7.4 Soil Carbon

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Preamble: There are multiple measures for soil carbon (C) discussed in this document. We have listed some of the commonly used measures for soil carbon below. The measurements most used for soil carbon are total carbon, soil organic carbon, water extractable carbon, and the carbon to nitrogen (C:N) ratio. More detail on these measurements are outlined as follows:

- Total C concentration (%) in soils, commonly used in soil quality monitoring of mineral soils and expressed as a percentage of soil by weight (i.e., g C/100 g soil). Total carbon (and nitrogen) in soils is usually quantified using combustion. In New Zealand, total carbon is generally considered to be analogous to organic carbon due to negligible amounts of inorganic carbon. However, total carbon would include organic and inorganic carbon.
- Soil organic carbon (SOC). A measure of the total organic carbon pool in soils. This is determined following removal of any inorganic carbon after acid digestion. In New Zealand, this acid digestion step is usually not carried out. SOC can be further differentiated into different C fractions that are considered to differ in function and turnover. For example, particulate organic C (POC) is considered more labile and vulnerable to loss than mineral associated organic C (MAOC) which is more stable and persistent due to the interaction of C with minerals. Resistant organic C (ROC) is a fraction that is considered resistant to turnover and is typically associated with charcoal or pyrogenic carbon. In New Zealand soils, SOC generally consists of POC and MOAC as ROC is usually very negligible although there is limited data on this.
- Soil inorganic carbon (SIC) relates to carbon associated with inorganic constituents such as carbonates. Generally, New Zealand soils contain negligible amounts of SIC. However, in some soils (e.g., pH>7) SIC will contribute to the Total C measured in soils. The inorganic component would be the difference between total carbon and soil organic carbon.
- Soil organic C stock is the quantity of SOC in a soil for a given layer, usually defined by depth. The stock is calculated using the bulk density and total C concentration for a given layer of soil over a given area. The unit for stocks of SOC is typically given in tC/ha. The stock of SOC is considered a better measure than total carbon as it accounts for changes in bulk density that are often associated with changes in management. The stock of SOC should be assessed on an equivalent soil mass basis rather than a fixed

depth basis particularly if comparisons between treatments, through time, are being considered.

- Water extractable carbon is the soluble fraction of carbon in soils that is typically associated with carbon cycling and microbial activity. Hot water extractable carbon (HWEC) has been proposed as a replacement for anaerobically mineralisable N in regional soil quality monitoring, also used as a measure of biological activity in soils [1, 2].

- Soil organic matter (SOM) comprises the organic material in soils, including organic carbon, nitrogen and other nutrients. This is typically determined using loss on ignition and measuring the weight lost. This method is cheaper than other methods but generally not preferred as there is no universal standard protocol and results can vary due to furnace settings.

- C:N ratio – this measure can indicate whether there are potential nitrogen (N) limitations to plant growth and has therefore been used to indicate mineralisation rates of organic matter in soils [3]. This measure provides information about the nature of the biological communities in soils – soils with higher ratios have more fungal-dominated communities [4]. It is important to note that other nutrients are also linked to SOC cycling, including P and S, therefore nutrient stoichiometry of soil organic matter may be more appropriate [5].

- CO_2 respiration: this represents the carbon that has been mineralised by microbial activity. The amount of carbon respired over a three-month period has been demonstrated to correlate well to the quantity of water extractable carbon [6].

- The CO_2 burst method is another method for measuring CO_2 respiration from soils. This measures microbial respiration under disturbed conditions and is a quicker method than described above. This method is used in soil quality monitoring in the US [7].

- Less common methods of measuring organic carbon in soils include spectroscopy methods, namely mid-infrared spectroscopy (MIR), nuclear magnetic resonance (NMR) spectroscopy [8]. It should be noted that some commercial laboratories in New Zealand routinely use spectroscopy, as opposed to combustion, as the main method to determine total carbon (and nitrogen) in soils due to the rapid assessment.

Remote/Hyperspectral sensing of SOC has received increasing interest recently due to the low cost associated with acquiring data. However, many of the studies that have assessed this approach rely on the use of existing large datasets where spectral data is already collected (e.g., LUCAS dataset in Europe) for ground truthing [9 - 11]. Another caveat is that generally the hyperspectral imagery is collected from bare soil with no plant cover. To our knowledge, this technique has not been applied for New Zealand soils.

State of knowledge of "Soil C" attribute: Medium / unresolved – some studies/data but conclusions do not agree. While there are some studies in New Zealand on soil carbon these have largely focussed on changes related to land use or specific management practices and related to greenhouse gas emissions. These studies have been summarised in review papers but knowledge gaps remain particularly related to impacts on ecological integrity.

Part A—Attribute and method

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

Ecological integrity: Soil C affects many soil properties and functions influencing soil resilience [12-15]. Soil C is linearly correlated to aggregate stability, an indicator of soil structural quality [16], therefore effects on soil C will impact the resilience of soil to water stress and drought - a feature dependent on good soil structure [17]. Soil C also provides nutrients through cycling of organic matter and climate regulation through carbon sequestration in soil [12] therefore declines in soil C will negatively impact these soil functions.

Greenhouse gas emissions: Soil contains the largest pool of the Earth's terrestrial C. Loss of this stored C will cause feedback to and contribute to increasing atmospheric CO_2 concentration [18]. There has been a large amount of research in New Zealand, and globally, on management practices that could increase this pool of soil carbon or reduce losses. Internationally, the 4per1000 initiative was created recognising the importance that increases to the global stock of soil carbon could have for mitigating greenhouse gas emissions. However, carbon is important for soil functions and health beyond just the GHG mitigation potential.

There are also links between soil and other attributes. For example, soil C relates to the ecological integrity of water, as organic matter cycling in soils affects nutrient loss (namely N and P) to waterways which can result in negative impacts on aquatic ecosystems [5].

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

Weight of evidence for C depletion under certain management (e.g., irrigation [19]) and land use (e.g., cropping [6, 20-22]) is high.

Land use change is generally considered the largest driver of change in soil carbon in New Zealand and the impacts on land use change on soil carbon between 1990 and 2016 was estimated by Whitehead et al. [23]. Management effects on soil carbon are less certain and inconclusive for New Zealand although this was limited to grassland soils only [24].

On-going monitoring is carried out on soil carbon (e.g., shallow sampling in SOE monitoring) and a recent large scale monitoring programme (National Soil Carbon Monitoring, NSCM [25]) has been established to sample approximately 500 sites across New Zealand in the dominant land use classes (e.g., Dairy, Sheep and Beef, Horticulture and Cropping). These sites will be visited multiple times over an extended period and will give information on any changes to carbon stocks to 60 cm depth. This programme will contribute to improving understanding on impacts of soil carbon change across New Zealand. However, it does not specifically address management effects on soil carbon.

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)?

At a national level the New Zealand Greenhouse Gas inventory [26] uses IPCC methodology and the CMS model to quantify change in SOC stock with land use change (0-30 cm depth). Within this CMS model, grassland soils are assumed to contain higher mean stocks of SOC than other land uses (e.g., annual cropping, perennial cropping, natural and planted forest). This change in SOC, through land use change, is assumed to occur over a 20-year period before a new steady state is reached. Furthermore, if any land use was to return to its original state the assumption is that the SOC would return to what it started as (e.g., reversible). However, there is limited evidence to support this assumption. There is also very little evidence to support the 20-year timeframe to reach a new steady state with some studies internationally demonstrating change can carry on for much longer.

The original 500 Soils project, from 1995-2001 constituted the inception of soil quality monitoring in New Zealand. Results from this initial project showed total C was depleted in soils under cropping land use [20-21]. Recent monitoring data showed that 26% of cropping sites monitored between 2014-2018 had total C lower than the target range [27-28]. This consistency between older and more recent data indicates that this loss of C under cropping has remained somewhat steady over the past ~30 years. There has been no overall improving trend or increases in soil carbon [28].

The pace or trajectory of change in the future 10-30 years is unknown and depends on the extent to which current management practices known to affect soil C change or remain the same [29]. Research indicates that some soils, particularly those under cropping, have a larger C deficit (due to their higher levels of C depletion) and therefore have the capacity to sequester more C [30]. Whether or not this eventuates will be dependent on land management practices.

The national soil carbon monitoring (NSCM) programme is currently underway with baseline sampling completed. This programme samples multiple productive land uses across New Zealand and assesses C stocks from 0-60 cm [25]. In time this programme will provide better information on trajectory and size of change for SOC. Currently, the baseline sampling has been completed but the data is not yet available.

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?

Most regional councils in New Zealand monitor total C (%) under their soil quality monitoring programmes for SOE reporting. Environment Canterbury also have a wealth of data within their arable and pastoral programme. Total C has been one of the seven key soil quality indicators since the implementation of SOE monitoring in the early 2000s. More recently, HWEC has been more widely monitored since it has been proposed as a replacement for anaerobically mineralisable nitrogen, used as an indicator of microbial activity on soils [1; 31-32]. The NEMS [33] for soil quality and trace elements specifies a standard for sampling and analysis of total C. This specifies a shallow sampling depth of either 0-10 cm (primary method) or 0-15 cm (alternative method). Data are usually compared to provisional target values for this soil quality indicator, with the development of these target values described in a recent report [34].

Long-term field trials at Winchmore, Ballantrae and Tara Hills have also assessed and reported soil C and under grazed grassland in multiple reports and journal papers [35-38]. A review on changes in soil C under grassland soils summarising many of these trials and additional studies has been published [24].

More recently, New Zealand's National Soil Carbon Monitoring (NSCM) programme has been established with the aims of providing a benchmark for soil organic carbon stocks across agricultural land use classes in New Zealand and monitoring changes over time [25]. The initial benchmarking has been completed however the results are not yet available.

Several measures of soil C including total C, total organic C and C:N ratio are also measured in relation to productive requirements to inform farmers of their soil characteristics. The Fertiliser Association of New Zealand (FANZ) has produced a guide for cropping farms that mentions laboratory testing for soil carbon and C:N ratio [39].

As stated in A3, at a national level, the GHG inventory applies IPCC methodology and uses the CMS model to quantify change in SOC stock with land use change (0-30 cm depth). At a simple level, reference soil carbon stocks (0-30 cm depth) are quantified for each land use and these are applied to change in land use area quantified using spatial layers. This methodology assumes a linear change to the new reference stock over a 20-year period. Any change is considered reversible if land use is reverted.

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

For all direct soil measures, 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 to inform SOE or for other 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).

Variables estimates provided by Regional Council scientists to MfE:

- $10,000 per year estimated by Marlborough Regional Council, broken down as: Chemical laboratory analyses of which total C is included, for ~20 sites/ soil samples. Two people sampling eight full time days per year.
- $85,000 total cost per year (pers comm Waikato Regional Council), broken down as follows: ~$1000 per sample/site for all seven basic soil quality indicators (including total C). For approximately 30 sites, one scientist spends approximately one third of their time on soil quality monitoring.
- $80-100,000 per year (pers comm Horizons Regional Council), for monitoring of the seven soil quality indicators, not including staff training and farmer outreach.
- $250,000 per year monitoring costs plus Regional Council soil scientists’ time (unspecified, 5 staff in team) (pers comm Environment Canterbury).

Various measures of soil carbon are available from commercial laboratories, typically in combination with N or as part of a wider suite of different tests e.g., organic matter suite (includes Total carbon C:N ratio), with costs typically ranging between $25 to $75.

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

We are not aware of any monitoring being carried out by representatives of iwi/hapū/rūnanga. However, we know that soil carbon is of high interest to Māori through partnership with hapū/iwi entities. We know that Māori monitor soil health holistically, and that mātauranga Māori indicators are applied to the soil ecosystem rather than single attributes like soil carbon. See for example https://www.landcareresearch.co.nz/assets/Discover-Our-Research/Land/Soil-resilence/Maori_soil_health_research-v2.pdf.

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

Soil attributes are correlated in various ways with:

- Peatland/peat soil subsidence control: Drainage of Organic, or peat soils, results in large amounts of soil C loss [45-46].
- Bacteria composition: Cycling or organic matter in soils is dependent on soil microbiology, and therefore bacterial composition [47].
- Soil N and P: Through the C:N ratio of soils. Lower C:N ratios with high total N are associated with increased losses of N [48]. Loss of soil C results in reduced nutrient supply from organic matter [17], meaning agricultural land use may become reliant on inorganic fertilisers.
- As above other nutrients are also linked to SOC cycling, including P and S, therefore soil C is linked to other nutrients through stoichiometry of soil organic matter [5].
- Soil contaminants: The mobility and bioavailability of trace element contaminants in soils including Cd, Zn, As and Pb can be affected by soil C. Generally, increases in soil C result in decreased bioavailability of these trace elements [49].
- Surface erosion/runoff (and other erosion related attributes): Soil C contained in topsoils (and subsoils, if affected) is lost through erosion and runoff.
- Soil water storage, capacity and fluxes: Soil C is linearly correlated to aggregate stability, a measure of soil structural quality [16]. Reductions in soil C reduces soils' resilience to water stress/drought [17].

Part B—Current state and allocation options

B1. What is the current state of the attribute?

New Zealand soils contain moderate to high stocks of SOC (approximately 100 tC ha^{-1} in top 30 cm) compared to other countries partly due to soils being geologically young in development [50].

Current SOE monitoring only reports on SOC concentration of topsoil (mostly 0-10 cm) and knowledge now considers this depth to be inadequate for a true indicator of SOC change to depth. For example, shallow sampling as in SOE monitoring, will not capture any redistribution of SOC due to some tillage practices. Therefore, new programmes (e.g., NSCM) have been established to measure changes to soil carbon to depth (e.g., 0-60cm). However, the topsoil (0-10 cm) is generally where most of the root activity in agricultural crops will be contained, so this data is still useful as an indicator of soil health.

While we know that some land use and land management result in large losses of SOC, many of these studies have been focussed on specific regions or managements. The NSCM programme will give a better coverage of the state of soil C stocks across multiple land use and soil types throughout New Zealand. However, forest soils are not represented in this programme.

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

Within the GHG inventory methodology, reference states are assumed for each land use class. These states represent a mean stock of soil carbon within each land use across New Zealand. While there are some slight differences in this reference state driven by climate and soil differences, they are generally small. The benchmarking sampling of the NSCM could potentially be used to improve the reference states within these land uses and will provide better coverage of soils across New Zealand.

SOE soil quality monitoring of total C in soils under indigenous vegetation could potentially represent reference states for these measures in New Zealand soils, however there are few indigenous sites included in SOE monitoring, and where included, they may not necessarily represent undisturbed indigenous vegetation. Additional studies of soils under indigenous vegetation, including those on C stocks (rather than the total C measure), could add to this knowledge base.

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)

'Target values' have been developed for use in regional council state of the environment reporting, with a review of the derivation of these values recently undertaken by Manaaki Whenua – Landcare Research [34]. These values were based on combining production optima and environmental considerations, although limited environmental data was available at the time of development [34]. These values vary with land use and soil order, with the current recommendations for total C concentrations in soils detailed in Table 1. The values in Table 1 are similar but not identical to those used in *Our Land 2021 [27]* (Table 2).

Table 1. Provisional soil quality target ranges for total C (%). The numbers in bold are generally used as the minimum target value. Table from Cavanagh et al. [34].

Soil type	Very depleted		Depleted	Normal	Ample
Allophanic	0.5	**3**	4	9	12
Semi-arid, Pallic, & Recent	0	**2**	3	5	12
Organic			excluded		
All other soil orders	0.5	**2.5**	3.5	7	12

Table 2. Minimum target values for total C used by MfE and StatsNZ in Our Land 2021 [27]

Soil order	**Minimum target value (% gravimetric)**
Pallic, Pumice, Raw, Recent, Semi-arid	2
Brown, Gley, Granular, Melanic, Oxidic, Podzol, Ultic	2.5
Allophanic	3
Organic	NA

NB: Anthropic soils not mentioned

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

There is very limited data on effects associated with soil carbon loss particularly in the context of tipping points or thresholds. There is limited evidence that production of certain crops decreases once SOC concentration gets below certain thresholds [51] However, these thresholds don't exist for New Zealand. Furthermore, New Zealand soils (e.g., Allophanic) which have high stocks of SOC may experience negative impacts on production and soil quality well above these global thresholds.

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?

While soil carbon losses can be rapid (e.g., in cropping/fallow periods, [22; 52-53]) gains in soil carbon are very slow and difficult to quantify without an intensive sampling approach. Legacy effects influencing changes in SOC are likely to occur although evidence is limited, particularly within New Zealand.

Within the CMS model (used in the LUCAS framework) any change is assumed to occur, linearly, over a 20 year period before a new steady state is reached. There is evidence that changes in SOC are not always linear, and that changes can occur for much longer [24].

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.

Māori utilise a holistic approach to assessing the condition of all parts of the soil ecosystem (and beyond). 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. Observations of ill-health of plants/animals/soil through a Māori lens may provide some insight for bands for this attribute.

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?

Drainage of Organic, or peat soils, results in large amounts peat subsidence and soil C loss [45-46].

Decreases in soil C can occur following change from pasture to cropping (e.g., as rotational cropping in pastoral systems) or through changes in management though the severity of this can vary with soil type [16, 54, 60]. Allophanic and Organic soils naturally contain more C than other soil orders and Allophanic soils appear to retain more soil C in the medium-long term following conversion to cropping [16]. However, losses of soil carbon were observed under Allophanic soils under more intensive management [54]. This loss of soil C is attributed to tillage practices on cropping farms, resulting in oxidation of C exposed to air, the period of time within cropping cycles that have no plant inputs (e.g., fallow period [22]), and or biomass removal under cropping (P. Mudge, pers. comm.). There have been two reviews summarising the current knowledge on the drivers of soil carbon change within New Zealand with very little evidence to demonstrate management practices that increase soil C [24, 29]. However, some management practices that have been observed to decrease soil C are irrigation and frequent cultivation for cropping [6, 19].

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

SOE monitoring is undertaken by Regional Councils, however the extent of interventions to effect change in soil C status, is largely limited to reporting soil quality monitoring results, which may include reporting back to the individual landowners on whose properties the sampling has been undertaken. Lower soil C concentrations have been reported in agricultural – namely cropping – soils since the commencement of the 500 Soils programme in 2000 [20-21].

C2-(ii). Central government driven

New Zealand has obligations to create an inventory and report on the greenhouse gas emissions as part of the UNFCCC. Within this inventory, SOC change due to land use change is quantified and reported.

New Zealand's national emissions reduction plan [55] includes very limited reference to soil carbon but acknowledges increasing knowledge on practices that may increase soil carbon (e.g., regenerative agriculture) and offset emissions will contribute to the net-zero emissions target for 2050.

C2-(iii). Iwi/hapū driven

As above, we note that hapū/iwi take a holistic approach to soil health monitoring. Iwi planning documents such as Environmental Management Plans and Climate Change Strategies/Plans may contain policies/objectives/methods seeking to influence soil health outcomes for the benefit of current and future generations.

C2-(iv). NGO, community driven

Voluntary carbon markets where SOC stocks are measured using measurement, reporting and verification (MRV) protocols to credit SOC sequestration. Multiple MRV protocols exist as summarised by Oldfield et al. [56]. To our knowledge, these are not being extensively used in New Zealand at present.

C2-(v). Internationally driven

GHG inventory reporting (mineral soil carbon change through land use change) as required as part of New Zealand's obligation to UNFCCC. Reducing losses of SOC are of benefit to New Zealand's reporting obligations. International markets may also play an increasingly important role in these indicators.

Part D—Impact analysis

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

Soil carbon is considered natural capital and is important for many soil functions and ecosystem services including food and fibre production, climate regulation through carbon sequestration in soil and nutrient cycling [12]. Substantial losses of SOC through lack of monitoring and management will likely contribute to the loss of soil structure and function impacting many ecosystem services.

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)

Loss of SOC could cause economic impacts to agricultural/horticultural production. Loss of SOC would also be associated with increased loss of other nutrients within SOM (e.g., N, P, S) which could compromise food production and increase costs associated with providing these nutrients through fertiliser.

Losses of SOC also contribute to increasing atmospheric carbon dioxide concentrations which could be valued as the C credit cost required to offset this loss (e.g., using the NZ ETS).

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

Changes to soil temperature and moisture because of increasing air temperature and changes in rainfall distribution will impact the cycling and change in SOC. Respiration of SOC generally increases as soil temperature and moisture increase [57]. Recent studies have explored the response of microbial respiration of soil organic matter to better understand and predict soil carbon losses due to climate change [58-59]. This increase in SOC respiration may be partly offset by increases in C inputs to soil through greater plant production though evidence of this is unclear.

Loss of stored soil C will result in increased atmospheric CO_2, contributing to climate change, which is predicted to drive a positive feedback loop that intensifies further C losses from soils [18].

Microbial cycling of nutrients has been demonstrated to be affected by temperature variations [47].

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