock areas, as those areas are typically not trampled nor affected by vehicles. My opinion is that indigenous vegetation reference states would not be useful to inform specific agricultural management for this indicator (compaction). Use of undisturbed fence line areas may be useful as a reference state for a predominantly undisturbed paddock area, but its use would be depended on the objectives of the study.

B3. Are there any existing numeric or narrative bands described for this attribute? Are there any levels used in other jurisdictions that could inform bands? (e.g., US EPA, Biodiversity Convention, ANZECC, Regional Council set limit)

There are existing 'target values' for macroporosity, bulk density, aggregate stability that are used in council SOE monitoring [57] although revision of these target values is being undertaken through a contract with MfE (Revision of Soil Quality Indicator Target Ranges).

For macroporosity in New Zealand, there is some literature about minimum macroporosity to support crop and pasture yield, much of which is reviewed in [1, 66]. The reference [1] reviews some of the science behind the typically used value of <10% macroporosity. Similarly, bulk density and cone penetration resistance affects crop and pasture yield, typically via impedance to roots) and this is more commonly described in the literature, and is included in [1, 66] and other studies.

B4. Are there any known thresholds or tipping points that relate to specific effects on ecological integrity or human health?

There is some information about minimum values of macroporosity that can impact on crop and pasture productivity [62] [1, 66] [67]. The reference [1] reviews some of the science behind the typically used value of <10% macroporosity. Bulk density is more commonly used as a measure of compaction (as it is easier to measure and useful) and effects on crop and pasture yield and this is more commonly described in the literature, and is included in [1, 66] and other studies.

Specific impacts on ecological integrity occur but thresholds are generally ecosystem, plant species and plant-growth stage specific and mediated by climate – such impacts include vulnerability to disease, (especially root rots), anoxic conditions, drought and wind-throw.

Tipping points result in changes in relative competitiveness of different species, e.g., from kiwifruit or avocado (intolerant of poor drainage or waterlogging, i.e., wet soil;[97]) to pipfruit (more tolerant); titoki and kanuka (less tolerant) to kahikatea and manuka (more tolerant) (R Simcock pers comm). There are also differences in tolerance to drought and drainage/waterlogging between cultivars in grapes and apples, as different cultivars have different drought and drainage tolerances. Soil drainage, aeration and water storage properties should be used to guide plant selection [66]. Different species have different tipping points as they have different vulnerability to water stress (exacerbated in droughts and where there is no supplemental irrigation) and to anaerobic soil conditions (linked to higher water tables or higher rainfall, thus decreasing the air-filled volume in soils). Tipping point is also influenced by the stresses plants experience as they grow, especially long-lived species such as trees – plants with larger and deeper root systems are more resilient to drought (R Simcock pers comm). However, tipping points and changes in species occur in crops where compacted soil restricts root systems, so smaller root systems have access to a smaller soil water volume, and reflected in plant indicators [98]. Areas that are compacted or degraded, especially in wetter hollows, have lower aeration and/or slower drainage reflected as poorer crop emergence, stunted plants, more root diseases, increases in species (often weeds) that are more competitive [67, 99] (R Simcock pers comm).

B5. Are there lag times and legacy effects? What are the nature of these and how do they impact state and trend assessment? Furthermore, are there any naturally occurring processes, including long-term cycles, that may influence the state and trend assessments?

There are 'lag times' for the recovery of compacted soil, which also depends on the extent of deliberate intervention to remediate compactions, but more importantly the natural processes that help rejuvenate shallow soil (cracking, roots, worms). Without intervention, there can be natural recovery – or reversibility - in shallow soil depths through soil cracking, drying, root and macrofauna activity, especially in surface soils where root and biological activity is abundant [41, 68]. A study in Southland showed that compaction at various soils depths typically occurred in Spring, recovery occurred in Summer due to drying and cracking of the soil, and winter (when stock are off-farm). However, compaction is much more difficult to remediate at greater soil depths (>15 cm depth) [41, 44, 45]. Deliberate interventions to remediate compaction in shallow soils include tillage while mechanical aeration (subsoiling, deep-ripping), and spot mounding, remediate compaction in deeper soils [48-50].

Impacts of compaction may only be seen under specific climate conditions because of its impact on water and air-filled pore volume; typically near-surface compaction effects are highlighted either when plants are actively growing under wet conditions, reflected as nitrogen stress or spread of root diseases – with young drops most vulnerable. In contrast, deep compaction that limits root volume is revealed during climate cycles that induce drought stress or have unusually strong storms, and/or when trees reach specific heights; in this case long-lived crops and ecosystems can be highly vulnerable to toppling or failure [69, 70].

B6. What tikanga Māori and mātauranga Māori could inform bands or allocation options? How? For example, by contributing to defining minimally disturbed conditions, or unacceptable degradation.

As noted previously, soil health is an area of high interest to Māori and there are many tohu/indicators that are utilised according to mātauranga-ā-hapū and mātauranga-ā-iwi [94, 95]. In addition to discussing this attribute directly with iwi/hapū/rūnanga, there is likely to be tikanga and mātauranga Māori relevant to informing bands, allocation options, minimally disturbed conditions and/or unacceptable degradation in treaty settlements, cultural impact assessments, environment court submissions, iwi environmental management and climate change plans, etc.

Part C—Management levers and context

C1. What is the relationship between the state of the environment and stresses on that state? Can this relationship be quantified?

The relationship between attribute state (as measured by macroporosity and bulk density), land management pressures and potential management interventions is generally well understood, particularly for soils where soil compaction is a problem, hence the studies on such soil types. Some studies on, for example, pasture or crop yield relationships (response curves) to macroporosity etc are presented in [1, 11, 71]. For soil compaction and/or compaction with pugging, pasture damage occurs from treading in wet conditions [68, 72, 73]. Note that pugging tends to be more visibly damaging and is a separate process. There are five critical factors that influence the degree of soil compaction damage under livestock pastoral grazing [6]: inherent soil susceptibility to damage (strength); soil wetness (rainfall or irrigation); livestock loading (weight/hoof contact area); grazing management: intensity (animals/ha), duration (time on soil), and livestock movement (stationary or walking); and type/extent of vegetative cover.

On cropping farms, continued vehicle movement or ploughing on wet soil, can lead to soil compaction or a 'plough pan'. Soil compaction on cropping farms is also reviewed by [5], and there are numerous New Zealand studies on soil compaction [76, 77], and international studies [47]. Soil compaction occurs in plantation forestry especially associated with ground-based harvesting [7, 100]. Soil compaction can occur in urban areas and land development – primarily through use of heavy machinery [9, 34]. Compaction in vineyards is likely under the wheel track areas, but not under vines. Soil quality samples taken from Marlborough vineyards, showed compaction (low macroporosity) but the soil was much less compact under the vines [48, 78], but this has not been related to production.

C2. Are there interventions/mechanisms being used to affect this attribute? What evidence is there to show that they are/are not being implemented and being effective?

C2-(i). Local government driven

Some regional councils produce brochures or information on soil management including compaction (e.g. GWRC, Waikato). Information on soil compaction may be less common. GWRC produced a brochure on soil compaction by the science and land management teams, 'Soil compaction and pugging on dairy farms'. I'm not aware of specific regulations etc for this attribute.

C2-(ii). Central government driven

I'm not aware of specific regulations etc for soil compaction. However, regulations were introduced for soil pugging (which can compact soil too) to protect water quality, and the related MfE-produced guidance material for farmers and consultants that is promoting the avoidance of soil pugging under forage crops [78-81]. There are recommendations to create soil profiles that have subsoil conditions (primarily relief of compaction) that allow trees to grow in urban environments [9].

C2-(iii). Iwi/hapū driven

We are not aware of other interventions/mechanisms being used by iwi/hapū/rūnanga to directly affect this attribute.

C2-(iv). NGO, community driven

The dairy industry and cropping industry have produced information on soil compaction (and pugging), and off-paddock grazing such as stand-off pads etc. Examples include [83, 84]. Since the introduction of intensive winter grazing regulations, pastoral industries have soil compaction /mitigation information on their websites.

A factsheet by MWLR is available: https://www.landcareresearch.co.nz/assets/Discover-Our-Research/Land/Soil-health-resilence/factsheet-compaction-pugging.pdf

AgResearch produced a booklet called 'Managing treading damage on dairy and beef farms in New Zealand: booklet for farmers and industry', (5000 copies printed) which was distributed to farmers to help avoid and mitigate soil compaction and pugging [84]. Various guides for farmers and material have been produced by Plant and Food Research to manage soil compaction and soil quality [85,86].

C2-(v). Internationally driven

Recent legislation on soil health has been proposed in the EU. The new law aims to address key soil threats in the EU, including compaction.

Part D—Impact analysis

D1. What would be the environmental/human health impacts of not managing this attribute?

Refer to A1 for context on ecological and environment affects.

D2. Where and on who would the economic impacts likely be felt? (e.g., Horticulture in Hawke's Bay, Electricity generation, Housing availability and supply in Auckland)

Economic impacts are likely be felt by farmers directly, and industry where crop or pasture production is affected, but these farmers are also the people who have the direct ability to prevent or minimise compaction occurring, if it is practical to do so. There have been few specific economic studies, other than farm economic modelling that have been undertaken [37, 49, 87]. Studies that have assessed the agronomic benefit (in terms of crops and pasture yields) from remediation of compacted soil through subsoiling/aeration or restricting grazing duration [48, 88, 89], can of course be translated into economic benefits.

Economic impacts via environmental effects are difficult to determine on a larger scale, and few studies have attempted this, but some are available [5, 90]. Others have evaluated ecosystem services affected by soil compaction [91].

There is also impact of compaction in urban areas on flooding and flood risk (notably in urban catchments) where soils lose their sponginess, and health of perennial species and trees can be affected [9, 92].

D3. How will this attribute be affected by climate change? What will that require in terms of management response to mitigate this?

Soil compaction is affected by climate through cracking in drying conditions, cracking in frosty conditions, but compaction is likely to get worse (due to susceptibility of soils to become compact under wet conditions), under increasing frequency of high soil moisture and rainfall events, and crop and pasture growth can therefore be affected [1, 5]. It is likely under wetter soil conditions, with treading and machinery present in wet conditions, there may be more soil compaction, including if there is greater extent of irrigation use [93]. In drier conditions, there may be some benefit from limited compaction in 'dry years' (vs 'wet years') as soil water can be more tightly held in compacted soils and therefore less likely to evaporate and therefore benefit crops [1]. However, where soil compaction limits root volume and rooting length, drought effects on plants are exacerbated. Here, deep compaction is a more severe issue than shallow compaction. Effects of soil compaction are likely greater in cities due to heat island effect increasing air temperatures, therefore increasing the moisture demand of vegetation (for cooling). Soil compaction that results in lower infiltration and/or soil water storage will result in more flooding under most climate change scenarios of higher-intensity rainfalls.

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