Garrett et al.
Carbon Balance and Management (2025) 20:28
https://doi.org/10.1186/s13021-025-00323-2

Carbon Balance and Management

RESEARCH Open Access

Lifting the profile of deep soil carbon in New Zealand's managed planted forests

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Abstract

Background Forest soils are a globally significant carbon-store, including in deep layers (> 30 cm depth). However, there is high uncertainty regarding the response of deep soil organic carbon (DSOC) to climate change and the resulting impact on the total OC budget for forest ecosystems. Managed forests have an opportunity to reduce the risk of DSOC loss with climate change, however, the basic understanding of DSOC is lacking. Planted forests in New Zealand are managed with very limited knowledge of DSOC, both in the amount and the capacity of the soil to continue to store carbon with climate change. In this study, we explore DSOC stocks to at least 2 m depth at 15 planted forest sties in New Zealand. We also explore DSOC radiocarbon age and soil mineralogy, then contextualise our results within international SOC datasets and climate change vulnerability frameworks to identify research priorities for New Zealand's planted forest soils.

Results DSOC stocks and soil mineralogy in New Zealand's planted forests were diverse both horizontally across soil types and vertically throughout the soil profile. Critically, limiting measurements of SOC to the top 30 cm misses more than half of the SOC stocks present to at least 2 m depth (mean 57%; range 33–72%). At depth, mineral-associated OC was the dominant fraction of DSOC (average > 90%) and was on average much older (> 1000 years) than the current planted forest land use (< 100 years).

Conclusions This small case study highlights that New Zealand's planted forests contain substantial stocks of DSOC, much of which is older than the current forest land use. The deep soils were dominated by reactive metals, and although the age of DSOC suggest long-term stability, the large contribution of reactive metal-mediated SOC stabilisation may indicate vulnerability to warming soil temperatures relative to other climate change factors. There is a pressing need to expand soil sampling to greater depths and establish a robust SOC baseline for New Zealand's planted forests. This is essential for enabling spatial predictions of DSOC dynamics under future climate scenarios, identify the key controls on DSOC persistence, and concomitant impacts on forest ecosystem function and resilience.

Keywords Deep soil organic carbon, Forest carbon stocks, Soil carbon stocks, Climate change, Plantations, New Zealand

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Background

Forests cover over 4 billion hectares globally [1]. Their soils are a large and significant organic carbon (OC) store, with estimates of 383 Pg OC to 1 m depth, nearly half of the total forest OC store [2]. Findings show that soils can be deep (> 1–2 m) [3] and that trees can be deep rooting [4], supplying OC deep into the soil [5, 6]. The resulting deep soil organic carbon (DSOC), > 20–30 cm depth to at least to 2 m depth, can store significant amounts of OC [7]. The size of the forest OC stock, including DSOC, makes forest ecosystems critically important to the global C budget [2], as changes to C flux into or out of forest soils and concomitant impacts on forest ecosystem function and resilience could translate into significant changes in sinks or sources of atmospheric carbon dioxide. Where forests can be managed there is an opportunity to reduce the risk of DSOC loss with climate change. However, there is limited knowledge on DSOC spatial abundance, cycling, or the vulnerability of DSOC to climatic or environmental disturbances, and forest management [8–10].

The OC cycle underpins the flow of ecosystem benefits from forests. As SOC is a key driver of soil fertility and nutrient provision to trees and other plants [11], it is directly linked to total forest-ecosystem productivity (net primary productivity; NPP). As such, the best recognised ecosystem benefit of SOC is growing the standing biomass for provision of wood, fibre and food products. SOC is also fundamental to hydraulic regulation, water quality, biodiversity, and interactions among environmental, biological, chemical, and physical properties and processes that determine forest functionality [12, 13]. Indeed, the value of these non-monetary ecosystem benefits vastly exceeds that of harvested wood and fibre [14, 15]. The sustainable delivery of both economic returns and broader ecosystem benefits from forests is inexorably connected with SOC cycling, including DSOC cycling, its vulnerability with climate change and the opportunities for its management.

DSOC is, on average, much older than topsoil OC and can be thousands of years [16, 17], with much of the DSOC protected through mineral associations [18]. Although the persistence of SOC reportedly increases with depth, very little is known about the mechanistic processes underpinning DSOC stabilization, and the sensitivity of these processes to climate change. A limited number of studies have reported DSOC to be dynamic, responding to land use change and forest management [10]. Climate change is also predicted to influence DSOC [8, 9]. For example, it is predicted that with climate change deep soil (1 m depth) will warm at almost exactly the same rate as near-surface soils [19] and extreme weather conditions will also have impacts deep within the soil profile [20, 21]. Moreover, climate driven forest disturbances will increase including fire, wind throw and erosion [22, 23]. Indeed, DSOC has been shown to be vulnerable to climate induced shifts in temperature and moisture conditions (e.g., Possinger et al. [24]). DSOC is also impacted by tree root-soil-microbiome interactions and their associated climate responses [8]. These are important observations, as changes in factors such as root structure, function, or exudation of labile OC may all have complex interactions with the soil microbiome. Limited knowledge of these interactions in deep soils heightens uncertainty of potential changes in DSOC cycling, and the soil-atmosphere OC feedback within the forest ecosystem [8].

Globally, information on SOC abundance deeper than 1 m is particularly sparse, despite evidence that substantial amounts of SOC may be stored below this depth [7]. Most studies have typically only sampled soil to 30 cm depth [25], and often country level SOC stock reporting have adopted the default soil depth of 30 cm under the United Nations framework on Climate Change [26]. As a result, the exclusion of the DSOC leads directly to an underestimate of total SOC stocks, thereby missing a significant contribution to total forest OC inventories and limiting the ability to predict and mitigate DSOC vulnerability to climate change [2]. Given the continued rise in global temperatures [27] and climate change impacts on forests [23] it is a priority to close the knowledge gap for DSOC for both climate change resilience and securing productive managed forests (e.g., Evans et al. [28] and Balks et al. [29]).

In New Zealand, planted forests cover 2.1 M ha of which 1.7 M ha are managed for timber harvest with the remainder in reserves (e.g., riparian or erosion control forests) [30, 31]. These managed planted forests support the country's third biggest primary industry with export revenue in 2024 of $5.87 billion [32], and are expected to be impacted by climate change [33]. Planted forests are also important to New Zealand's greenhouse gas commitments the under the Paris Agreement [30]. A key strategy in New Zealand's climate change mitigation plan is afforestation to offset gross emissions [34], particularly with fast growing commercial soft wood species [35].

Despite the importance of forest OC in New Zealand's climate mitigation strategy, there is limited data on planted forest SOC to any depth [30, 36], SOC stocks are not monitored, and there are only two sites where DSOC has been measured below 1 m depth [37]. This represents a critical knowledge gap in understanding the processes that influence DSOC and limits the ability to predict and manage DSOC in New Zealand's planted forests, now and under future climate change. To address this gap, we first summarised existing SOC datasets to at least 1 m depth across New Zealand's forests. We then collected new SOC data, to at least 2 m depth, from planted forests to build a small case study of 15 sites. This information was used to inform research priorities for DSOC in New Zealand's planted forests. Specifically, we (1) explored the contribution of DSOC to the total forest C pool, and (2) used international studies to place New Zealand's planted forest DSOC within a climate change risk profile to inform research priorities.

Methods

Case study sites

The study was undertaken at 15 sites located in planted *Pinus radiata* D. Don forests in New Zealand, which make up 91% of the planted trees species [38]. The case study dataset comprised both historical and newly collected data. First, existing New Zealand forest DSOC datasets from which SOC stocks can be calculated were sourced. This utilised information from existing literature focused on reporting New Zealand's SOC stocks [30, 36] as well as from expert knowledge on existing datasets. Of these existing datasets, only two planted forest sites had been sampled to at least 2 m depth [37]. Additional data capable of reporting SOC stocks to 1 m depth in planted and indigenous forests were also complied to illustrate the broader availability of DSOC data (Table S1). Second, new SOC data to 2 m depth were collected from 13 sites, resulting in a small case study of 15 sites with DSOC to at least 2 m depth. These sites cover the range of dominant soil types in New Zealand's planted forests (Table 1, Fig. 1, Table S2–3). The 13 new sites were selected from the New Zealand National Planted Forest Inventory (NPFI), a field monitoring inventory network within the

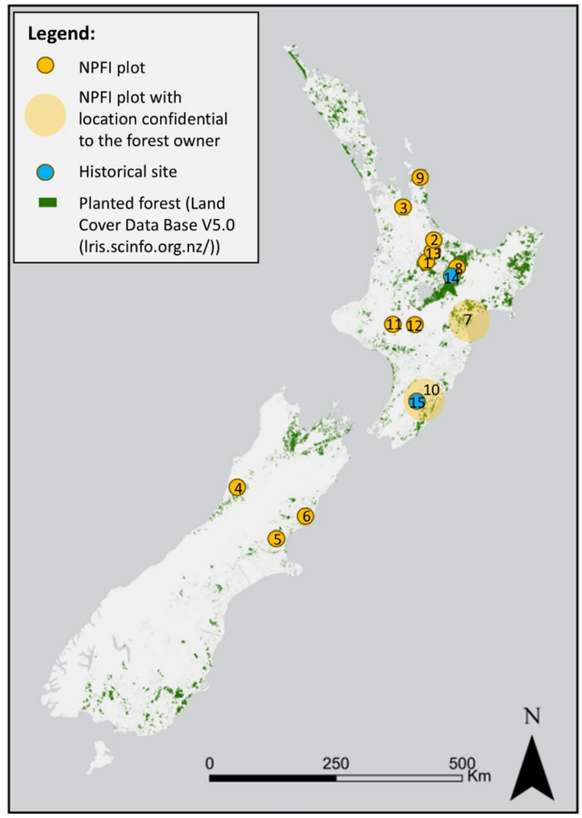

Fig. 1 Location of the 15 case study sites and distribution of New Zealand's planted forests

Table 1 Summary of New Zealand's planted forest dominant soil order and the case study dataset

New Zealand soil classification order	Soil Taxonomy order	Percent of New Zealand planted forest area within each soil order #	Case study data set	
			New Zealand region	Site ID
Brown	Inceptisols	33%	Waikato	9
			Manawatu-Wanganui	12
			Manawatu-Wanganui	10
			Canterbury	5
Pumice	Andisol	21%	Waikato	1
			Bay of Plenty	8
			Waikato	14*
Recent	Entisols	14%	Manawatu-Wanganui	11
Podzol	Spodosols	6%	Bay of Plenty	13
			West coast	4
Pallic	Inceptisols	6%	Hawke's Bay	7
			Wellington	15*
			Canterbury	6
Allophanic	Andisol	6%	Bay of Plenty	2
Ultic	Ultisol	5%	Waikato	3

[#] Data from Garrett et al. [86], [*]Historical sites from Oliver et al. [37]

intensively managed planted forest estate, designed to report on planted forest OC stocks [39].

Soil sample collection, preparation and testing

Sample collection and preparation

Soil samples were collected from the NPFI sites between 2022 and 2023 using a handheld motorised percussion rammer and steel cores to a depth of 2 m. Sampling was conducted at up to eight locations situated 2 m outside the perimeter of a circular 0.06 ha plot. These locations were positioned at the four cardinal directions (N, E, W, and S), with two sampling points spaced 2 m apart at each coordinate (Figure S1). Slope was record at each sampling point using a clinometer. At sites where time constraints limited sampling capacity (e.g., remote locations), the number of sampling points was reduced to four (one at each cardinal direction) or, in some cases, to two randomly selected points.

The 0–100 cm soil depth was collected as single intact core using a steel corer with an internal plastic sleeve and a 4 cm internal cutting diameter. After extracting the 1 m core using a hand jack, a narrower diameter steel corer with a 3.2 cm internal cutting diameter was carefully inserted into the same hole and driven down to a depth of 2 m. During extracting and placement of the corers, care was taken to prevent soil from falling into the hole and causing contamination the 100–200 cm depth sample. If the corer reached bedrock, this depth was recorded. Soil samples were divided into 0–10, 10–30, 30–50, 50–100, and 100–200 cm depth increments. Each sample was weighed fresh, then a sub-sample taken and weighed for the bulk density determination, with the remainder set aside for chemical analysis. All samples were air dried (< 40 °C) and sieved into < 2 mm fraction, > 2 mm mineral soil fraction (rock), and > 2 mm organic matter fraction. If present, > 2 mm pyrogenic OC (charcoal) was visually identified and removed from the organic matter and weight recorded. Bulk density samples were then oven dried at 104 °C, and each sieved fraction weighed to enable calculation of bulk density by sample volume for each fraction.

Soil samples from the two historical sites were collected in 1996, with the sampling method described in Oliver et al. [37] and data available in Garrett et al. [85]. In summary, five soil pits spaced at approximately 20 m apart were excavated by mechanical digger. Each pit was about 4 m in length and 2 m in width and was excavated down to bedrock. Soil was collected using steel rings to obtain 8–10 cores by uniform depth increments from three vertical pit faces. For the 0–10 cm depth increment, cores were driven into the soil from the surface and for deeper increments, cores were driven horizontally into the pit face. Samples were then bulked, by each uniform depth increment. Depth increments for site number 14 and 15 were 0–10, 10–50, 50–100, 100–200, 200–300, and > 300 cm, and 0–10, 10–30, 30–50, 50–10, 100–200, 200–300, > 300 cm, respectively. Soil samples were air-dried (< 40 °C), sieved into < 2 mm and > 2 mm fractions (the latter including rock plus carbonised wood fragments if present), and weighed. A moisture factor was determined for each sample and applied to calculate bulk density by sample volume for each fraction.

Soil organic carbon

The soil samples from the NPFI and historical sites were analysed for total C and total nitrogen (N) concentration using a LECO FPS-21000 CNS thermal combustion furnace. The exception was the OC concentration for the coarse fraction (> 2 mm) at the historical sites, which was estimated using a site-specific regression analysis between loss on ignition values and CNS thermal combustion values across a range of OC concentrations and soil depths (see Supporting Information). Most New Zealand soils have negligible inorganic C, as they are predominantly derived from quartz-rich volcanic and sedimentary soil parent material [40]. Therefore, total C is typically equivalent to OC. However, the presence of carbonates in New Zealand's deep soils is unknown and therefore assessed by observing effervescence, and if carbonates were present samples were pre-treated with acid using standard procedures [41] (see Supporting Information). NPFI samples that contained some organic matter and pyrogenic OC in the > 2 mm fraction were not analysed for total OC concentration and were assumed to be 50% OC. Pyrogenic OC is the < 2 mm fraction was not quantified.

Soil carbon composition and age

A random sub-set of samples were selected from the 13 NPFI sites for density fractionation into free particulate organic carbon (free POC), occluded particulate organic carbon (occluded POC), and mineral-associated organic carbon (MAOC) fractions and radiocarbon abundance analysis. One core per site was selected with a full sampling depth down to 2 m, or deepest sample to bedrock. From each core, fine earth (< 2 mm) samples were taken from the 0–10, 30–50, and 100–200 cm depth increments. A sub-sample of the soil was weighed, targeting 10 g for the 0–10 cm depth and 20 g for the deeper depths, and separated using a solution of sodium polytungstate adjusted to a density of 1.65 g cm^{-3} and sonicated to disrupt soil aggregates at 750 J g soil^{-1} following standard procedures [42, 43]. In five of the samples, pumice particles were observed floating on the surface with the light fraction. The pumice particles were removed from the light fraction sample using a dissecting microscope and forceps, followed by an electrostatically charged plate over the pumice pieces to remove any microscopic organics. The pumice pieces were then included back within the heavy fraction [44]. The proportion of sample recovery from the density fractionation method averaged 1.02 (SE = 0.01).

A representative sub-sample of all recovered density fractions were prepared for radiocarbon measurement using the method outlined in Heckman et al. [45] with further details in the Supporting Information. Radiocarbon abundance (reported in units of $\Delta^{14}C$ (‰) and conventional radiocarbon age) was measured by accelerator mass spectrometry (AMS) at the Keck Carbon Cycle AMS Facility, Earth System Science Department, University of California, Irvine. The remaining sample was measured for total C and total N concentrations on an Elementar Vario MAX cube dry-combustion elemental analyser (Elementar, Hanau, Germany).

Extractable metals and base cations

A sub-set of samples from the 13 NPFI sites was selected for extractable metals and base cation analysis on the fine earth fraction (< 2 mm). The same set of cores used for density fraction testing was used for extractable metals and base cation analysis at selected depth increments of 30–50, 50–100, and 100–200 cm. Extractable calcium (Ca) and magnesium (Mg) (cmolC kg^{-1}) were determined by ammonium (NH_4^+) acetate extraction following USDA NRCS protocols [46] and measured by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Reactive iron (Fe) and aluminium (Al) (%; g 100 g^{-1}) were determined via extraction with acid NH_4^+ oxalate extraction and analysed by ICP-MS following USDA NRCS protocols [46].

Live tree and forest floor carbon stocks

Live tree and forest floor OC stocks were modelled using the Forest Carbon Predictor model [47], parameterised with silvicultural and tree data collected from each site (see Supporting Information). The Forest Carbon Predictor model estimates were standardised to a tree age of 26 years for all sites, which aligns with the typical harvest age range for *P. radiata* in New Zealand (26–32 years; MPI [31]). The model outputs were grouped into live above ground (tree crown and stem), live below ground (roots), forest floor (branch and leaf/needle fall), and deadwood (decayed stems and roots).

Data analysis

Plot level total SOC stocks were calculated as the average of each depth, 0–30, 30–100, 100–200, and > 200 cm, from individual sample points around each NPFI plot and from individual pits in the two historical sites (see Supporting Information). Total SOC stocks are reported as the sum of the < 2 mm and > 2 mm fraction (> 2 mm rock and > 2 mm pyrogenic OC fraction). Deep soil in this case study is defined as soil depths below 30 cm. Inspection of the data showed significant heteroscedasticity of variance in the data among groups (Brown-Forsythe $p < 0.001$); as such the Kruskal–Wallis test was used to assess if OC stocks were influenced by forest compartment, followed by Dunns's post hoc test for corrected pair-wise comparisons among the treatment means. These tests were conducted in Prism10 (GraphPad Software).

The mass of OC in each soil density fraction (free POC, occluded POC, and MAOC) was determined by using the SOC concentration measured in each fraction multiplied by the corresponding fraction mass recovered. Where the mass of the sample was too small for OC concentration testing the OC mass was given a very small value of 0.01 mg C (see Supporting Information). The OC distribution among density fractions was normalised to sum to 100%. Analysis of soil sampling depth and density fraction type (free POC, occluded POC, and MAOC) on the distribution of C age ($\Delta^{14}C$), SOC mass (mg g^{-1}), and percentage SOC allocations between density fractions were tested using restricted maximum likelihood (REML) mixed effects models. Full models were fitted that included depth and fraction effects, as well as the interaction effect. Models were fitted with the Geisser-Greenhouse correction to avoid assumptions of equal variability. These analyses were similarly performed in Prism10.

To summarise the range in soil chemical properties of the NPFI soils (13 sites and 30–50, 50–100, and 100–200 cm depths), a soil chemistry gradient was generated, ranging from more reactive metals (iron and aluminium (Fe and Al)), to the more exchangeable base cations (calcium and magnesium (Ca and Mg)), following the methodology described by Possinger et al. [24]. The gradient in NPFI soil properties was calculated together with a dataset describing soil chemistry variation across the U.S. National Ecological Observatory Network (NEON) (20 sites using upper B-horizons) [24], to contextualise the NPFI measurements within the NEON dataset. The soil chemistry axis was generated using first principal component axis of natural log-transformed Fe + Al (mol g dry $soil^{-1}$) and natural log-transformed Ca + Mg (mol g dry $soil^{-1}$) for each soil sample. The soil mineralogy data from the NPFI sites are presented in a box and whisker plot to show the distribution of the data.

Results

Soil carbon stocks

The case study from 15 planted forests sites showed the average planted forest OC stocks and standard error, including live biomass and forest floor, down to 2 m soil depth averaged 453 Mg ha^{-1} (SE = 33 Mg ha^{-1}). As such, 61% of the OC in these forests was below ground (soil plus live roots) (Fig. 2). Summary data are presented in Fig. 2 and Table S4.

Across all sites the average total SOC stocks down to 2 m depth accounted for 46% of the total forest OC stock, with an average of 209 Mg C ha^{-1} (SE = 25 Mg C ha^{-1}), ranging from 96 Mg C ha^{-1} to 409 Mg C ha^{-1} (Fig. 2, Figure S2-3). Within the mineral soil 0–2 m depth, 57% (range 33–72%) of the total SOC stock was located below 30 cm depth, and 22% (range 9–42%) was found below 1 m depth (Figure S4). At two sites, where the soil was sampled deeper than 2 m to bedrock, on a Pumice and Pallic soil (Table 1), an additional 71 Mg ha^{-1} of SOC was captured – shown in the grey bar on Fig. 2. For these two sites the maximum depth of soil was 440 cm and 240 cm (site 14 and 15, respectively (Figure S5)). The OC stocks by forest component for each site are shown in Figure S3 and pair-wise comparison tests among these compartments are summarised in Table S4.

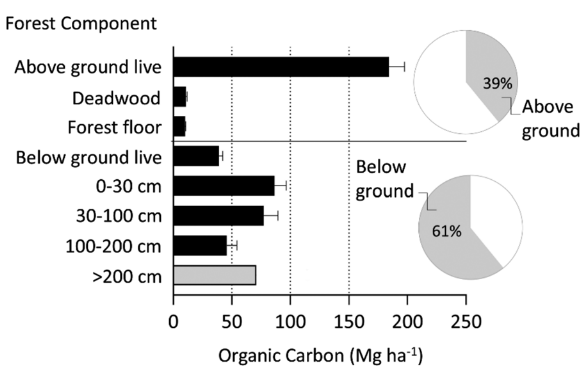

Fig. 2 Forest OC stocks between above and below ground live, forest floor, deadwood, and total SOC

The SOC coarse fraction (> 2 mm rock and pyrogenic OC) in the 0-2m depth contributed on average 1.5% or 2.4 Mg ha^{-1} (range 0–6%) to total SOC stocks with a greater contribution at depth (0–30 cm average 0.5 Mg ha^{-1} and > 30 cm depth average 1.9 Mg ha^{-1}). Within the NPFI sites the organic matter coarse fraction (> 2 mm, excluding pyrogenic OC), not accounted for in the total SOC stocks for the NPFI sites, on average contributed another 14.5 Mg ha^{-1} of the SOC within the 0–2 m depth range (0–30 cm average 10.7 Mg ha^{-1} and > 30 cm depth average 3.8 Mg ha^{-1}).

The maximum soil depth at the NPFI sites was unknown for all except site number 4, where the maximum depth was 160 cm and average depth was 84 cm (Figure S5, Table S5). At seven of the 13 NPFI sites, bedrock was struck before reaching the 2 m sampling depth, but only at some of the sampling points, around the 0.06 ha plot (Table S5). At the historical sites, soil pits were excavated to bedrock, revealing maximum soil depths of 440 cm (average 391 cm) at site 14 and 240 cm (average 214 cm) at site 15 (Figure S5).

Soil carbon fractions and persistence

The SOC density fractionation from the New Zealand NPFI sties show that with increasing soil depth the average radiocarbon Δ^{14}C (‰) decreases across all fractions (Fig. 3a). The deepest soil layer (100–200 cm) had the widest range in Δ^{14}C (‰) for all three SOC fractions (Fig. 3a). MAOC was the oldest SOC with an average age of 1328 years (range 380–2610 years) and 5572 years (range 2985–9020 years) for soil depths 30–50 cm and 100–200 cm, respectively (Fig. 3a). With increasing depth, the concentration of OC in the MAOC decreased

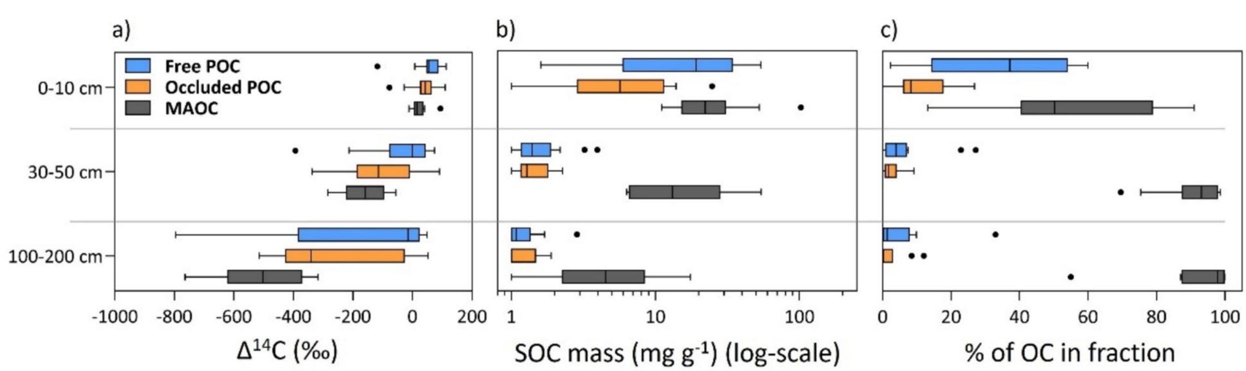

Fig. 3 The SOC density fractions for **a** radiocarbon Δ^{14}C, **b** SOC mass, **c** percent (%) SOC

(Fig. 3b) from 33, 18 and 6 mg C g^{-1}, for 0–10, 30–50, and 100–200 cm, respectively. In the deep soil layers below 30 cm the MAOC was the most abundant with on average over 90% of the SOC in this fraction (Fig. 3c). The free POC was the next most abundant in deeper soil layers (below 30 cm) with on average 6% or less, however, the maximum range was out to 27% and 33% for the 30–50 and 100–200 cm depth, respectively (Fig. 3c). The occluded POC in deeper soil layer (below 30 cm) was on average 3% of the SOC (Fig. 3c). The radiocarbon and SOC mass both showed significant ($P<0.05$) depth, fraction, and depth by fraction effects and the percent OC showed a fraction, and depth by fraction effect (Table S6–8).

Deep soil chemistry gradient

The deep soil mineralogy from the New Zealand NPFI sites was largely dominated by reactive metals (Fe/Al) with only a few sites within the base cation (Ca/Mg) dominated mineralogy (Fig. 4a). Compared to the US-wide NEON upper B-Horizon dataset [24] the New Zealand deep soil dataset was more dominated by reactive metals with some sites exceeding the NEON data set range with more reactive metal domination in the 30–50 cm and 50–100 cm depth increments (Fig. 4a). With increasing soil depth at a site, the soil chemistry axis can change with some sites showing large shifts in the soil chemistry gradient (Fig. 4b).

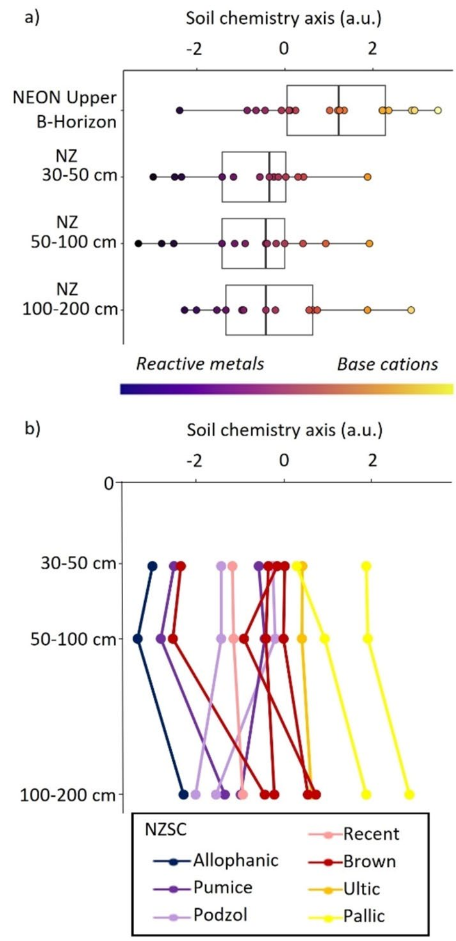

Fig. 4 The NPFI deep soil on the soil chemistry axis of Possinger et al. [24]

Discussion

Contribution of deep soil to planted forest carbon stocks

In the small case study, we found that, on average 46% of the planted forest OC was stored in the mineral soil to a depth of 2 m (Fig. 2). Notably, on average 57% of the SOC was located below 30 cm depth to 2 m (Fig. 2) and planted forest soils can be deep, 2 m or more in some cases (Figure S5). These findings demonstrate that a considerable proportion of New Zealand's planted forest OC stocks can be held in the soil, and that more than half of the SOC stocks are missed when measurements are limited to the top 30 cm – the current depth used in New Zealand's greenhouse gas inventory reporting [30]. Other studies in managed forests have also found considerable DSOC stocks (e.g., Harrison et al. [48]). Comparison of DSOC stocks (30–200 cm) across land uses in New Zealand is limited by sparse deep soil data. Available examples show that at two pasture sites (paired with the historical forest sites in this study), DSOC accounted for 38–49% of total SOC, compared to 48–52% under planted forests [37]. In another study, DSOC contributed 42–45% of total SOC under pastoral and horticultural land uses on Allophanic and Pumice soils [49], compared to 56–66% under planted forests on the same soil types in this study.

We explored the contribution of the soil coarse fraction to total SOC stocks and found an additional 2.4 Mg ha^{-1} of OC (rock and pyrogenic OC), with higher contributions at depth. Although the coarse fraction is not typically included in SOC stock reporting, it can represent a significant component in forest soils, particularly due to contributions from rock [48, 50–52] and pyrogenic SOC (e.g., Maestrini and Miesel [53]). For example, rock-derived SOC can make up (<1–25%) of the coarse fraction, with increasing contributions at depth [52]. Pyrogenic SOC may originate from forest biomass fires which can be an important component of upper SOC stocks (<30 cm depth) [54], and from volcanic deposits which can be an important component of DSOC stocks [55]. Although fire occurrence is low in New Zealand planted forests, historical land use change practices included forest clearance by burning [56, 57]. In addition, some volcanic derived soils in New Zealand contain deep deposits of pyrogenic OC [58] and buried soils (paleosols), which can form OC-rich deep soil horizons [55]. To our knowledge, the contribution of pyrogenic SOC or buried SOC below 1 m depth in New Zealand soils has not been quantified. Beyond rock and pyrogenic inputs, the organic matter component of the coarse fraction (>2 mm free POC) can also contribute to SOC stocks, averaging 14.5 Mg ha^{-1} to 2 m depth. Current New Zealand forest OC reporting assumes that dead and decaying tree roots do not contribute to SOC, and that deep roots have the same decay rate as roots in the upper soil [47, 59]. To our knowledge, the contribution of organic matter in the coarse fraction and its long-term role in forest SOC stocks has not been quantified.

There is growing recognition of the importance of measuring SOC stocks at greater depths, including below 1 m depth (e.g., James and Harrison [60], Strey et al. [61], Wade et al. [62]), to better understand forest OC cycling and contributions to the global C budget. This trend is driven by increasing awareness that significant amounts of SOC can be stored in subsoil layers, which can be substantial in some ecosystems. Moreover, limited data on SOC to depth represents a critical knowledge gap for Earth system models aiming to predict the soil-atmosphere OC climate feedbacks [63]. The IPCC also highlights the importance of SOC stocks to depth in understanding the biogeochemical interactions between land, atmosphere, and climate [64]. Observations of deep soil formation [3] and the presence of deep-rooting trees in forest systems [4] support this emphasis, as tree roots can deliver OC, via root exudates and fine root turnover, deep into the soil profile [5, 6]. Finally, deep soil in managed ecosystems presents an opportunity for climate change mitigation and adaption for long-term DSOC sequestration [10, 65].

Deep soil carbon change

In the New Zealand case study, the age of SOC increased with increasing soil depth and was predominantly held within the MAOC fraction which was the oldest SOC fraction (Fig. 3). These results are consistent with what would be generally expected in mineral soils [18]. The data from this study is the first DSOC data in New Zealand's forests to be density fractionated and radiocarbon dated, characterising the different SOC pools (free POC, occluded POC and MAOC) which are linked to different SOC protection mechanisms [18]. The average age of the case study deep MAOC was over 1000 years (Fig. 3a), much older than the current planted forest land use across all sites, which ranged from 29 years to less than 100 years in planted forest (Table S3). This implies that the deep MAOC has come from a historical land use, likely indigenous forest cover (cleared around the early twentieth century). However, there are no baseline measurements to compare to and understand if there has been a shift in the average age or amount of MAOC between land uses. Globally DSOC radiocarbon abundance data is rare, with data entries in the International Soil Radiocarbon Database (ISRaD v.2.6.6 [66]) that have measured soil greater than 1 m depth in forest land use accounting for less than 6% in bulk soil and 2% in soil fractions (Figure S6).

While MAOC has been predicted to be less responsive to changing climate factors than POC [67], the stabilising processes involved in OC-mineral associations have been reported to be dynamic at depth [68], reversible and sensitive to change in environmental conditions [69, 70]. For example, increasing temperature and moisture can impact sub-soil SOC by promoting microbial decomposition of MAOC [67], and the relative impact of these factors may be tied to the nature of the predominant OC-mineral interaction mechanism [24]. New Zealand's planted forests soils are highly dominated by reactive metals (Fig. 4), which suggests more MAOC is protected via stable covalent bonding mechanisms [71]. Possinger et al. [24] found that elevated temperature had a greater effect than moisture on soils dominated by reactive metals, possibly due to temperature-sensitive microbial processes to overcome stable SOC-mineral bonds.

The case study results showed that, on average 6% of the DSOC was in the form of free POC (Fig. 3c). The free POC was also highly variable, with a maximum of about 30% at one forest site (Fig. 3c). This proportion may increase further if the coarse organic matter fraction (>2 mm) is included. Free POC is typically younger compared to other soil fractions, as also observed in our case study results (Fig. 3a), and represents the most responsive SOC pool to change [18, 72]. In addition to the important contribution of MAOC to DSOC observed in the case study, the free POC fraction would also be important to consider in understanding the dynamics of New Zealand's planted forest DSOC stocks.

Blind spots in existing deep soil knowledge

The inclusion of the new case study sites from the NPFI increased the number of sites with measured SOC stocks to at least 2 m depth from just two to 15 sites (Fig. 5), which still represents a very limited spatial coverage of New Zealand's planted forests. SOC data to at least 1 m depth in both planted and indigenous forests are also scarce (Fig. 5; Table S1). The soils supporting New Zealand's planted forests are naturally diverse [40], comprising volcanic deposits with buried soils [55], deep pyrogenic C [58], and variation arising from previous land use for pastoral production [73], forest management [10, 74], erosion [75], and the heterogenous nature

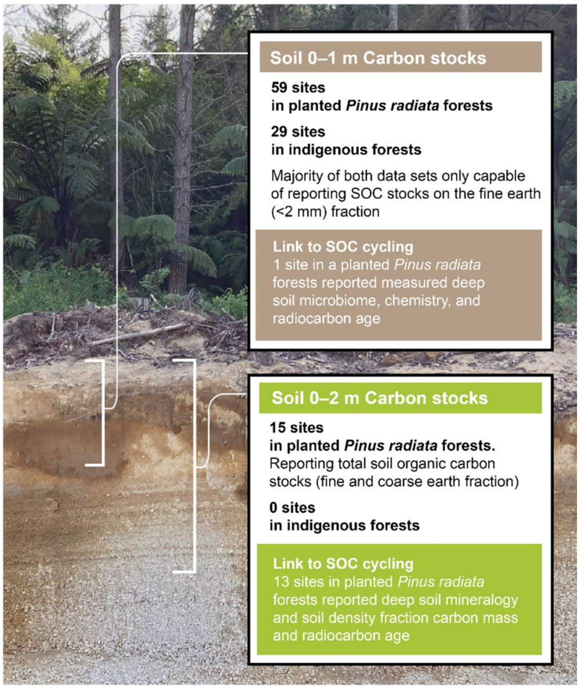

Fig. 5 A summary of New Zealand's deep forest SOC datasets including the case study sites (from Table S1)

of trees, woody debris and forest disturbances [76]. These soils can also be deep, as shown at the historical site on Pumice soil, which reached a maximum depth (soil thickness) of 440 cm (Figure S5). This highlights an uncertainty in estimating soil thickness, particularly below 1 m depth, which is the maximum depth used for soil mapping in New Zealand [77]. Because soil depth to bedrock is often unknown beyond 1 m, this uncertainty constrains the accuracy of DSOC stock estimates and remains a key limitation in scaling soil data (e.g., Dai et al. [78]).

Limited DSOC data are not only a challenge for planted forests but also for other land use systems in New Zealand. Only three additional studies have measured SOC stocks below 1 m depth in pastoral and horticultural land use [37, 49, 79]. There is no knowledge of the amount of DSOC that has been lost or gained through time or land use change. This lack of deep soil data is not surprising, as the focus of much soil research has been in soil < 30 cm depth [25] and New Zealand's greenhouse gas reporting focus is on SOC stocks to 30 cm depth [30]. As a result, a critical knowledge gap persists in understanding the magnitude, distribution, and controlling processes of DSOC in New Zealand.

Preliminary data suggest that DSOC is vulnerable to climate induced carbon loss to the atmosphere over short (annual) to medium (decades) timescales [9]. Changes in DSOC have also been observed within a decade following forest management activities (e.g., harvesting and afforestation), with both positive and negative changes in DSOC depending on site-specific factors [80, 81]. However, evidence is currently limited in describing the reasons for this variation at large spatial scales [82], including how DSOC in planted forest that pre-dates the current land use might respond to future climate or forest management. Given the limited data available for planted forests in New Zealand, we used the small case study dataset to explore climate change related risk to DSOC. Importantly, the case study results showed that over half of the SOC stocks to 2 m depth are located below 30 cm depth and held in the MAOC pool (Fig. 6) which has implications for how DSOC may respond to environmental change. For example, with increasing soil depth SOC cycling can be impacted by different drivers making DSOC persistence unique compared to upper soil [8, 9, 82].

Using our dataset, we explored the risk profile of DSOC under future climatic conditions (increasing temperature and change in soil moisture, [83, 84]). The comparison of New Zealand's deep soil mineralogy to that presented by Possinger et al. [24] showed that New Zealand's soils are highly dominated by reactive metals (Fe/Al) (Fig. 4), resulting in metal-mediated DSOC protection. There also appears to be a soil type distribution along the mineralogy gradient (Fig. 3b) that cannot be resolved with the small dataset. The overlap between the New Zealand data and the Possinger et al. [24] dataset supports the inference that New Zealand's DSOC may be more sensitive to increasing temperatures relative to other climate change factors. Notably, the New Zealand data also extend beyond the range for the reactive metals (Fe/Al) end of the mineralogy gradient (Fig. 4). The New Zealand soils with the highest reactive metal (Fe/Al) mineralogy are dominated by volcanic soil parent material, in particular Pumice and Allophanic soils [40], which account for 18% of planted forests area (Table 1). The exploratory data also demonstrated that soil mineralogy can change with increasing soil depth (Fig. 4), implying that DSOC vulnerability to climate change factors may also vary with depth.

New Zealand planted forests are currently managed without consideration for DSOC, and SOC stocks at any depth are not monitored. DSOC sampling efforts elsewhere, are elevating the importance of DSOC in forest ecosystem OC budgets (e.g., Hong et al. [81]). In New Zealand's planted forests, there is a pressing need to sample more soil to at least 1 or 2 m depth and characterise a SOC baseline, both spatially and vertically, to inform on SOC amount to depth and turn-over rate. Alignment with the existing New Zealand National Planted Forest Inventory (NPFI) [30] would allow integration

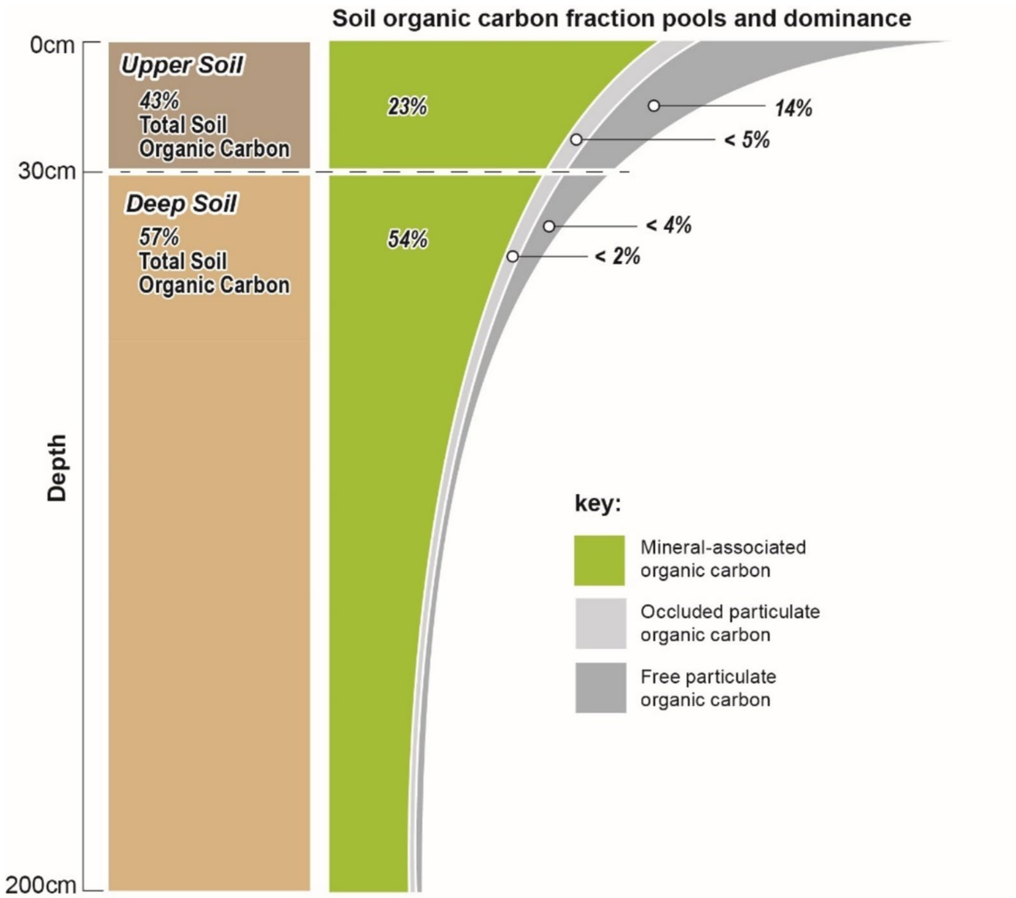

Fig. 6 The case study SOC stock distribution by depth and density fraction

with national reporting on above and below ground OC stocks. There is also a need to understand what DSOC is at risk to climate change, and to investigate the use of soil indicators to predict spatial vulnerability of DSOC with climate change. This includes application of the mineralogy gradient method of Possinger et al. [24] to New Zealand's planted forest soils and extending the analysis to consider the microbial processes that influence DSOC losses (to carbon dioxide) across the mineralogy gradient. Lastly, given the potential for trees to interact directly with deep soil through extensive rooting systems, forest management options including afforestation, should be evaluated for their role in maintaining DSOC and enhancing the resilience of New Zealand's planted forests with climate change.

Conclusion

In the face of climate change, understanding DSOC and its response to shifting climatic conditions is essential for developing resilient managed planted forests. Currently, there is very limited knowledge of New Zealand's deep soils, their maximum extent, spatial distribution, and DSOC stocks and cycling. Furthermore, there is limited knowledge to draw upon to predict how DSOC in planted forests will respond to future climate or forest management practices. Our small case study provides the only existing dataset measuring DSOC data to at least 2 m depth in New Zealand's planted forests. Based on the limited dataset, the study demonstrates that over half of the SOC stocks can be found below 30 cm depth and are dominated by minerally-associated OC that is on average older than the current land use. The quartz-rich volcanic and sedimentary soil parent materials, and resulting metal-mediated DSOC protection, may indicate vulnerability to warming soil temperatures relative to other climatic change factors. At present, there is no comprehensive evidence base to support conclusions about DSOC distribution, climate impacts, or the effects of forest management or afforestation in New Zealand's planted forests. We identify the need to sample and characterise more deep soils in New Zealand's planted forest to enable the spatial prediction of SOC cycling to depth in an uncertain climatic future. This is necessary to assess the magnitude of climate-related risk and its implications for planted forest ecosystem function and resilience, and to identify forest management options to support carbon secure DSOC and forests.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13021-025-00323-2.

Supplementary material 1. Methods Results.

Supplementary material 2. Dataset.

Acknowledgements

We thank the technical team from Scion for sample collection and testing. The authors thank the New Zealand Ministry for the Environment for support to use New Zealand's National Planted Forest Inventory (NPFI), the forest owners for access to the NPFI plots and the landowners for permission to collect soil samples. Thanks to Thomas Paul (Scion) with support with the Forest Carbon Predictor model exports and Nick Lambert (Scion) for support with imagery. We also thank two anonymous reviewers for their supportive comments.

Author contributions

Conceptualization, L.G.; Methodology, L.G., K.H., A.P., B.S., J.H., and F.F.; Investigation, L.G., K.H., and A.P.; Formal analysis, S.W., L.G., and A.P.; Visualization, L.G., K.H., A.P., and S.W.; Data curation, L.G., and K.H.; Writing—original draft, L.G.; Writing—review & editing, L.G., K.H., A.P., B.S., J.H., F.F., and S.W.; Supervision and project administration, L.G.

Funding

This work was funded by the New Zealand Ministry of Business, Innovation and Employment (MBIE) Strategic Science Investment Fund held by Scion (C04X1703).

Data availability

The data from the NPFI sites is available as a supplementary file with this publication. The data from the historical sites is available in Garrett et al. 85, https://doi.org/10.6084/m9.figshare.24635583.v2

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Received: 3 October 2024 Accepted: 8 August 2025
Published online: 14 August 2025

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