Ministry for the
Environment
Manatū Mō Te Taiao

OIAD-646

9(2)(a)

Dear 9(2)(a)

Thank you for your email of 4 May 2023 requesting the following under the Official Information Act 1982 (the Act):

> *Could I please have the final version of the draft report: DRAFT Carbon stock and stock changes in pre90 Natural forests 20221119 (prepared by Scion), which was due to be completed in March. This document is referred to in a response by Climate Director Megan Hurnard to my previous OIA request.*

The Ministry for the Environment (the Ministry) is releasing the requested report titled *'Carbon Stocks and Stock Changes in New Zealand's Pre-1990 Natural Forest'* to you in full.

Please note that this is an interim report based on the first six years of the third measurement cycle (2014 – 2020) for New Zealand's pre-1990 natural forest, and the full measurement cycle has not yet been completed. This interim report has not yet gone through a formal scientific peer-review process.

You have the right to seek an investigation and review by the Office of the Ombudsman of my decision relating to this request, in accordance with section 28(3) of the Act. The relevant details can be found on their website at: www.ombudsman.parliament.nz.

Please note that due to the public interest in our work the Ministry for the Environment publishes responses to requests for official information on our OIA responses page shortly after the response has been sent. If you have any queries about this, please feel free to contact our Ministerial Services team: ministerials@mfe.govt.nz.

Yours sincerely

Megan Hurnard
Director - Climate

Confidential

Carbon Stocks and Stock Changes in New Zealand's Pre-1990 Natural Forest

TSH Paul & SJ Wakelin

Report information sheet

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Executive summary

Objectives

The objective of this report is to provide updated estimates of carbon stocks and stock changes in New Zealand's pre-1990 Natural Forest. This update incorporates data recorded between 2014 and 2020, during the third Cycle of the pre-1990 Natural Forest inventory, which is still in process. Carbon stocks and their change based on three measurement cycles spanning between 2002 and 2020 are reported. This update also incorporates corrections made to the full dataset undertaken by Scion and documented in (Paul and Wakelin 2023). The analysis uses these corrected data and previously developed procedures to estimate carbon stocks and stock change for each inventory plot, using imputation to predict carbon stock estimates for the remaining unmeasured plots of the third inventory Cycle and any previously unmeasured plots. Estimates of carbon stocks and carbon stock change are now provided for the subcategories of Tall Forests and Regenerating Forests of pre-1990 Natural Forests, providing results aligned with the Land-Use classifications used for LULUCF reporting.

Key Results

Analysis of inventory data from 1028 permanent plots measured in Cycle 1, 923 plots with a measurement in Cycle 2 and 663 plots measured in the third Cycle within New Zealand's pre-1990 Natural Forest, showed that the forest has remained approximately in carbon balance. Over the 7.7 years between the first and second Cycle, using only remeasured plots, it is estimated that there was a small increase in total carbon of 0.43 ± 0.20 t C ha^{-1} yr^{-1}. In the 5.7 years between the second and third Cycles we estimated a decrease in total carbon of -0.71 ± 0.28 t C ha^{-1} yr^{-1}. Between the first and third Cycle we estimated a small decrease of -0.14 ± 0.24 t C ha^{-1} yr^{-1} across the full lifetime of the inventory, which statistically does not differ significantly from zero.

Carbon stocks in all pools averaged 226.54 ± 13.67 t C ha^{-1} in the first inventory Cycle, 229.37 ± 13.99 t C ha^{-1} in the second inventory Cycle and 218.69 ± 14.53 t C ha^{-1} in the third inventory Cycle . The total carbon stocks in each Cycle were not statistically significantly different from each other. Looking at plots that were re-measured in the relevant cycles, total carbon stock change between Cycle 1 and Cycle 2 was estimated as 3.30 ± 1.54 t C ha^{-1}, between Cycle 2 and Cycle 3 was -4.06 ± 2.12 t C ha^{-1} and between Cycle 1 and Cycle 3 was -1.90 ± 3.14 t C ha^{-1}. While carbon stock changes between Cycles 1 and 2 and Cycles 2 and 3 were significantly different to zero, carbon stock change since measurements began was not significantly different to zero.

To account for the reduced sampling effort in Cycle 2 and the currently incomplete sampling of Cycle 3, a double sampling approach was used to impute missing carbon stocks and carbon stock changes via regression. Using this approach total carbon stocks in Cycles 1, 2 and 3 were estimated to be 226.53 ± 13.52 t C ha^{-1}, 229.64 ± 13.65 t C ha^{-1} and 221.00 ± 13.37 t C ha^{-1} respectively, with no significant difference in stocks between the measurement cycles. Total Carbon stock change estimates using both measured and imputed plots were 3.31± 1.55 t C ha^{-1} between Cycle 1 and 2 and -4.13 ± 2.09 t C ha^{-1} between Cycle 2 and 3 and -1.32 ± 3.10 t C ha^{-1} between Cycle 1 and Cycle 3.

The classification of pre-1990 Natural Forests into Tall and Regenerating Forests based on satellite imagery was used to estimate carbon stocks and carbon stock changes in these two classes. While Tall Forests had more than three times the carbon stocks of Regenerating Forests the estimated carbon stocks in the three cycles in Tall Forests and in Regenerating Forests followed the trend of all natural forests of being not significantly different from each other. Carbon stocks in Tall Forests increased between Cycle 1 and Cycle 2 and decreased between Cycle 2 and Cycle 3 with a non-significant overall decline in carbon since measurements began. Regenerating Forests showed an ongoing trend of being a small net carbon sink per hectare since the Inventory was established.

This study follows procedures used previously (e.g. Paul et al 2021) for estimating carbon in New Zealand's natural forest. Stock estimates are based on:

- Extensive data checking and correction across three Cycles of measurements.
- Unbiased and more precise estimates of carbon in large stems by using external plot (EXT) data
- Inclusion of carbon contained in the coarse woody debris (CWD) of decay class 4 and carbon in below ground CWD
- Bias in stock change calculations has been reduced by use of the "Stem Following" method
- Estimates of uncertainty include the effects of both model prediction error and sampling variation.

The classification of Tall and Regenerating Forests has changed. Carbon stocks and carbon stock changes are now reported for Tall and Regenerating forests based on their classification via LandCoverDatabase classes, which is methodologically aligned with the estimate of land-use areas as the basis for reporting.

Recommendations

It is recommended that:

- The "Stem Following" method be used for estimating stock change in future analyses. This will require ongoing checking of measurement data to ensure the correct matching of stem measurements as the third Cycle of measurements nears completion and for the continuation of the forest inventory. Given that data correction procedures resulted in substantial changes in carbon stock estimates at the plot level, it is possible that field procedures and data checking could be improved further. The focus for improvements should be on key measurements including stem heights, diameters, tree status, and on the tracking of individual stems between measurements.

- Every effort should be made to measure and remeasure all available plot locations determined by the 8km grid to ensure a sample size that is sufficient to achieve small uncertainties (up to 10% around estimates). Consistent re-measurement of permanent plots also improves estimates, especially those of stock change. Not all plots have been remeasured throughout the past measurement cycles and the third Cycle is still incomplete, so a regression approach was used as part of a double sampling framework to overcome this inconsistency. While such an approach is an approximation, the method has been successfully implemented in forest inventories for estimating carbon stocks. However, it is only intended for intermediate reporting, not as the standard approach for reporting in the future.

- Pre-1990 Natural Forest mapping is synchronised with the inventory Cycles to ensure the required sample size is achieved. A small proportion of grid-points may not be re-measured due to denial of access or inaccessibility, but this makes it even more important that all possible available grid-points are included as potential plot locations.

- Once measured, plots should be remeasured in fixed intervals (e.g. 10 years) wherever possible. The most robust estimates of carbon stocks and stock changes can be derived from a sampling design that include sufficient numbers of plots (overall and across subclasses) with multiple re-measurements done using the same standardised period. The length of the period between measurement cycles will need to be short enough that the sample plot can be relocated and measured without loss of accuracy, but long enough that the change due to growth is sufficient to not be "masked" by measurement error. Identifying the ideal schedule for re-measurement could improve the pre-1990 Natural Forest Inventory and with longer timeframes (resulting in reduced costs) spatial sampling intensity could be increased for Forest Classes that are currently poorly represented, such as Regenerating Forest on private and public lands.

  For reporting in the National Greenhouse Gas Inventory, stock changes should be reported over an interval of ten years or more, so the overall stock change between Cycle 1 and Cycle 3 should be reported rather than reporting stock changes for Cycle 1 to Cycle 2 and Cycle 2 to Cycle 3 separately.

- Imputing carbon stock for non-measured plots can increase precision of overall carbon stock estimates. However, imputation should only be used as an intermediate step when data is as-yet unavailable (e.g. as in the case in annual inventories when estimates need to be reported half way) and provided the imputation approach is robust (in the present analysis this is the case for stocks, but not stock change). To maintain consistency in methods, carbon stocks and stock changes in the National Greenhouse Gas Inventory should use the results for measured plots only.

Carbon Stocks and Stock Changes in New Zealand’s Natural Forest

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Introduction

The Land Use and Carbon Analysis System (LUCAS) is a cross-government programme administered by the Ministry for the Environment (MfE) which supports New Zealand's international reporting requirements under the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and Paris Agreement. LUCAS combines information from field-based inventories and wall-to-wall mapping based on satellite imagery. An important part of LUCAS is the pre-1990 Natural Forest Inventory which consists of a network of permanent plots laid out on an 8 x 8 km grid covering all pre-1990 indigenous forest and shrubland. This inventory is designed to provide unbiased estimates of per hectare natural forest carbon stocks and stock change with known precision (Coomes et al. 2002).

At each grid location in the inventory, a permanent nested measurement plot was installed and received its initial measurement between 2002 and 2007. Each nested plot consists of an outer 20 m radius circular plot (EXT) and an inner 20 m x 20 m square plot (Department of Conservation 2019). All stems ≥ 60 cm diameter at breast height (DBH, measured at 1.35 m height) and dead wood ≥ 60 cm diameter are measured in the outer plot and all stems ≥ 2.5 cm DBH and dead wood ≥ 10 cm diameter are measured in the inner plot.

Carbon stocks are summarised into four IPCC pools (Intergovernmental Panel on Climate Change 2019):

1. live above ground biomass (AGB) in trees ≥ 2.5cm diameter at breast height (DBH, measured at 1.35 m height);
2. live below-ground biomass (BGB);
3. dead wood or coarse woody debris (CWD); and
4. litter. The litter pool comprises fine woody debris (dead wood from 2.5 centimetres to 10.0 centimetres in diameter), the litter (all material less than 2.5 centimetres in diameter) and the fermented humic horizons.

Dead wood arises from mortality of trees and branches ≥ 10 cm in diameter, while litter arises from litterfall < 10 cm in diameter and mortality of trees < 10 cm in DBH. Carbon in these pools is estimated from plot measurements using allometric functions described by Beets et al. (2012).

The first analysis of the inventory based on 1,256 plots measured between 2002 and 2007 (Cycle 1 for the pre-1990 Natural Forest Inventory) was carried out by Beets et al. (2009). This analysis found that the total carbon stock in pre-1990 Natural Forest and shrubland averaged 173 t C ha^{-1}. The stock in natural forest excluding shrubland was 218 t C ha^{-1}. These estimates did not include above ground CWD in decay class 4 or any below ground CWD.

Robust estimates of changes in carbon pools over time became possible after the completion of the second Cycle in early 2014. An analysis of stocks and stock changes from 874 grid locations (remeasured plots only) was reported in Holdaway et al. (2014a), Holdaway et al. (2017). Their analysis indicated that total carbon stock in pre-1990 Natural Forest measured in 2002-07 (Cycle 1) averaged 228.7 t C ha$^{–1}$, and 231.5 t C ha$^{–1}$ for the second measurement 2009-14 (Cycle 2). The overall net change in carbon across all pre-1990 Natural Forest was slightly positive (+0.34 t C ha$^{–1}$ yr$^{–1}$) although statistically indistinguishable from zero. These estimates also did not include above ground CWD in decay class 4 or any below ground CWD. Furthermore, the analyses by Holdaway (both papers) were based solely on data from the 20 m x 20 m inner plots and did not include measurements in the EXT plot, i.e., the area outside the inner plot but within the larger 20 m radius plot. Apart from not using all available data, evidence has emerged that, owing to their set up as square plots, the 20 m x 20 m plots used in the National Inventory over-sample large stems, meaning that estimates of carbon stocks based only on these plots are too high ((Paul et al. 2019b). I. It was therefore considered essential to use all data, including measurements from the EXT plots, to provide reliable estimates of carbon stocks and stock changes.

Kimberley and Beets (2016a) carried out a preliminary analysis based on the same 874 plots used by Holdaway et al. (2014a) but including EXT measurements and found lower stocks than initially reported by Holdaway et al. (2014). The carbon stock in all pools averaged 203.1 t C ha^{-1} in the first period and 203.4 t C ha^{-1} in the second period, with no significant stock change between measurements.

Paul et al. (2021) presented the most recent analysis of carbon stocks and carbon stock change in pre-1990 Natural Forests for the first two completed measurement cycles making use of the full available dataset and for the first time including estimates of carbon in difficult to assess CWD, including modelling of highly decayed and buried CWD (Kimberley et al. 2019). Carbon stocks in all pools averaged 227 tC ha^{-1} in the first inventory Cycle (2002-2007) and 227.2 tC ha^{-1} in the second inventory cycle with no significant carbon stock changes between the two cycles.

The third Cycle of the pre-1990 Natural Forest inventory began in late 2014 and will be completed in early 2024, extending the previous in-between-measurement period from 7 years to 10 years (Carswell et al. 2015).

By Mid-2020, 676 plots had been measured in Cycle 3. This represents approximately three quarters of the full measurement cycle and a decision was made to estimate carbon stock and stock changes for the this measurement cycle based on the data available at this time.

The objective of this report is to provide national carbon stock and carbon stock change estimates for all plots measured prior to mid-2020 in the three Cycles of the pre-1990 Natural Forest Inventory.

Materials and methods

Plots and measurements

New Zealand’s plot-based national forest inventories are based on a randomly placed 8 km grid for pre-1990 Natural Forests, intensified to a 4km grid for Planted Forests and post-1989 Natural Forests (Department of Conservation 2019, Herries et al. 2019). Periodic mapping aligned with each calculation period is used to determine the extent of the various forest types. The number of inventory plots that are used as a representative sample of the mapped forest type is determined by the sample grid overlaid on the mapped forest type area.

The mapping of pre-1990 Natural Forests was initially based on LCDB1. The resulting map was overlaid with the 8 km grid and this resulted in 1,371 grid locations considered to be within pre-1990 Natural Forest. In 2012 land-use mapping was renewed which resulted in 1,208 locations considered to be within pre-1990 Natural Forest and served as the sampling frame for the first two cycles of the pre-1990 Natural Forest Inventory. As outlined in Paul et al. (2021), out of the 1,208 available grid locations 1,116 were assumed to be representative of pre-1990 Natural Forest and scheduled for measurement in the first Cycle. Resources did not allow the measurement of the remaining 92 plots. From this sample of 1,116 potential plot locations a further 93 locations were not measured due to (a) denied access (47 locations); (b) inaccessibility (33); or (c) re-mapping as a non-pre-1990 Natural Forest class (13). This leaves 1,028 measured plots.

In the second Cycle the plots were classified into Regenerating and Tall Forest classes (Wiser 2016) with a nearly complete sample of Regenerating Forest plots. Only two out of the 79 plots representing the Regenerating Forest stratum were not remeasured during the 2nd Cycle of the inventory (97.5% remeasurement rate). Out of the remaining 957 plots in the Tall Forest stratum 836 were randomly selected for re-measurement (87.3% remeasurement rate). In addition, 10 plots from the 92 plots not measured in Cycle 1 were selected randomly for measurement in the 2nd Cycle with a total of 923 plots available for analysis.

In the third Cycle, which started in late 2014, a total of 662 plots had been measured by mid-2020 and were available for this analysis. Of these, 546 plots have now been measured three times, 10 of the 10 plots that were added in Cycle 2 were remeasured and 59 plots that were measured in Cycle 1 but not in Cycle 2 were remeasured. In addition, 47 plots were added in the third Cycle not measured in any previous inventory Cycle. It is unclear if these were additional plots added due to mapping changes or were part of the 80 plots that were inaccessible or had access denied or the 69 plots not measured in either of the first two cycles due to budget constraints.

In the third Cycle of measurements, 322 plots remain unmeasured. At the time of the analysis 33 plots had been abandoned as access was denied and seven had been excluded from consideration in the third cycle. None of these exclusions were due to mapping changes. This left 282 plots that still awaited their measurement in the 3rd Cycle of the inventory as of March 2020.

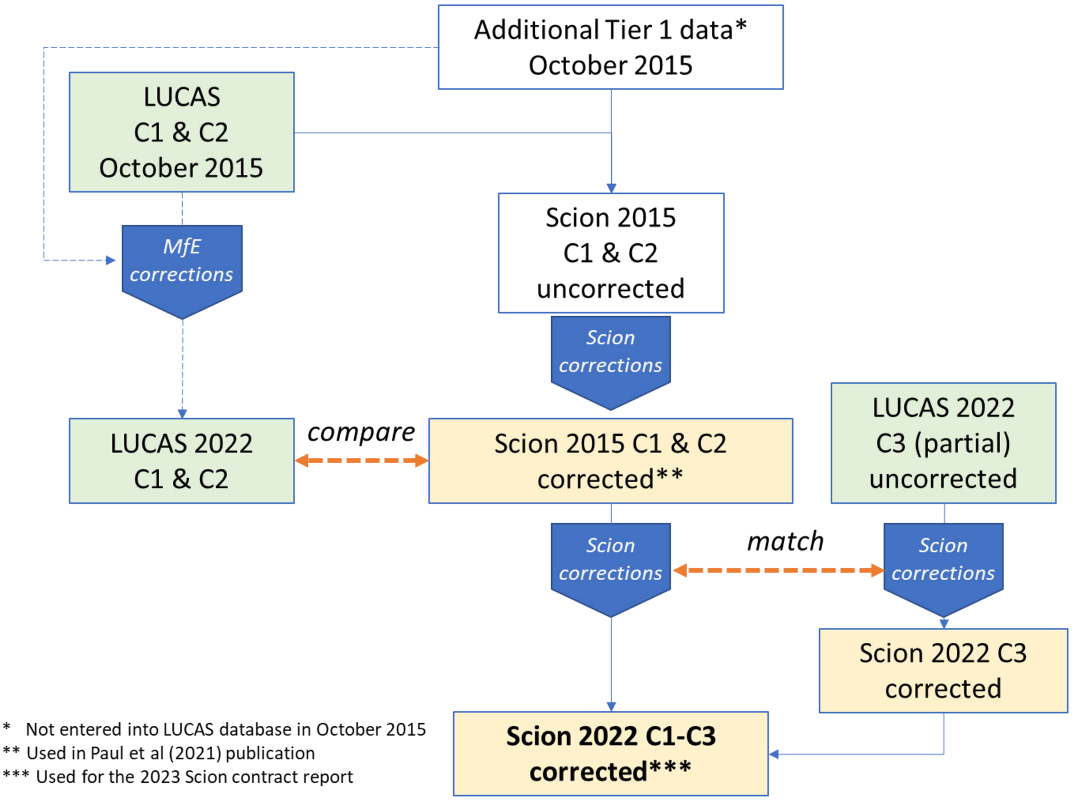
During Cycle 3 plot measurement, field teams followed protocols that have been developed since 2002 (Payton et al. 2004, Environment 2017, Ministry for the Environment 2018, Department of Conservation 2019) to tag, measure and record individual trees as a timeseries.

While stems are repeatedly measured over time, litter was only assessed during the first Cycle to estimate carbon for this pool. Litter was sampled as part of the soil assessment (Davis et al. 2004) for a random subset of grid locations . Data were obtained from 361 grid locations, but for 30 locations sampled in 2002-03, and a further 11 locations sampled later, data from the Fine Woody Debris sub-pool were not available (Garrett 2009). This left 320 grid locations where data from all sub-pools were obtained (although in most South Island locations, the FWD and Litter sub-pools were obtained only as a combined total). However, only 250 of these grid locations were mapped in 2012 as pre-1990 Natural Forest and used in the current study. Litter pool data (combined total of the three sub-pools) from these grid locations were used to estimate the carbon stocks in litter for the first Cycle, but no estimation of stock change was attempted based on this single assessment. Coarse Woody Debris was also measured to establish the baseline of the CWD pool (Kimberley et al. 2019). Soil carbon is not included in the analysis in this report.

Base dataset

Data for the first two cycles of the pre-1990 Natural Forest Inventory were extracted from the LUCAS database in October 2015, with additional data from 44 plots (not entered at that point into the LUCAS database) provided by MfE (*Scion 2015 C1 & C2 uncorrected* dataset, Figure 1).

Data checking procedures and manual checking of the various data issues were carried out and corrections applied where possible (Paul and Wakelin 2023). This *Scion 2015 C1 & C2 corrected* dataset (Figure 1) was used for the estimation of carbon stocks and stock change in 2019 (Paul et al. 2019a, Paul et al. 2021). This dataset was compared to the *LUCAS 2022 C1 & C2* dataset and found to have a lower error rate, so was used as the basis for this report, after further error corrections and imputation of missing values, and in combination with data for the currently incomplete third cycle, extracted from the LUCAS database in January 2022.



* Not entered into LUCAS database in October 2015
** Used in Paul et al (2021) publication
*** Used for the 2023 Scion contract report

Figure 1. Summary of error checking process and datasets used. The individual datasets are subsets of the LUCAS database managed by MfE (from Paul and Wakelin 2023).

A fuller description of the base dataset used in this analysis can be found in Paul (2023).

Data checking and corrections

A full description of the data checking and correction procedure is given in Paul and Wakelin 2023. In summary, the steps taken were:

1. **Stem matching.**
   In the pre-1990 Natural Forest inventory, a timeseries of measurements for individual trees is compiled by matching repeated measurements to a stem tag number. Screening identified systematic mismatches due to a change in tag specifications, and these were corrected. Apparent ingrowth in Cycle 2 (i.e. stems present in Cycle 2 but not in Cycle 1) were manually checked against stems present in Cycle 1 but not in Cycle 2.

   Further stem matching checks revealed that in 56 plots measured in the first year of Cycle 3 (2014/2015) field teams did not measure some EXT subplots and therefore left 274 EXT trees unassessed. We included these unmeasured tree records so their carbon content could also be estimated using the stem following method. We assumed that their status would have not changed since the last measurement. This assumption is supported by the fact that the ratio between dead and live trees in the missed EXT subplots was 0.31 (based of the tree status in Cycle 2), which was slightly higher than the overall ratio of dead to alive trees in all measured Cycle 3 plots (0.28). Of the missed trees, 205 were recorded previously as alive and 63 as dead. Not accounting for them would have effectively resulted in an apparent large carbon loss in these plots.

2. **DBH and Height increment outlier check and replacement**
   Outliers were identified using standardised residuals from plotting the DBH and Height in the second and third cycles against corresponding measurements in the previous cycle. The largest positive and negative standard residuals were manually checked against plot sheets, and erroneous measurements either corrected or replaced with a missing value method (Paul and Wakelin 2023).

3. **Other corrections**
   Other corrections were made to account for constant tree fern diameters, exclusion of lianas, removal of diameters under the threshold for measurement of live and dead trees and CWD, and to ensure consistent naming of species (Paul and Wakelin 2023).

Carbon calculations

Carbon calculations are based on a series of procedures using the pre-1990 Natural Forest measurements and remeasurements of a plot. The initial procedures were developed for the first analysis of the inventory data (Beets et al. 2009) and now have been further refined. In this section the methods used to estimate carbon from repeated measurements of tagged stems are presented in full. For this study, the procedures were coded into SAS Version 9.3 macros.

Height estimation for trees and shrubs

Due to the cost and difficulty of measuring stem heights compared with diameters, only a sample of stems are measured for height. As the allometric carbon equations require both height and DBH for every stem, heights were estimated using height/DBH regression models fitted to height measurements of all live, non-leaning trees and shrubs that had been measured three times. A different method was used for tree ferns, cabbage trees and palms (see below). Measurements of leaning trees were considered less reliable and were not used in the analysis (Kimberley & Beets 2016a). Kimberley and Beets (2016b) presented evidence that suggested different criteria had been used to select the trees measured for height in each Cycle. To ensure that modelled height changes represented genuine growth effects, only stems measured in all three Cycles were used to develop the models.

The method used the following underlying height/DBH function:

(1) $$height = 1.35 + exp\ (a + b\ x\ DBH^{-0.3})$$

which was fitted in its linearized form:

(2) $$\ln(height - 1.35) = a + b\ x\ DBH^{-0.3}$$

The function was firstly fitted using the SAS procedure MIXED to the pooled data across all plots and measurements as a random coefficient regression model with separate a_i and b_i parameters for each species i (provided in the supplementary).

All height measurements of live, non-leaning trees and shrubs measured three times were then converted into a variable Y which has a common relationship for all species, using the following equation:

(3) $$\mathrm{Y} = \ln(height - 1.35) - \mathrm{a}_i - \mathrm{b}_i\ x\ DBH^{-0.3}$$

A linear regression between Y and $DBH^{-0\ 3}$ was then fitted for each plot with separate intercepts for each plot measurement and predicted values Y_{Pred} obtained from these regressions for all stems. The equation in step 3 was then reversed to provide predictions of Height-1.35 using:

(4) $$Y_{Pred} - 1.35 = \exp\left(Y_{Pred} + a_i + b_i\ x\ DBH^{-0.3}\right)$$

Finally, because these back-transformed height predictions are known to be biased, a bias-correction procedure (as follows) was applied using the ratio R, calculated for each species with live, non-leaning trees and shrubs measured three times:

(5) $$R = mean(height - 1.35)/mean(PredHt - 1.35)$$

R was calculated for each species with three or more heights recorded in a plot in one measurement. For species with fewer than three height measurements, the mean value of *R* across all species was used. The final predicted height of each stem was calculated using:

(6) $$height_{Pred} = 1.35 + R\ x\ PredHt - 1.35$$

Height estimation for tree ferns and monocots

For tree ferns, cabbage trees and palms there is no strong relationship between stem height and DBH, and a simpler approach was used to estimate stem heights. When three or more height measurements of non-leaning live stems for a given species in a plot and measurement cycle were present, their mean height was used as the predicted height for all stems of that species. For tree fern species with less than three height measurements, the mean of all tree fern height measurements for each time period in a plot and measurement cycle was used.

Above-ground carbon in live trees and shrubs

Over-bark volumes (m^3) of all live stems measured for DBH other than tree ferns, cabbage trees and palms were predicted using the allometric equation of Beets et al. (2012) from DBH (cm) and predicted height (m):

(7) $$Volume_{stem} = 0.0000483\ x\ (DBH^2 x\ height_{pred})^{0.978}$$

Stem carbon (kg) was then estimated using:

(8) $$Carbon_{stem} = Volume_{stem}\ x\ Density\ x\ Carbon_{fraction}$$

Where $Carbon_{fraction}$ is 0.51 for gymnosperms and 0.48 for all other species and $Density$ (kg dry matter m^{-3}) is whole stem basic density tabulated by species. For species with no tabulated density, the mean density of the genus, or failing that, of the plant type (tree, subcanopy tree, or shrub) was used.

Branch and foliage carbon (kg) of live trees was estimated directly from DBH (cm) using the equations of Beets et al. (2012):

(9) $$Carbon_{branch} = 0.0175\ x\ DBH^{2.20}$$

and,

(10) $$Carbon_{foliage} = 0.0171\ x\ DBH^{1.75}$$

Above-ground carbon in live tree ferns and monocots

For tree ferns, cabbage trees and palms, carbon was estimated directly from DBH (cm) and *Height*$_{Pred}$ (m) using the equation:

(11) $$Carbon_{treefern} = 0.00270\ x\ DBH^2 x\ {height_{pred}}^{1.19}$$

Above ground carbon in dead standing spars

For dead standing spars of tree and shrub species, at each measurement the volume of each standing spar (m3) was firstly predicted from DBH and $Height_{Pred}$ using Equation (7). Because standing spars are often broken, the volume of the truncated spar was then calculated from DBH and measured height. Note that all spars are supposed to be measured for height but when this was not the case the predicted height was used in its place assuming the spar maintained its full height. The volume was calculated using:

(12) $Volume_{Spar} = Volume_{stem} x(1 - 0.06501\ x\ X^2 - 2.92127\ x\ X^3 + 3.37103\ x\ X^4 - 1.35551\ x\ X^5 - 0.02924\ x\ X^{81})$

Where, $X = (height_{pred} - height_{measured})/height_{pred}$

As dead wood is at least 10 cm in diameter, the function was only applied to stems ≥ 10 cm DBH, and X was calculated using the smaller of the measured height and the height corresponding to a stem diameter of 10 cm. Carbon in dead spars (kg-C tree^{-1}) was then estimated using:

(13) $Carbon_{spar} = Volume_{spar} x Density\ \ x Decay_{modifier} x Carbon_{fraction}$

Where $Carbon_{fraction}$ is assumed to be 0.50 for dead material (because species was unknown), $Density$ (kg dry matter/m^3) is as for live stems and $Decay_{modifier}$ adjusts for the loss in density of dry matter due to decay and is determined on the basis of the decay class assigned to the spar by the field team. In this study, the decay modifiers for unspecified species in Coomes et al. (2002) were used. These are 1.00, 0.82, 0.66, and 0.47 for decay classes 0, 1, 2, and 3 respectively.

For tree ferns, cabbage trees and palms, carbon was calculated from measured height (m) and DBH (cm) using:

(14) $Carbon_{treefern\ spar} = 0.00270\ x\ (DBH^2 x\ height_{pred})^{1.19} x Decay_{modifier}$

Carbon in Dead Stumps

Volume (m^3) of dead wood in stumps was estimated from the stump small end diameter (SED, m) and height (Height, m) using the formula for a cylinder:

(15) $Volume_{Stump} = \pi\ x\ height\ x\ (SED/2)^2$

Carbon was calculated in the same way as for standing spars using the same decay modifiers and carbon fraction (0.50):

(16) $Carbon_{Stump} = Volume_{Stump}\ x\ Density\ x\ Decay_{modifier}\ x\ Carbon_{fraction}$

Carbon in fallen pieces of above-ground Dead Wood

Volume (m^3) of fallen pieces of dead wood was estimated from large and small end diameters (LED and SED, m) and piece length (Length, m) using the formula for a truncated cone:

(17) $Volume_{Piece} = \frac{1}{3} x(\pi\ x\ Length) x \left(\left(\frac{LED}{2}\right)^2 + \frac{LED}{2}\ x \frac{SED}{2} + \left(\frac{SED}{2}\right)^2 \right)$

Only pieces with LED ≥ 10 cm (inner plot) or 60 cm (EXT subplot) were used in the calculation. Carbon was calculated in the same way as for standing spars using the same decay modifiers and carbon fraction (0.50):

(18) $Carbon_{piece} = Volume_{piece}\ x\ Density\ x\ Decay_{modifier}\ x\ Carbon_{fraction}$

Adjustment to the above ground Dead Wood pool

Recent analysis by Kimberley et al. (2019) has demonstrated that the plot measurements of dead wood obtained in the inventory tend to significantly understate the true amount of dead wood in a plot. This error is thought to be due to a consistent tendency for dead wood material to be missed during the measurement process. For example, field audits conducted in the first two Cycles revealed that dead wood stocks were often underestimated due to unmeasurable piece shapes, loss of bark, shattered logs and spars and debris inaccessibly piled in gullies. Furthermore, under current measurement protocols (Department of Conservation 2019), there is no attempt to measure Decay Class 4 (heavily decayed) material, nor to measure fallen stems and other dead wood material buried more than 50% in the forest floor and which is not captured anywhere else (e.g. as litter or soil carbon; (Davis et al. 2004)). There is also uncertainty around the assignment of decay classes and species identification made in the field and uncertainty about the robustness of currently used density modifiers(Kimberley et al. 2019).

To estimate dead wood carbon stocks and their change we therefore followed the approach described by (Kimberley et al. 2019). The dead wood measurements from Cycle 1 were used as an initial starting value. The mortality between the first two inventory Cycles was accounted for as input into the dead wood pool, while the predicted loss from decay over the period between measurements was calculated based on models developed by Garrett et al. (2019). This approach produced a higher estimate of dead wood for 2009–2014 than the actual field assessments in Cycle 2, probably due to the various subsets of CWD excluded by the measurement protocols as described above. To compensate for this, we determined an adjustment factor by an iterative procedure such that, when multiplied by the measured dead wood in both 2002–2007 and 2009–2014, the modelled estimate for 2009–2014 was the same as the adjusted measurement at that time. The adjustment factor derived using this approach was 1.763. In other words, the adjusted estimates of dead wood carbon for all Cycles were obtained by increasing the measured values by 76.3%.

Carbon in Litter

Using 250 grid locations with carbon measurements for the Litter pool made during the first Cycle, a weak but statistically significant relationship with Carbon_AGB provided the following regression model (R^2 = 0.08) which was used to estimate carbon in the Litter pool (tC ha^{-1}) for all locations:

(20) $Carbon_{Litter} = 2.938275 = 0.190852\ x\ Carbon_{AGB} - 0.000299\ x\ Carbon\ _{AGB}{}^{2}$

Carbon in below-ground biomass

The carbon in below-ground biomass in each live tree or shrub was calculated as a ratio (root/shoot ratio) of the carbon in above ground biomass (stem + branch + foliage). The ratio used was 0.234 for angiosperm trees and palms, for cabbage trees 0.437, for tree ferns 0.194, and 0.245 for shrubs and gymnosperm trees as suggested by Easdale et al. (2019).

Carbon in below-ground dead roots

There are no direct measurements of carbon in below-ground dead roots in the pre-1990 Natural Forest Inventory. Modelled estimates of the carbon in dead roots were only recently provided by Paul et al. (2021) and are included in the Dead wood pool. For completeness, the current study provides estimates of carbon in this pool from the best information currently available.

Garrett et al. (2019) studied decay rates in roots of native trees using data from three rimu and two silver beech trees and found roots decayed more quickly than above-ground dead wood. Exponential decay constants for rimu were of λ=0.0322 for roots and λ=0.0279 for above-ground dead wood (a larger decay constant indicates faster decay) while for silver beech the decay constant was λ=0.0383 for roots and 0.0249 for above-ground dead wood. Averaged across both species, the ratio of above ground to below-ground decay constants was 0.76. Under the exponential decay model, this implies that if the same amount of material enters both pools at a constant rate, the total dry weight of the below-ground material will be 76% of the dry weight of the above ground material at any point in time.

Therefore, as the root/shoot ratio for live trees implies that the dry weight of below-ground material in a tree or shrub that dies is approximately one quarter of its above ground material, the faster decay rate below-ground implies that below-ground dead wood carbon will be 0.25 × 0.76 = 0.19 times the above-ground dead wood carbon. Therefore, in the current study, below-ground dead wood carbon was estimated using:

(21) $Carbon_{deadroots} = 0.19\ x\ Carbon_{aboveground\ CWD}$

Missing DBH estimation

Some stems measured during re-measurement Cycles (C2 and C3) were found to have been missed during previous Cycles (C1), but were clearly far too large to be genuine ‘ingrowth’. Ignoring this issue would produce underestimates of carbon for the first cycle, and lead to an overestimate of any increase or underestimate of any decrease in carbon.

To correct this, estimates of missing DBHs were predicted using linear regressions fitted using the SAS MIXED procedure. These models were fitted separately for each plot, predicting (backcasting) DBH at Time X from DBH at Time X+1 and including species as a random effect. This approach was used for tree and shrub species. For tree ferns, palms and cabbage trees, a missing DBH at Time X was set equal to DBH at Time X+1 on the assumption that for these species, DBH does not change greatly over time. Although it was considered far more likely that this procedure would correct for an under-prediction of carbon at Time X, it is acknowledged that there is some potential for the procedure to cause over-predictions of carbon at Time X if in fact the missing stem was actually present but misidentified with an incorrect or missing tag. In that case the stem would then be counted twice at time X).

A similar procedure (forecasting) was used for estimating missing DBH at Time X+1 from DBH at Time X for the small number of stems with missing DBH in the second and third Cycle.

Combining data from 20 m radius circular plots and 20 m × 20 m square plots

With the nested plot design used in the inventory, larger diameter stems and dead wood were measured within the 20 m radius circular plot while smaller diameter material was only measured within the inner plot. This meant that larger diameter material at any grid location was sampled over a larger plot area of 0.1257 ha (the horizontal area of all 20 m radius plots). Smaller diameter material was sampled over an inner plot area averaging only 0.0345 ha based on the horizontal distances measured between permanently marked corner-pegs and angles that were used to calculate the true horizontal area using the Bretschneider formula for the area of a convex quadrilateral (Paul et al. 2019).

Estimates of carbon per hectare were then calculated for each grid location by summing the carbon estimate (kg) in each live stem and dead wood piece, divided by the horizontal area of the relevant nested plot it was sampled in, and dividing the sum by 1000 to convert to $tC{\cdot}ha^{-1}$. Thus, all pieces and stems ≥ 60 cm diameter were divided by the area of the 20 m radius subplot (0.1257 ha) while smaller stems which were only measured in the 20m× 20 m square plot were divided by the horizontal area of that plot. To ensure the strict application of the minimum diameter size for dead wood in each nested plot, minimum diameter thresholds for fallen material of 10 cm and 60 cm were applied in inner and outer plots respectively. The estimated carbon in fallen pieces lying in the inner plot with LED greater than 60 cm and SED less than 60 cm were split into two values based on an assumption of uniform taper over the length of the piece, with the carbon calculated for the portion of the length greater than 60 cm in diameter assumed to be sampled over the larger plot area, and the remainder assumed to be sampled over the inner plot area. Carbon stock change in live stems was estimated in the same way as for carbon stocks, using the sum of the change in weight of carbon in each followed live stem divided by the relevant plot area. However, no attempt was made to follow existing individual pieces of fallen dead material between measurements and stock change in dead wood was estimated as the difference in stocks at times 1, 2 and 3 calculated at the plot level (including occurring mortality).

Carbon stock change calculation based on the "Stem following" method.

To estimate changes in the AGB pool between two inventory Cycles, each measured stem was followed over time. With this approach carbon change is calculated for each stem and summed for the plot. This method requires accounting for ingrowth stems (below the DBH threshold size at Time X) and missed DBH measurements occurring over the three Cycles (see above section on missing stems).

Trees measured at Time X which were not measured at Time X-1 always had missing values predicted using the missing value method and were used in the calculation of stock change provided that the DBH at Time X was above the threshold. For example, if the DBH at Time X was 60.5 cm and the predicted DBH at Time X-1 was 59 cm (in the EXT so not measured), the 59 cm estimate was used at Time X-1. Likewise, if the DBH at Time X was 2.6 cm and the predicted DBH was 2.3 cm at Time X-1 (in the internal plot), the 2.3 cm estimate was used at Time X-1. The stem following method avoids the issue of inflated stock change estimates in conventional stock change approaches that would simply account for the difference between 0 tC at time X-1 (not measured, as below the threshold) and a potentially large carbon stock after passing the threshold and being measured for the first time in Time X.

Errors of estimates

Estimates of uncertainty obtained in forest inventories are usually calculated on the basis of plot-to-plot sampling variation. However, estimates of carbon such as those provided in this study rely on complex allometric relationships and models used to estimate carbon from stem and log measurements. It is desirable to account for prediction errors in these models when considering the uncertainties of carbon estimates. We combined these two sources of uncertainty using simple statistical rules suggested by IPCC (Intergovernmental Panel on Climate Change 2006).

Model prediction error

Estimates of model prediction uncertainties for carbon in each pool and for total carbon based on an analysis of the underlying models used to estimate each pool, are shown in Table 1.

Table 1: Model prediction uncertainty for carbon stocks for each pool and for the sum of all pools. Uncertainties are shown as 95% confidence intervals expressed as a percentage of the mean stock.

Pool	Uncertainty
AGB	± 4.5%
BGB	± 4.9%
Dead Wood (CWD)	± 25.6%
Litter	± 2.0%
All pools	± 5.2%

Details of their derivation are presented in the Supplementary Documentation. Because the same models are used for predicting stocks at all three Cycles, their errors are clearly not independent, and in practice may be close to identical. If these errors, expressed as percentages of each respective mean are indeed identical, then the estimate change in stocks (i.e., stock at Time X minus stock at Time X-1), will also have the same percentage error. For example, from Table 1, the model uncertainty for carbon stock in all pools is ±5.2% and it can be assumed that the uncertainty for stock change will therefore also be ±5.2% of its mean.
This implies, for example, that if the estimated stock change is close to zero, then its prediction error will also be close to zero. As model prediction errors are independent of errors from sampling variation, they can be combined using standard methods of combining independent variances giving the following estimates of uncertainty (see Page 3.28 in Volume 1 of Guidelines for national greenhouse gas inventories (Intergovernmental Panel on Climate Change 2006):

$$CI_{s\&p} = \sqrt{CI_s^2 + CI_p^2} \tag{22}$$

where, $CI_{s\&p}$is uncertainty accounting for both sampling variation and model prediction error expressed as a 95% confidence interval, CI_s is sampling uncertainty (see next section), and CI_p is prediction error obtained by multiplying the percentage value in Table 2 by the estimate of stock or stock change and dividing by 100.

Sampling error

Plot measurements were obtained from 1087 grid locations (total available grid-locations in pre-1990 Natural Forests based on LUM v8 are 1184), but not all of the 1087 locations were measured in all Cycles, and only a subset of plots was measured for litter and only in the first Cycle. Sample plots can be divided into eleven subsamples based on their measurement history which for convenience are labelled A – K (Table 2), with the combined samples measured labelled L.

Table 2: Eleven subsamples of the pre-1990 Natural Forest inventory. With L summing up all combined samples for each Cycle. "×" indicates subsamples of plots that were imputed by using regressions, based on the immediate earlier or later measurement. 105 events were not imputed (×).

Subsample	Number of plots	Cycle 1 Stems & Dead	Cycle 2 Stems & dead	Cycle 3 Stems & dead	Litter
A	106	✓	✓	✓	✓
B	440	✓	✓	✓	(×)
C	104	✓	✓	×	✓
D	262	✓	✓	×	(×)
E	18	✓	×	✓	✓
F	41	✓	×	✓	(×)
G	10	×	✓	✓	(×)
H	18	✓	×	(×)	✓
I	40	✓	×	(×)	(×)
J	2	×	✓	×	(×)
K	47	(×)	(×)	✓	(×)
L	1087	1028	923	662	245

The imputation approach via double sampling using a regression approach (Cochran 1977) added 12 plots to Cycle 1; 117 plots to Cycle 2 and 368 plots to Cycle 3.

Estimates of per hectare carbon stocks for each pool in all Cycles were obtained on the assumption that the sampling method adopted for all Cycles was equivalent to simple random sampling of the mapped forest area. Mean stocks for AGB, BGB, and dead wood were therefore estimated using standard methods for simple random sampling (e.g., Cochran 1977, Chapter 2), i.e.:

(24)

$$\bar{y}_1 = \sum\nolimits_{i \in F} y_i / n_D$$

where, y_i is per hectare carbon at Time 1 for AGB, BGB, or dead wood in plot *i*, and n_D is the number of locations in subsample *D* (i.e., nD= 262). The variance of $\bar{y}_1$ was estimated using:

(25)

$$v(\bar{y}_1) = s_F^2 / n_D$$

where s_F^2 is the sample variance of y_i in subsample *D*.

Ninety-five percent confidence intervals based on sampling variation for $\bar{y}_1$ and all other carbon estimates from the inventory were obtained by multiplying the square root of the variance by a t-value with appropriate degrees of freedom. Note that these confidence intervals are based on sampling variation and take no account of errors in the underlying carbon models which were described in the previous section.

The estimated per hectare mean carbon stock in litter $\bar{l}$ and its variance $v(\bar{l})$, were estimated from l_i, the mean litter carbon in plot *i*, as in Eqs. 24 and 25 except that the summation and variance was over locations measured for litter, i.e., A U C U E U H.

Total carbon for Time 1 in the AGB, BGB, dead wood, and litter pools, was estimated using:

(26)
$$\bar{t}_1 = \bar{y}_1 + \bar{l}$$

where, $\bar{y}_1$ was calculated using Eq. 24 with y_i being the summed carbon in AGB, BGB, and dead wood in plot *i*. The variance of $\bar{t}_1$ was estimated using the standard method for calculating the variance of a sum, being the sum of the variances of each component together with a covariance term accounting for the lack of independence between the litter and the sum of the other pools in plots measured for all components, i.e.:

(27)
$$v(\bar{t}_1) = v(\bar{y}_1) + v\left(\bar{l}\right) + 2s_{yl}/n_f$$

where, s_{yl} is the sample covariance between y_i and l_i in the combined subsamples A U C U E U H.

Carbon stock changes for the AGB, BGB and dead wood pools and their sum were estimated using Eq. 24 and the variance estimated using Eq. 25. Note that it was not possible to estimate change in the litter pool which was only measured in Cycle 1.

Double sampling with regression estimator

Carbon stocks

While some plots have not been sampled in one or two of the cycles across the inventory we can assume that in every cycle plots are sampled randomly (incomplete random sample). In the case of the third Cycle, we can assume that plots measured so far were a random sample that is not yet complete. We can use a double sampling framework with regression estimators (Cochran 1977) to impute the remaining unmeasured plots.

(28)
$$\bar{y}_1 = \frac{\sum_1 y_i + \sum_2 (a + by_i)}{n}$$

with $\bar{y}_1$ being the calculated mean carbon stock at time 1, with y_i is per hectare carbon at either Cycle 1 or 2 for AGB, BGB, or dead wood in plot *i*, for Cycle 2 estimated by linear regression (29) with coefficients a and b fitted to plots measured twice. n is the total number of plots:

(29)
$$C_{pool\ t_{i\pm1}} = a + bxC_{pool\ t_i}$$

Our regression models for individual carbon pools and their total had very high R^2 values (0.96 to 0.73). Using the regression approach we imputed carbon stocks for 12 more plots (G, J) for Cycle 1, 117 plots (E,F,H,I) for Cycle 2 and 368 plots (C,D,J) from previous Cycles.

Our estimates of carbon stocks using measured and imputed plots for a certain cycle and estimates of stock changes again using measured and imputed plots are regression estimates using double sampling. Errors for these are given by Cochran (1977). These can be expressed using the following formula:

(30)
$$CI_s = t \times \sqrt{\frac{S^2}{n'}\left(1 - \frac{n'R^2}{n'+n''}\right)}$$

where, *CIs* is the uncertainty of the estimate accounting only for sampling variation expressed as a 95% confidence interval, *t* is a *t*-value, S^2 is the variance of the estimated carbon stock or stock change in plots measured twice, *n'* is the number of plots measured twice, *n''* is the number of plots only measured once, and R^2 is the coefficient of determination of the regression model used in the estimator.

Means and CIs for carbon stocks were calculated for double sampling combinations (see Table 2) were a direct previous or recent estimate of carbon stocks was available across the three Cycles.

Carbon stock change

To use information from plots only measured once when estimating carbon stock changes, regressions predicting carbon stock change for a pool from its initial carbon stock were used. Although these stock change models had very low R^2 values, they allowed for consistent patterns in the relationship between carbon stock change and carbon stocks to be taken into account. However, examination of these relationships indicated they were nonlinear with intercept zero. After testing various regression models, the following model fitted to data from plots measured at least twice was found appropriate for predicting change e.g. in $C_{AGBchange}$ from the C_{AGB} stock:

$$C_{AGB_{changeC1C2}} = a \times ln(C_{AGBc1} + 1) + b \times ln[(C_{AGBc1} + 1)]^2 \quad (31)$$

This led to the following estimator:

$$Mean\_C_{AGB_{changeC1C2}} = \frac{\sum_{\substack{Plots \\ measured \\ twice}} \left(C_{AGB_{changec1c2}}\right) + \sum_{\substack{Plots \\ measured \\ once}} \left(a \times ln(C_{AGBc1}+1) + b \times ln[(C_{AGBc1}+1)]^2\right)}{n} \quad (32)$$

In this estimator, for plots measured only once, C_{AGB}, (either known from Cycle 1 or Cycle 2) was used to predict the change in C_{AGB} for the following period. Similar estimators using log-transformed carbon stock in the relevant pool in a quadratic regression with no intercept were used to estimate carbon stock change for BGB and Dead Wood and change in the sum of all three pools.

Using the quadratic regression, we imputed 116 carbon stock changes between Cycle 1 and Cycle 2, 368 carbon stock changes between Cycle 2 and Cycle 3 and 424 carbon stock changes between Cycle 1 and Cycle 3.

National estimates of carbon stocks and stock changes

New Zealand’s natural forest has previously been classified into Forest Alliances based on species composition assessed in the second Cycle of the natural forest inventory (Wiser 2016, Wiser and De Cáceress 2018). This classification was previously applied to assign the calculated carbon stock and carbon stock change to 28 Forest Alliances identified in New Zealand (plus one unclearly classified group) and their grouping into two broad physiognomic groups of Tall Forest and Regenerating Forest (Wiser et al. 2011). However, while plot-based vegetation classifications based on tree and ground vegetation composition represent vegetation types well, they only allow the assignment of carbon stocks to a mapped area through a plot-to-area-ratio approach. Therefore, changes in area through land-use change cannot be directly related to carbon stock changes for specific forest types (unless a sample plot is affected). To overcome this, pre-1990 Natural Forests are now stratified into Tall and Regenerating Forests using the Land Cover Database mapping approach (which is aligned to MfEs LandUseMap). The classes used (Easdale et al. 2020) are shown in Table 3:

Table 3: Mapping classes (LCDBv5) grouped into the two forest classes used for reporting.

Pre-1990 Natural Forest Class	LCDBv5 mapping class
Tall Forests	Indigenous Forests Broadleaved Indigenous Hardwoods
Regenerating Forests	Deciduous Hardwoods Exotic Forest Fernland Gorse and Broom High producing exotic Grassland Manuka and/or Kanuka Mixed Exotic shrubland Sub-alpine shrubland

The overlay of all 1087 inventory plots with LCDBv5 identified 11 plots where the LCDBv5 mapping class differed to those in Table 3. Four plots were mapped in low producing grassland; three were on landslides and one on gravel and rock. One was located in Tussock Grassland, one plot was mapped in a lake and one was mapped as mangrove. These eleven plots were all classed as Regenerating Forest.

Ratio of means for carbon stock change

Ratio estimates are a feature of Forest Inventories (Johnson 2000) and deal with data that is expressed as a "per unit" value. The most common method in forest inventories is the use of plot area (that can vary between plots) to scale up to a per hectare basis using the ratio of means approach (Bechtold and Patterson 2005).

To obtain annualized carbon stock change for a forest type based on a sample with a varying remeasurement time period across the sample (e.g. the in-between-measurement periods vary by plot, as no strict plot assignment to a remeasurement panel was maintained between the measurement cycles), the basic procedure was to use a ratio of means estimator (Rao 2002) consisting of the estimated carbon sequestration per plot summed across all plots, divided by the summed time period across all plots to estimate the mean annualized carbon sequestration for a forest type.

$$(33)\quad \bar{y}_{forest\ type} = \sum_{i=1}^{n} y_i / \sum_{i=1}^{n} a_i$$

where $\bar{y}$ is the mean annualized carbon change, y_i the measured carbon stock change for a plot and a_i is the calculated time between measurements.
An estimate of the variance of this ratio of means estimator is (e.g., Cochran 1977),

$$(34)\quad V(\bar{y}_{forest\ type}) =$$

$$\frac{n}{(n-1)}\left(\sum_{i=1}^{n} y_i^2 - 2\bar{y}_{forest\ type}\sum_{i=1}^{n} y_i a_i + \bar{y}_{forest\ type}^2 \sum_{i=1}^{n} a_i^2\right) / \left(\sum_{i=1}^{n} a_i\right)^2$$

Ninety-five per cent confidence intervals for the mean annualized carbon stock change were derived from the variances in the usual manner.

Results

Overall carbon stocks and stock changes

Our analysis of inventory data from permanent plots at 1087 grid locations within New Zealand's pre-1990 Natural Forest shows it is in a state of carbon balance.

Carbon Stocks - measured plots only

When using estimates from measured-only plots, carbon stocks in all live and dead pools combined averaged 226.54 ± 13.67 tC ha^{-1} in the first Cycle, 229.37 ± 13.99 tC ha^{-1} in the second and 218.69 ± 14.53 in the third yet not completely measured Cycle (Table 4).

Importantly estimated carbon stocks across the three measurement cycles are not statistically significantly different from each other based on the sampling and model error that is inherent in the data and expressed through the confidence interval. Around 73 % of assessed carbon was stored in the living biomass (AGB and BGB), while dead wood and litter stored the remaining 27% and this approximate ratio is maintained across all three measurement cycles.

Based on its mapped area of 7.7M ha, pre-1990 Natural Forest in New Zealand contained 1,744 ± 105 MtC in Cycle 1, 1,763 ± 108 MtC in Cycle 2 and 1,684 ± 112 MtC in Cycle 3 of the inventory in live and dead biomass pools excluding soil carbon and has not significantly changed between these inventory Cycles.

The average of total carbon stocks in Tall Forests was more than approximately three times the carbon stocks in Regenerating Forest. Total carbon stocks in Tall Forests averaged 242.89 ± 14.41 tC ha^{-1} in the first Cycle, 246.11 ± 14.75 tC ha^{-1} in the second Cycle and 236.58 ±15.39 tC ha^{-1} in the third, compared to 73.15 ± 16.38 tC ha^{-1}, 75.91 ± 16.65 tC ha^{-1} and 77.84 ± 17.83 tC ha^{-1} in Regenerating Forest for the same Cycles.

Carbon stocks - measured and imputed plots

Using plot estimates that include imputed plots via our regression approach, estimated total carbon stocks were very similar with carbon stocks totalling in all pre-1990 Natural Forests on average 226.53 ± 13.52 tC ha^{-1}, 229.64 ± 13.65 tC ha^{-1} and 221.00 ± 13.37 tC ha^{-1} for the three Cycles respectively with slightly tighter Confidence Intervalls (Table 5).

Tall Forests carbon stocks and their CI were similar in size for the first and second Cycle when using only measured plots (see above). However, carbon stocks for Tall Forests in Cycle 3 were slightly higher (238.16 ± 14.30tC ha^{-1}) with slightly less uncertainty when imputed plots were added (36% more plots). For Regenerating Forests, estimates of carbon stocks were slightly lower for Cycle 1 and Cycle 3 and higher for Cycle 2 when a small number of imputed plots were added. Adding imputed plots reduced the uncertainty slightly compared to the analysis based on measured plots only, which is a result of the increase in plot numbers (e.g for the third Cycle the number of incoporated plots for all forest increased by 35% (an increase of 36% for Tall Forests and 33% for Regenerating Forest).

The estimated precision around the carbon stock estimates for the three measurement cycles shows that the variability in Tall Forests - a wide category with many forest types but represented by nearly nine times the plots - is less than for the Regenerating Forests. Regenerating Forests also cover a wide range of mapped types including grasslands with trees, partial landslides, exotic forests to manuka/Kanuka forests and is represented by fewer than 100 plots across the whole country.

Since measurements began, Tall Forests carbon stock estimates have switched from a small non-significant increase between Cycle 1 and 2 to a still non-significant decline between Cycle 2 and 3. This seems to be an effect of a decline in estimated live biomass stocks (AGB and BGB pools), indicating that small oscillations of stocks around a long-term mean could be present. Improved measurements of live biomass pools (and their change), which will be the result from longer measurement intervals and correctly locating and identifying each stem, will confirm whether these oscillations are a consistent /regular pattern of if there are any other long-term trends. For regenerating pre-1990 Natural Forests a non-significant trend of increasing carbon stocks is indicated with higher stocks in all carbon pools in every consecutive Cycle.

Table 4: Estimates of carbon stocks based on plots measured in pre-1990 Natural Forest. Number of plots measured in each Cycle are given for each Cycle and forest type. Estimates are shown for all forests, and for Tall Forest and Regenerating Forest based on the LandCoverDatabase Version 5 (Easdale et al. 2020). Estimated 95% confidence intervals combine the effects of sampling variation and model prediction error (CI$_{s\&p}$).

Forest group[1]	Pool	Stocks Cycle 1		Stocks Cycle 2		Stocks Cycle 3	
		tC ha^{-1}	±CI $_{s\&p}$	tC ha^{-1}	±CI $_{s\&p}$	tC ha^{-1}	±CI $_{s\&p}$
All plots	AGB	134.35	7.91	136.36	8.16	129.34	8.66
	BGB	31.51	1.96	31.99	2.02	30.34	2.12
	Dead wood	40.24	10.64	40.58	10.72	38.57	10.35
	Litter[2]	20.44	3.69	20.44	3.69	20.44	3.69
	All pools	226.54	13.67	229.37	13.98	218.69	14.53
Number of plots		*1027*		*925*		*661*	
Tall Forest	AGB	144.06	8.31	146.59	8.58	139.81	9.15
	BGB	33.77	2.06	34.38	2.13	32.78	2.25
	Dead wood	43.22	11.41	43.84	11.56	42.15	11.29
	Litter[2]	21.84	4.01	21.84	4.01	21.84	4.01
	All pools	242.89	14.41	246.11	14.75	236.58	15.39
Number of plots		*930*		*833*		*587*	
Regenerating Forest	AGB	41.26	7.85	44.02	8.44	46.28	10.10
	BGB	9.87	1.88	10.44	1.99	10.96	2.37
	Dead wood	11.64	7.46	11.07	7.62	10.21	6.5
	Litter[2]	10.39	8.58	10.39	8.58	10.39	8.58
	All pools	73.15	16.38	75.91	16.65	77.84	17.83
Number of plots		*97*		*92*		*74*	

Table 5: Estimates of carbon stocks based on measured and imputed plots in pre-1990 Natural Forest inventory. Number of plots used in each Cycle are given for each Cycle and forest type. Estimates are shown for all forests, and for Tall Forests and Regenerating Forests based on the LandCoverDatabase Version 5 (Easdale et al. 2020). Estimated 95% confidence intervals combine the effects of sampling variation and model prediction error (CI$_{s\&p}$).

Forest group[1]	Pool	Stocks Cycle 1		Stocks Cycle 2		Stocks Cycle 3	
		tC ha^{-1}	±CI $_{s\&p}$	tC ha^{-1}	±CI $_{s\&p}$	tC ha^{-1}	±CI $_{s\&p}$
All plots	AGB	133.92	7.88	135.96	7.92	130.04	7.83
	BGB	31.42	1.94	31.89	1.96	30.50	1.93
	Dead wood	40.12	10.52	40.67	10.63	39.30	10.41
	Litter[2]	21.09	3.59	21.09	3.59	21.09	3.59
	All pools	226.53	13.60	229.64	13.71	221.00	13.46
Number of plots		*1039*		*1039*		*1029*	
Tall Forest	AGB	143.83	8.29	145.65	8.35	140.13	8.35
	BGB	33.72	1.94	34.15	2.07	32.86	2.07
	Dead wood	43.17	10.52	43.76	11.40	42.67	11.51
	Litter[2]	22.26	3.90	22.26	3.90	22.26	3.90
	All pools	242.98	14.36	245.87	14.44	238.16	14.30
Number of plots		*939*		*939*		*919*	
Regenerating Forest	AGB	40.86	7.74	44.94	8.14	45.72	8.45
	BGB	9.77	1.94	10.72	1.93	10.82	1.98
	Dead wood	11.49	10.52	11.69	7.48	11.14	5.92
	Litter[2]	9.88	8.59	9.88	8.59	9.88	8.59
	All pools	71.84	16.20	76.97	16.21	76.17	15.64
Number of plots		*100*		*100*		*110*	

Carbon stock change – measured plots only

Between the first and second Cycles of the inventory, there was a significant positive change in total carbon across all pre-1990 Natural Forests. The estimated carbon stock change, using only remeasured plots was 3.30 ± 1.55 tC ha^{-1} over this period (Table 6). The difference in carbon stocks between the second and third Cycle was however negative and in absolute terms slightly larger with -4.06 ± 2.12 tC ha^{-1}.

Tall Forests and Regenerating Forests showed different levels of carbon stocks (Table 4), and also showed differences in carbon stock change (Table 6). In Tall Forest, the stock change between the first and second Cycles was 3.08 ± 1.66 tC ha^{-1}. However, between the second and third Cycle Tall Forests lost 4.74 ± 2.32 tC ha^{-1}. For Regenerating Forests carbon stock change between the first and second measurement was also significantly positive, with stocks increasing by 5.39 ± 3.64 tC ha^{-1} between measurements. Between the second and third Cycle Regenerating Forests sequestered 2.00 ± 2.00 tC ha^{-1} indicating a decline of sequestration over time. Overall Regenerating Forests sequestered 6.76 ± 5.88 tC ha^{-1} since the first Cycle

Carbon stock change – measured and imputed plots

Estimates of carbon stock changes using measured and imputed plots of the inventory are shown in Table 7 for comparison. While the imputation does only allow the calculation of change between Cycles (as actual measurement dates of imputed plots are unknown), it serves as a way to improve the certainty of estimates, mainly through the increase in samples (Cochran 1977). It also indicates if the sample of measured plots is very different to the plots that were excluded from measurement in a Cycle.

Improvement in the uncertainty of carbon stock change estimates is small as sample numbers in most groups only increase by a factor of less than 2. Where the increase was greatest (e.g. stock changes in Cycle 2 to Cycle 3 and Cycle 1 to Cycle 3), the CI improved to a small degree and the stock change estimated also changed slightly. The latter indicates that missed plots would have increased by 0.82 tC ha^{-1} in case of Regenerating Forests and decreased for Tall Forests by 0.16 tC ha^{-1} between the second and third Cycles.

Table 6. Estimates of carbon stock change in pre-1990 Natural Forest using stock differences between Cycles. Averaged estimates are shown, calculated as the plot-based difference calculated between re-measured stocks. Shown are values for all pre-1990 Natural Forests and for Tall Forest and Regenerating Forest classes based on LCDB v5 classification. Estimated 95% confidence intervals shown combine the effects of sampling variation and model prediction error (CI$_{s\&p}$).

Forest group	Pool	Change in stocks C1-C2		Change in stocks C2-C3		Change in stocks C1-C3	
		tC ha^{-1}	±CI$_{s\&p}$	tC ha^{-1}	±CI$_{s\&p}$	tC ha^{-1}	±CI$_{s\&p}$
All natural forests	AGB	2.09	1.20	-2.60	1.48	-1.30	2.28
	BGB	0.49	0.28	-0.61	0.35	-0.31	0.35
	Dead wood	0.72	1.37	-0.85	1.76	-0.30	2.57
	Litter[1]	-	-	-	-	-	-
	All pools	3.30	1.55	-4.06	2.12	-1.90	3.14
Number of plots		*911*		*555*		*603*	
Tall Forest	AGB	1.85	1.31	-3.31	1.63	-2.11	2.46
	BGB	0.43	0.31	-0.77	0.38	-0.50	0.58
	Dead wood	0.79	1.50	-0.66	1.94	-0.21	2.80
	Litter	-	-	-	-	-	-
	All pools	3.08	1.66	-4.74	2.32	-2.82	3.42
Number of plots		*822*		*499*		*545*	
Regenerating Forest	AGB	4.27	1.98	3.73	1.78	6.37	5.30
	BGB	1.00	0.47	0.85	0.43	1.48	1.25
	Dead wood	0.11	2.52	-2.58	2.18	-1.09	4.74
	Litter	-					
	All pools	5.39	3.64	2.00	3.20	6.76	5.88
Number of plots		*89*		*56*		*58*	

Table 7. Estimates of carbon stock change in pre-1990 Natural Forest using measured and imputed plots (via regression double sampling) between Cycles. Averaged estimates are shown calculated as the plot-based difference calculated between measured and imputed stocks. Shown are values for all pre-1990 Natural Forests and for Tall Forest and Regenerating Forest classes based on LCDB v5 classification. Estimated 95% confidence intervals shown combine the effects of sampling variation and model prediction error ($CI_{s\&p}$).

Forest group	Pool	Change in stocks C1-C2		Change in stocks C2-C3		Change in stocks C1-C3	
		tC ha^{-1}	$\pm CI_{s\&p}$	tC ha^{-1}	$\pm CI_{s\&p}$	tC ha^{-1}	$\pm CI_{s\&p}$
All natural forests	AGB	2.09	1.19	-2.60	1.46	1.81	2.25
	BGB	0.50	0.28	-0.61	0.34	-0.20	0.53
	Dead wood	0.87	1.37	-0.81	1.74	0.33	2.49
	Litter[1]	-	-	-	-	-	-
	All pools	3.31	1.55	-4.13	2.09	-1.32	3.10
Number of plots		*1027*		*923*		*1027*	
Tall Forest	AGB	1.88	1.30	-3.28	1.60	1.54	2.42
	BGB	0.45	0.31	-0.76	0.38	-0.40	0.57
	Dead wood	0.93	1.50	-0.84	1.92	0.23	2.72
	Litter	-	-	-	-	-	-
	All pools	3.10	1.67	-4.90	2.30	-2.48	3.37
Number of plots		*930*		*831*		*930*	
Regenerating Forest	AGB	4.19	1.98	3.53	1.75	4.38	5.22
	BGB	0.97	0.47	0.78	0.43	1.77	1.23
	Dead wood	0.34	2.51	-0.50	2.18	1.29	4.60
	Litter	-	-	-	-	-	-
	All pools	5.33	3.66	2.82	3.15	9.80	5.81
Number of plots		*97*		*92*		*97*	

Carbon stocks and stock change on Public and Private land

Pre-1990 Natural Forests on private land have significantly lower total carbon stocks than those on public land (Table 8). This is in parts caused by the ratio of Tall Forest versus Regenerating Forest. On public land 20 times more Tall Forest plots were assessed than Regenerating Forest plots that have in general lower carbon stocks; while on private land only three times more Tall Forest plots were measured than Regenerating Forests plots. It is also worth noting that both Tall Forests and Regenerating Forests on public land have higher carbon stocks than on private land. On private land Tall Forest carbon stocks were on average 25% lower (across the three Cycles). Regenerating Forest carbon was on average 41% lower.

Carbon stocks on public land did not differ significantly between Cycles with 247.82 ± 15.19 tC ha^{-1}, 250.09 ± 15.57 tC ha^{-1} and 244.53 ± 16.71 tC ha^{-1} for the three Cycles respectively using only measured plots.

Carbon stocks of pre-1990 Natural Forests on private land for the three cycles were 173.70 ±18.19 tC ha^{-1}, 173.02 ±18.46 tC ha^{-1} and 158.39 ±18.50 tC ha^{-1} respectively. These carbon stocks were not significantly different to each other.

Using measured and imputed plots to estimate carbon stocks for public and private ownership classes of pre-1990 Natural Forests did not change the overall outcome compared with measured-only plots but reduced uncertainty, particularly for Cycle 3 estimates. This is due to the higher number of plots now used (Table 9).

Table 8: Estimates of carbon stocks for Private and Public Conservation Land (PCL) based on plots measured in pre-1990 Natural Forest at multiple times across the inventory Cycles. Number of plots measured in each Cycle are given for each Cycle and forest type. Estimates are shown for all forests, and for Tall Forests and Regenerating Forests, based on Easdale et al. (2020). Estimated 95% confidence intervals shown combine the effects of sampling variation and model prediction error (CI$_{s\&p}$).

Ownership	Forest group[1]	Pool	Stocks Cycle 1		Stocks Cycle 2		Stocks Cycle 3	
			tC ha^{-1}	±CI $_{s\&p}$	tC ha^{-1}	±CI $_{s\&p}$	tC ha^{-1}	±CI $_{s\&p}$
PCL	All plots	AGB	147.82	8.80	148.55	9.03	144.68	10.05
		BGB	34.69	2.18	34.87	2.23	33.95	2.46
		Dead wood	44.31	11.73	45.67	12.11	44.90	12.06
		Litter[2]	21.00	4.50	21.00	4.50	21.00	4.50
		All pools	247.82	15.19	250.09	15.57	244.53	16.71
	Number of plots		*733*		*676*		*463*	
	Tall Forest	AGB	152.65	8.96	153.78	9.21	148.86	10.23
		BGB	35.82	2.22	36.09	2.28	34.93	2.51
		Dead wood	45.39	12.00	47.02	12.45	45.90	12.32
		Litter[2]	22.06	4.84	22.06	4.84	22.06	4.84
		All pools	255.93	15.54	258.96	15.96	251.75	17.08
	Number of plots		*699*		*642*		*442*	
	Regenerating Forest	AGB	48.58	17.26	49.92	16.34	56.75	23.85
		BGB	11.48	4.05	11.80	3.84	13.40	5.61
		Dead wood	22.13	19.28	20.08	19.06	23.75	20.09
		Litter[2]	9.85	3.33	9.85	3.33	9.85	3.33
		All pools	90.61	32.75	90.21	30.39	102.31	39.77
	Number of plots		*34*		*34*		*21*	
Private	All plots	AGB	100.75	10.62	103.00	11.30	93.45	11.02
		BGB	23.60	2.53	24.11	2.69	21.89	2.62
		Dead wood	30.08	9.47	26.63	8.13	23.79	8.16
		Litter[2]	25.04	6.51	25.04	6.51	25.04	6.51
		All pools	173.70	18.19	173.02	18.46	158.39	18.50
	Number of plots		*294*		*247*		*198*	
	Tall Forest	AGB	118.05	12.26	122.17	13.13	112.21	13.05
		BGB	27.58	2.93	28.55	3.14	26.23	3.11
		Dead wood	36.66	11.54	33.03	10.02	30.71	10.53
		Litter[2]	21.29	7.25	21.29	7.25	21.29	7.25
		All pools	203.58	20.88	205.04	21.23	190.44	21.82
	Number of plots		*231*		*189*		*145*	
	Regenerating Forest	AGB	37.30	7.71	40.55	9.39	42.13	10.67
		BGB	8.99	1.88	9.65	2.22	10.00	2.48
		Dead wood	5.97	3.91	5.79	3.84	4.84	3.53
		Litter[2]	11.90	15.67	11.90	15.67	11.90	15.67
		All pools	64.17	19.62	67.88	20.91	68.87	21.62
	Number of plots		*63*		*58*		*53*	

Table 9: Estimates of carbon stocks for Private and Public Conservation Land (PCL) based on measured and imputed plots in pre-1990 Natural Forest inventory. Number of plots measured in each Cycle are given for each Cycle and forest type. Estimates are shown for all forests, and for Tall Forests and Regenerating Forests based on Easdale et al. (2020). Estimated 95% confidence intervals shown combine the effects of sampling variation and model prediction error (CI$_{s\&p}$).

Ownership	Forest group[1]	Pool	Stocks Cycle 1		Stocks Cycle 2		Stocks Cycle 3	
			tC ha^{-1}	±CI $_{s\&p}$	tC ha^{-1}	±CI $_{s\&p}$	tC ha^{-1}	±CI $_{s\&p}$
PCL	All plots	AGB	147.40	8.76	148.86	8.87	142.73	8.89
		BGB	34.59	2.17	34.93	2.20	33.50	2.19
		Dead wood	44.17	11.69	45.46	12.03	44.86	11.90
		Litter[2]	22.73	4.39	22.73	4.39	22.73	4.39
		All pools	248.87	15.10	252.03	15.33	244.09	15.23
	Number of plots		*743*		*743*		*735*	
	Tall Forest	AGB	152.45	8.94	153.80	9.04	147.63	9.11
		BGB	35.77	2.22	36.09	2.24	34.64	2.25
		Dead wood	45.34	11.98	46.76	12.35	46.12	12.23
		Litter[2]	23.30	4.72	23.30	4.72	23.30	4.72
		All pools	256.86	15.47	260.00	15.70	252.07	15.67
	Number of plots		*707*		*707*		*697*	
	Regenerating Forest	AGB	48.13	16.80	51.89	15.92	52.94	18.09
		BGB	11.38	3.94	12.25	3.75	12.49	4.26
		Dead wood	21.30	18.85	20.04	18.69	21.75	16.66
		Litter[2]	10.80	3.46	10.80	3.46	10.80	3.46
		All pools	91.32	32.06	94.81	29.63	96.45	30.28
	Number of plots		*36*		*36*		*38*	
Private	All plots	AGB	100.09	10.57	103.57	10.55	98.31	9.53
		BGB	23.45	2.52	24.26	2.52	23.02	2.28
		Dead wood	29.94	9.43	28.64	8.42	25.40	8.04
		Litter[2]	17.04	6.37	17.04	6.37	17.04	6.37
		All pools	170.48	18.08	173.47	17.45	163.27	16.40
	Number of plots		*296*		*296*		*294*	
	Tall Forest	AGB	117.55	12.23	120.83	12.11	116.61	11.15
		BGB	27.47	2.93	28.23	2.90	27.27	2.68
		Dead wood	36.55	11.51	34.60	10.17	31.85	10.15
		Litter[2]	19.13	7.12	19.13	7.12	19.13	7.12
		All pools	200.68	20.79	202.83	19.86	194.60	19.12
	Number of plots		*232*		*232*		*222*	
	Regenerating Forest	AGB	36.78	7.65	41.03	8.98	41.91	9.27
		BGB	8.87	1.86	9.86	2.12	9.94	2.16
		Dead wood	5.97	3.86	7.00	3.86	5.54	3.29
		Litter[2]	9.38	16.02	9.38	16.02	9.38	16.02
		All pools	60.91	19.85	66.95	20.79	65.46	20.60
	Number of plots		*64*		*64*		*72*	

Carbon stock changes in pre-1990 Natural Forests differed between forest types and ownership status (Table 10). All pre-1990 Natural Forests on public and private land showed significant positive stock changes between 1st cycle and 2nd cycle of the inventory. On public land stocks increased by 3.38 ± 1.88 tC ha^{-1} between measurements and on private land by 3.09 ± 2.58 tC ha^{-1}. In the second period between measurements this reversed to -4.18 ± 2.32 tC ha^{-1} on public land and -3.75 ± 4.70 tC ha^{-1} for private land, the latter not being significantly different from zero.

As mentioned, Tall Forests on public lands had higher carbon stocks than those on private lands, but they also showed greater and significant fluctuations between Cycle 1 and Cycle 2 (3.36 ± 1.94 tC ha^{-1}) and Cycle 2 and Cycle 3 (-4.32± 2.41 tC ha^{-1}) compared to private Tall Forests where changes were not significant from zero (C1-C2: 2.11± 3.21 tC ha^{-1}, C2-C3: -6.20 ± 6.23 tC ha^{-1}). The reverse is the case for Regenerating Forests. On public land no significant positive carbon sequestration occurred but Regenerating Forests on private land was sequestering carbon between every measurement cycle with 10.68 ± 5.49 tC ha^{-1} between C1 and C3.

This picture did not change when measured and imputed plots were used for the calculation of carbon stock change (Table 11). However, carbon stock changes in private Regenerating Forests increased to 12.80 ± 5.43 tC ha^{-1} between C1 and C3

Table 10. Estimates of carbon stock change in pre-1990 Natural Forest for public conservation land (PCL) and private land using measured plots. Estimates are shown for all plots, and for plots classified as Tall Forest and Regenerating Forest based on LCDB v5 classification (Easdale et al. 2020). Estimated 95% confidence intervals shown combine the effects of sampling variation and model prediction error (CI$_{s\&p}$).

Ownership	Forest grouping	Pool	Change in stocks C1-C2		Change in stocks C2-C3		Change in stocks C1-C3	
			tC ha^{-1}	±CI$_{s\&p}$	tC ha^{-1}	±CI$_{s\&p}$	tC ha^{-1}	±CI$_{s\&p}$
PCL	All natural forests	AGB	1.49	1.44	-3.49	1.64	-2.62	2.41
		BGB	0.35	0.34	-0.82	0.39	-0.62	0.57
		Dead wood	1.55	1.73	0.13	1.96	1.30	2.76
		Litter[1]	-	-	-	-	-	-
		All pools	3.38	1.88	-4.18	2.32	-1.94	3.10
	Number of plots		666		404		431	
	Tall Forest	AGB	1.35	1.50	-3.75	1.70	-2.78	2.45
		BGB	0.32	0.35	-0.88	0.40	-0.66	0.58
		Dead wood	1.69	1.79	0.31	2.03	1.46	2.82
		Litter	-	-	-	-	-	-
		All pools	3.36	1.94	-4.32	2.41	-1.97	3.50
	Number of plots		634		387		412	
	Regenerating Forest	AGB	4.10	3.07	2.47	3.64	0.76	13.62
		BGB	0.95	0.72	0.59	0.86	0.19	3.19
		Dead wood	-1.28	6.99	-4.00	6.47	-2.24	15.11
		Litter	-	-	-	-	-	-
		All pools	3.77	8.13	-0.94	8.88	-1.29	14.28
	Number of plots		32		17		19	
Private	All natural forests	AGB	3.73	2.12	-0.21	3.24	2.02	5.27
		BGB	0.87	0.28	-0.05	0.76	0.48	1.24
		Dead wood	-1.52	2.17	-3.49	3.85	-4.30	5.94
		Litter[1]	-	-	-	-	-	-
		All pools	3.09	2.58	-3.75	4.70	-1.80	7.04
	Number of plots		244		152		172	
	Tall Forest	AGB	3.53	2.66	-1.78	4.29	-0.06	6.67
		BGB	0.83	0.63	-0.40	1.00	-0.00	1.56
		Dead wood	-2.25	2.83	-4.02	5.14	-5.40	7.67
		Litter	-	-	-	-	-	-
		All pools	2.11	3.21	-6.20	6.23	-5.46	8.91
	Number of plots		188		112		133	
	Regenerating Forest	AGB	4.37	2.63	4.28	2.10	9.10	4.66
		BGB	1.03	0.63	0.96	0.52	2.10	1.11
		Dead wood	0.90	1.04	-1.96	1.57	-0.53	1.46
		Litter	-	-	-	-	-	-
		All pools	6.30	3.34	3.29	2.82	10.68	5.49
	Number of plots		57		39		39	

Table 11. Estimates of carbon stock change in pre-1990 Natural Forest for public and private land using measured and imputed plots. Estimates are shown for all plots, and for plots classified as Tall Forest and Regenerating Forest based on LCDB v5 classification (Easdale et al. 2020). Estimated 95% confidence intervals shown combine the effects of sampling variation and model prediction error ($CI_{s\&p}$).

Ownership	Forest group	Pool	Change in stocks C1-C2		Change in stocks C2-C3		Change in stocks C1-C3	
			tC ha^{-1}	±$CI_{s\&p}$	tC ha^{-1}	±$CI_{s\&p}$	tC ha^{-1}	±$CI_{s\&p}$
PCL	All natural forests	AGB	1.49	1.43	-3.38	1.61	-1.11	2.27
		BGB	0.36	0.34	-0.79	0.38	-0.51	0.56
		Dead wood	1.56	1.72	-0.47	1.93	0.88	2.67
		Litter[1]	-	-	-	-	-	-
		All pools	3.34	1.89	-4.58	2.30	-2.17	3.35
	Number of plots		*733*		*676*		*733*	
	Tall Forest	AGB	1.37	1.50	-3.69	1.67	0.98	2.41
		BGB	0.33	0.35	-0.86	0.39	-0.58	0.57
		Dead wood	1.68	1.78	-0.43	2.00	0.94	2.72
		Litter	-	-	-	-	-	-
		All pools	3.32	1.94	-4.87	2.38	-2.48	3.46
	Number of plots		*699*		*642*		*699*	
	Regenerating Forest	AGB	3.89	3.07	2.58	3.56	3.72	13.41
		BGB	0.91	0.72	0.57	0.84	0.86	3.13
		Dead wood	-0.88	6.97	-1.23	6.28	-0.32	14.60
		Litter	-	-	-	-	-	-
		All pools	3.78	8.99	1.03	8.70	4.23	14.06
	Number of plots		*34*		*34*		*34*	
Private	All natural forests	AGB	3.60	2.12	-0.48	3.18	3.56	5.20
		BGB	0.84	0.50	-0.12	0.74	0.59	1.22
		Dead wood	-0.86	2.14	-1.73	3.71	-1.05	5.66
		Litter[1]	-	-	-	-	-	-
		All pools	3.25	2.60	-2.91	4.63	0.81	6.94
	Number of plots		*294*		*247*		*294*	
	Tall Forest	AGB	3.40	2.65	-1.87	4.21	3.24	6.57
		BGB	0.80	0.62	-0.43	0.98	0.13	1.54
		Dead wood	-1.36	2.77	-2.24	4.99	-1.93	7.32
		Litter	-	-	-	-	-	-
		All pools	2.45	3.22	-4.99	6.13	-2.45	8.77
	Number of plots		*231*		*189*		*231*	
	Regenerating Forest	AGB	4.35	2.63	4.08	2.07	4.74	4.58
		BGB	1.01	0.62	0.90	0.51	2.26	1.09
		Dead wood	1.00	1.05	-0.08	1.47	2.15	1.52
		Litter	-	-	-	-	-	-
		All pools	6.17	3.37	3.87	2.79	12.80	5.43
	Number of plots		*63*		*58*		*63*	

Annualised Carbon stock changes

The time between measurements for remeasured plots ranged widely as the pre-1990 Natural Forest inventory has not applied a standardised re-measurement regime with fixed in between re-measurement periods common to most Forest Inventories (Tomppo et al. 2010). The measurement cycle length has also changed from 5 years to 10 years, with a randomised distribution of plots across the measurement cycle (Carswell et al. 2015). This means that time between measurements varied for C1–C2 between 6 and 9.3 years, for C2-C3 between 2.5 and 11 years and for C1-C3 between 11.1 and 18 years. To account for this variation that affects carbon stock change and its annualization, we calculated the ratio of means between time and carbon stock change across the sample (and subsamples e.g. public conservation land (PCL) and private plots).

Annualized carbon stock changes, based on re-measured plots only, are shown in Table 12. All pre-1990 Natural Forests were estimated to sequester carbon at an annual rate of 0.43 ± 0.20 tC ha^{-1} yr^{-1} between the first and second Cycle, but then lose carbon at a rate of -0.71 ± 0.28 tC ha^{-1} yr^{-1} between the second and third measurement. Carbon stock change between the first Cycle and the third was estimated as -0.14 ± 0.24 tC ha^{-1} yr^{-1} and therefore not significantly different to zero (no change). While the same pattern is present for Tall Forests with no change in stocks overall, Regenerating Forest are sequestering carbon overall. However, the magnitude is with 0.05 ± 0.04 tC ha^{-1} yr^{-1} low for the period C1-C3, with a peak of 0.70 ± 0.64 tC ha^{-1} yr^{-1} between C1 and C2.

Public land pre-1990 Natural Forest and Tall Forests follows a similar pattern to all pre-1990 Natural Forests with initial sequestration followed by losses (C1-C2: 0.44± 0.24 tC ha^{-1} yr^{-1}; C2-C3:

-0.53 ± 0.24 tC ha^{-1} yr^{-1}), with overall carbon balance. Public Regenerating Forest carbon stock changes are not significantly different to zero and appear also in carbon balance.

Private pre-1990 Natural Forests are estimated to be mostly in balance except in the C1-C2 period with a small positive carbon stock change of 0.41 ± 0.35 tC ha^{-1} yr^{-1}. Tall Forests show a small loss of carbon in C2-C3 (-0.22 ± 0.21 tC ha^{-1} yr^{-1}) and Regenerating Forests are estimated to provide a small sink between C2-C3 and C1-C3, with 0.04 ± 0.03 tC ha^{-1} yr^{-1} and 0.05 ± 0.03 tC ha^{-1} yr^{-1} respectively.

Table 12. Annualised carbon stock changes for all pools + total for all forest classes and on public conservation land (PCL) and private land. Estimates are based on the ratio of means calculation for plots that were re-measured (no imputed plots). Estimated 95% confidence intervals shown combine the effects of sampling variation and model prediction error (CI$_{s\&p}$).

	Forest grouping	Pool	Change in stocks C1-C2		Change in stocks C2-C3		Change in stocks C1-C3	
			tC ha^{-1} y^{-1}	±CI$_{s\&p}$	tC ha^{-1} y^{-1}	±CI$_{s\&p}$	tC ha^{-1} y^{-1}	±CI$_{s\&p}$
All pre-1990 Natural Forests	All natural forests	AGB	0.27	0.16	-0.46	0.26	-0.10	0.17
		BGB	0.06	0.04	-0.11	0.06	-0.02	0.04
		CWD	0.09	0.18	-0.15	0.31	-0.02	0.19
		Total	**0.43**	**0.20**	**-0.71**	**0.37**	**-0.14**	**0.24**
	Number of plots		*911*		*555*		*603*	
	Tall forest	AGB	0.24	0.17	-0.52	0.26	-0.14	0.17
		BGB	0.06	0.04	-0.12	0.06	-0.03	0.04
		CWD	0.10	0.19	-0.10	0.31	-0.01	0.19
		Total	**0.40**	**0.22**	**-0.75**	**0.36**	**-0.19**	**0.23**
	Number of plots		*822*		*499*		*545*	
	Regenerating forest	AGB	*0.55*	*0.44*	*0.07*	*0.04*	*0.05*	*0.04*
		BGB	0.13	0.10	0.02	0.01	0.01	0.01
		CWD	*0.01*	0.33	*-0.05*	0.04	*-0.01*	0.03
		Total	**0.70**	**0.64**	**0.04**	**0.06**	**0.05**	**0.04**
	Number of plots		*89*		*56*		*57*	
PCL	All natural forests	AGB	0.19	0.19	-0.45	0.21	-0.14	0.13
		BGB	0.05	0.04	-0.10	0.05	-0.03	0.03
		CWD	0.20	0.22	0.02	0.25	0.07	0.15
		Total	**0.44**	**0.24**	**-0.53**	**0.30**	**0.10**	**0.18**
	Number of plots		*666*		*404*		*431*	
	Tall forest	AGB	0.18	0.20	-0.46	0.21	-0.14	0.13
		BGB	0.04	0.05	-0.11	0.05	-0.03	0.03
		CWD	0.22	0.23	0.04	0.25	0.08	0.15
		Total	**0.44**	**0.25**	**-0.53**	**0.29**	**-0.10**	**0.18**
	Number of plots		*634*		*387*		*412*	
	Regenerating forest	AGB	0.53	1.07	0.01	0.02	0.00	0.03
		BGB	0.12	0.25	0.00	0.00	0.00	0.01
		CWD	-0.16	0.95	-0.02	0.04	-0.01	0.04
		Total	**0.48**	**1.39**	**-0.01**	**0.05**	**0.00**	**0.03**
	Number of plots		*32*		*17*		*19*	
Private	All natural forests	AGB	0.49	0.30	-0.01	0.15	0.04	0.11
		BGB	0.11	0.07	0.00	0.04	0.01	0.03
		CWD	-0.20	0.29	-0.17	0.18	-0.09	0.13
		Total	**0.41**	**0.35**	**-0.18**	**0.23**	**-0.04**	**0.15**
	Number of plots		*245*		*151*		*172*	
	Tall forest	AGB	0.47	0.37	-0.06	0.15	0.00	0.11
		BGB	0.11	0.09	-0.01	0.04	0.00	0.03
		CWD	-0.30	0.38	-0.14	0.18	-0.09	0.13
		Total	**0.28**	**0.43**	**-0.22**	**0.22**	**-0.09**	**0.15**
	Number of plots		*188*		*112*		*133*	
	Regenerating forest	AGB	0.57	0.68	0.05	0.03	0.04	0.03
		BGB	0.13	0.16	0.01	0.01	0.01	0.01
		CWD	0.12	0.18	-0.02	0.02	0.00	0.01
		Total	**0.82**	**0.95**	**0.04**	**0.04**	**0.05**	**0.03**
	Number of plots		*57*		*39*		*39*	

Discussion and recommendations

Comparison with earlier estimates

A comparison with previous studies is only possible by comparing the results from the first and second Cycle of the inventory as this is the first analysis that included data from the third measurement Cycle. The additional data from Cycle 3 and the further data corrections will have an effect on the models that use these additional data. Models for estimating DBH (e.g. where measurements are missed or incorrect) and heights will use these new and additional measurements and affect the results of volume estimates and finally carbon. Therefore, previous carbon stock and carbon stock changes are expected to change.

The most similar study is (Paul et al. 2019a) which provided carbon stocks and stock changes using similar methods. Our estimates of total carbon stocks in the current study are similar to those of the 2019 study with differences not greater than ~ 2 t C ha^{-1} for total carbon per hectare for all pre-1990 Natural Forests with both studies confirming that stock estimates for all forests combined are not significantly different between measurement cycles. Comparing other forest types using the previous classification approach shows that current stock estimates of Tall forests are also similar to previous estimates (Appendix). Estimates of carbon stocks of Regenerating Forests are also comparable to previous estimates. However, it is worth noting that the sampling population has changed and nine plots are now excluded based on renewed mapping of pre-1990 Natural Forests.

While stock estimates are similar, the current study showed larger stock changes that are significantly different from zero in contrast with Paul et al. (2019a) and Holdaway et al. (2017), which both agreed that stock change overall is minimal in pre-1990 Natural Forests, except for Regenerating Forests. In the current study Regenerating Forests have the greatest positive stock change between the first two measurement cycles, slightly higher than previously estimated. In contrast to the previous studies Tall Forests now show a small overall positive increase in stocks between Cycle 1 and Cycle 2 (previously negative but not significantly different from zero). The cause for this shift towards positive stock change in Tall Forests between Cycle 1 and Cycle 2 can be explained by (1) additional corrections made to the inventory data where additional errors were found in the measurements of the first and second cycle (although the number of additional errors found was relatively small); (2) the exclusion of some Tall Forest plots and addition of previously classified Regenerating Forest plots into the Tall Forest class through re-mapping (table 13); and (3) the addition of more re-measurements of tree metrics (height, DBH) that changed the performance of models that are the basis for estimating volume and carbon such as ingrowth, DBH estimation (missing values method) and height prediction for non-measured heights.

Table 13: Changes in the assignment of plots to Tall and Regenerating Forests in the dataset used to calculate carbon stocks and carbon stock change in Cycle 1 and Cycle 2. Diagonals show number of unchanged plots (grey).

Cycle 1		Previous classification (Wiser 2016)			
		Tall Forests	Regenerating Forests	Unclassified	Total
New LCDB classification	Tall Forests	885	45	0	930
	Regenerating Forest	20	76	1	97
	unclassified	0	0	0	0
	Total	905	121	1	1027
Cycle 2		Previous classification (Wiser 2016)			
		Tall Forests	Regenerating Forests	Unclassified	Total
New LCDB classification	Tall Forests	789	41	1	831
	Regenerating Forest	18	72	2	92
	unclassified	0	0	0	0
	Total	807	113	3	923

Sampling and methodological considerations

The estimates of carbon stocks and stock changes presented are the best yet provided for the vast expanse of natural forests in New Zealand and use remeasurements of three nearly complete measurement cycles. They are based on a representative forest inventory with a proven systematic sampling design with random starting location, use the complete plot data acquired using an appropriate permanent plot design, and include a sophisticated modelling approach to improve the prediction of dead wood.

Most national forest inventories are based on such nationally representative, often random or grid-based sampling designs covering the forested land area of the country (Tomppo et al. 2010) to ensure estimates are unbiased. Plot densities are chosen to achieve a desired level of precision for key variables (Tomppo et al. 2010). To achieve full representativeness, all grid-points should be sampled during an inventory period.

If only a subset of plots are measured in a particular inventory period, these need to be selected at random, or using some other appropriate methods to ensure that estimates are unbiased. Especially in forest inventories of large expanses of natural forests, such as in the tropics or in the boreal zones, grid-based field inventory approaches are challenging to implement due to topography and terrain. As such inherent difficulties are also an issue in New Zealand, incomplete inventory cycles have been a feature of the pre-1990 Natural Forest inventory.
This is evident over the first three measurement cycles with the first cycle providing the most complete attempt of measuring all grid locations. The second measurement cycle did not remeasure approximately 10% of the established plots, which affects the estimation of carbon stocks as the sample size reduced. Carbon stock change estimation between the first and second measurement cycle was affected even more with only 911 plots available. With the third cycle not fully completed, estimates of carbon stock are only based on roughly half the number of plots measured in the first cycle. Cycle 3 also includes 47 newly installed plots which are either the result of extending the pre-1990 Natural Forest mapped area or are previously unmeasured grid locations. Carbon stock changes are therefore based on a much smaller sample than proposed when the inventory was designed and the impact of this is exacerbated when calculations are restricted to subclasses. However this should only be a temporary effect until all plots have been re-measured in Cycle 3.

While incomplete measurement cycles are present we need to assume that the selection of plots measured through the cycles are random in nature, which allows the use of analytical approaches such as double sampling with regression estimators to “fill” unsampled measurement events as we have done in this study. However, a number of plots could not be used under the double sampling approach to predict carbon stock changes e.g the double-sampling approach did not allow prediction of c stocks in cycle 2 from the most recent additional plots in Cycle 3.

We are aware that because not all grid locations have been measured at least once, the possibility exists that our estimates have some degree of bias. This would be the case if carbon stocks and stock changes in the locations not included in the study differ appreciably from the national average. We can expect that vegetation in plots added following remapping might be different to vegetation originally identified as Natural Forest. However, if they are “fill-ins” from the previously estimated 1,208 plot locations found initially to represent the extent of pre-1990 Natural Forests area, we can assume they do not increase bias as long as they were not originally withheld for a specific reason (e.g. no trees present).

While the imputation of stocks for unmeasured plots works relatively well it adds complexity to the estimation of carbon stocks and does not account for a possible change in variability across the sample. Uncertainty about the quality of the imputation of carbon stock change is even greater when the prediction models perform poorly. The general solution to this problem of estimating carbon stocks and change with increasing model and sampling complexity is to ensure that the sampling frame is complete and all possible plots are measured and re-measured over time, with the exception of a percentage of plots that will need to be abandoned (we already have good information on this after three cycles).

The estimated fluctuations in carbon stocks and their changes across the three cycles requires careful interpretation. The most robust calculation of carbon stocks using only measured plots for each cycle shows that carbon stocks are not significantly different from each other, based on the sampling and model uncertainty associated with those estimates. Even if we add an assumed measurement error of 5% (similar to the model error for total carbon stocks) the estimates of carbon stocks would still only have an uncertainty of ±10% of the mean. The only current information of measurement error is provided by Holdaway et al. (2014b) and their estimated measurement uncertainty for stocks was only 1% but for carbon stock change this was 35%. With the already higher uncertainty around carbon stock change estimates only accounting for sampling and model error (~ 50% of the mean), estimates of carbon stock change presented here are certainly less reliable.

To enhance the "signal" of carbon stock change, other national forest inventories have adapted their re-measurement intervals for their forests. The re-measurement intervals are based on auxilliary knowledge of the growth rates of the common tree species and results in varying re-measurement cycles between countries (Tomppo et al. 2010). New Zealand also applies this approach, using a five-year remeasurement cycle for fast growing plantations and now a ten-year cycle for pre-1990 Natural Forests. However for the latter the average re-measurement period was ~ 7.7 years and ~ 5.6 years for the two re-measurement periods. In future a fixed re-measurement period in which every plot on the estabslihed grid is measured every 10 years should improve the estimation of carbon stock changes and their uncertainty, as trends should be less masked by measurement error and sufficient plots would be remeasured.

Extrapolating natural forest net emissions back to the 1990 base year

IPCC (2009) suggests that countries should use "*….the observed trend in emissions/removals during the period when detailed emissions are available*" as the basis for extrapolating carbon stock change estimates back to the 1990 base year, if the first measurement data is not available until a later date. It also states that if the trend is not constant over the period where detailed estimates exist, extrapolation should be based on the use of surrogate data. IPCC (2019) suggests that for forest land in particular, functional relationships can be used to extrapolate data based on a knowledge of stand carbon dynamics, and that this simulation approach must be able to replicate the observed trends in a 'calibration period' (2002 to 2020 for the natural forest NFI) before it can be applied to extrapolation.

In our case we have observed an apparent fluctuation in net emissions from natural forests, we have not identified surrogate data that explains the trend from C1 to C2 and C2 to C3, and we do not have models with proven ability to predict the growth, mortality and ingrowth of individual trees within the wide range of natural forest types in New Zealand. Therefore we recommend using the C1 to C3 annualized stock change trend as the best basis for extrapolation to 1990, because

- it represents the complete timeseries (2002-2020) of available measurements over the longer timespan that is more able to detect true changes in slow-growing forest stocks. Shorter intervals between measurements can compromise the detection of real change due to measurement errors, which are not included in our estimate of precision for the calculated carbon stock changes.
- There is no justification for using the first interval trend (C1 to C2) to extrapolate to 1990 given that this trend did not continue on to C3, and was in fact reversed between C2 and C3.
- There is currently no known surrogate data or forest carbon dynamics model that can explain and replicate the observed trends between C1 and C3 and therefore be used for extrapolation to 1990. Drivers for the observed trends at the plot level need to be investigated which may allow suitable surrogate data to be identified and tested.

To use the annualized change based on C1 to C3 for extrapolating back to 1990 the carbon stock estimates for plots measured in C1 and used for the estimation of carbon stock change between C1 and C3 should be used (shown in table 15 in Appendix). Extrapolation back to 1990 should start at the mid-point of the sampling period of these plots (e.g. ~2004). Extrapolation forward should start at the midpoint of C3 (e.g.~2017) using carbon stock estimates from C3. Carbon stock values would be interpolated between 2004 and 2017 (using the same midpoints) and the annualized change (based on the period between these midpoints). However once Cycle 3 is completed the starting point and annualized carbon stock changes should be recalculated.

Conclusions

The natural forest inventory as an unbiased monitoring framework will allow further analysis to identify long-term trends in the future. This will be critical to understand the national impact of past and future management of these mostly protected forests, specifically in regard to herbivore control or the continuous monitoring of long-term dynamics under climate change. The tagging of trees will allow the detailed analysis of mortality of specific tree species and their growth rates and ingrowth over the coming years. Moreover, when the third Cycle has been completed, the estimation of carbon stocks and stock changes can be expected to improve.

Our study presents a range of inventory-based calculation methods for estimating carbon stocks and stock change. The underlying biometric models were developed previously and used for past reporting on pre-1990 natural forests ((Beets et al. 2008, Beets et al. 2012, Kimberley and Beets 2016a, Paul et al. 2019a, Paul et al. 2021). The results of all calculation methods lead to the same conclusion: New Zealand’s pre-1990 natural forest are an important and significant terrestrial carbon pool for New Zealand and the southern hemisphere temperate biome.

Based on the current structure of the pre-1990 Forest inventory Cycle, we can provide the best available carbon stock estimates that include the full carbon stock assessment of live and dead tree biomass and include components of dead wood carbon that are very difficult to assess.
While all calculation methods provide the uncertainties of estimates of stocks and stock changes, taking into account both model prediction error and uncertainty associated with sampling variation between plots, the most robust and least model-reliant approach to report carbon stocks would be either the use of only measured plots or measured and imputed plots, as the regressions to estimate imputed carbon stocks are performing well. Regressions for imputation of carbon stock changes between measurement cycles are by contrast not performing well and the resulting carbon stock change estimates might not be as robust. This hypothesis can possibly be tested once the last measurement cycle is completed. Until then carbon stock changes should be calculated with measured plots only.

To calculate annualized carbon stock changes based on measured plots only, we applied the ratio of means approach to account for two different variables with possibly different distributions (Rao 2002). To improve the carbon stock change estimates, the inventory should ideally re-measure all available grid locations in the mapped area of pre-1990 Natural forests at an interval that leads to detectable growth by avoiding a large overlap between measurement error and growth. Ten years as a re-measurement period as it is now planned might suffice, but it needs to be ensured that re-measurement periods of that length are maintained for each individual plot.

Our results confirm previous studies that have shown that nationally New Zealand’s Tall Forests are more-or-less in carbon balance, with Regenerating Forests sequestering low amounts of carbon across the three measurement cycles. Due to its large size the natural forest carbon pool is an important reservoir that needs to be managed to ensure that large emissions through direct or indirect human-caused forest degradation are avoided. Investment in consistent long-term monitoring will be fundamental to detect any such changes in this critical terrestrial carbon pool.

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Appendix

Table 14. Estimates of total carbon stocks (measured plots only) for each cycle by tall forests and regenerating forests (shrublands) and their assigned alliances as defined by Wiser et al. (2016). Estimated 95% confidence intervals are calculated using sampling variation and model prediction error (CI$_{s\&p}$). 20 plots (2nd and 3rd cycle additions) lacked an alliance assignment.

		Stocks Cycle 1		Stocks Cycle 2		Stocks Cycle 3	
Tall forests and their alliances	n (C1/C2/C3)	tC ha^{-1}	±CI$_{s\&p}$	tC ha^{-1}	±CI$_{s\&p}$	tC ha^{-1}	±CI$_{s\&p}$
Beech-Broadleaved Forest							
Kāmahi-hardwood forest	73/64/44	286.73	*29.02*	294.56	*30.96*	290.86	*37.09*
Silver beech-broadleaf forest	69/64/41	256.27	*26.03*	262.61	*27.54*	264.58	*34.44*
Silver beech-red beech-kāmahi forest	71/66/46	350.01	*32.66*	355.95	*33.04*	368.89	*38.20*
Subtotal	213/194/131	297.08	*20.79*	303.85	*21.52*	308.86	*24.78*
Beech-Broadleaved-Podocarp Forest							
Kāmahi-Southern rata forest and tall shrubland	37/36/16	204.32	*38.46*	198.94	*36.33*	184.43	*42.48*
Pepperwood-hardwood forest and successional shrubland	52/47/29	294.92	*37.71*	305.95	*40.83*	287.46	*51.77*
Kāmahi forest	56/49/35	308.60	*33.36*	302.09	*33.87*	313.88	*43.26*
Kāmahi-silver fern forest	44/33/25	213.90	*29.32*	202.31	*31.12*	183.64	*39.45*
Subtotal	189/165/105	262.27	*21.08*	260.52	*27.96*	256.17	*27.22*
Beech Forest							
Black/mountain beech forest (subalpine)	28/24/16	197.47	*23.81*	211.48	*26.72*	196.61	*36.55*
Black/mountain beech-silver beech forest/subalpine shrubland	55/46/35	244.82	*47.68*	248.72	*48.93*	231.08	*52.63*
Black/mountain beech forest	33/30/23	178.59	*31.71*	191.32	*36.43*	168.86	*29.04*
Silver beech-red beech-black/mountain beech forest	29/27/20	330.01	*39.08*	330.53	*40.46*	322.84	*49.66*
Silver beech forest with mountain lacebark and weeping matipo	11/07/08	193.25	*83.77*	250.64	*122.87*	240.03	*83.65*
Hard beech-kāmahi forest	21/20/15	331.22	*154.64*	327.07	*154.25*	331.70	*155.68*
Subtotal	177/154/117	244.88	*22.87*	254.66	*23.66*	242.16	*25.03*
Broadleaved-Podocarp Forest (including kauri)							
Kāmahi-podocarp forest	85/80/57	306.76	*47.18*	299.31	*47.80*	299.47	*51.66*
Mahoe forest	60/54/34	168.08	*36.21*	166.76	*31.47*	158.98	*39.41*
Tawa forest	82/75/52	245.96	*35.15*	250.12	*36.07*	228.52	*32.66*
Silver fern-mahoe forest	61/49/39	146.96	*21.15*	146.42	*22.79*	147.10	*25.24*
Pepperwood-fuchsia-broadleaf forest	22/20/14	147.24	*43.03*	139.17	*35.39*	116.75	*25.71*
Mataī forest	7/6/1	170.33	*136.09*	195.18	*154.71*	95.33[1]	
Towai-tawa forest	8/8/8	238.97	*226.09*	267.47	*222.88*	176.75	*222.24*
Subtotal	325/292/199	215.01	*18.51*	216.59	*18.70*	204.57	*19.48*
Regenerating forest and shrublands and their alliances							
Shrublands							
S1Kānuka shrubland with Coprosma and prickly mingimingi	22/21/14	72.15	*19.41*	81.58	*22.81*	78.61	*20.82*
S2Grey scrub with kanuka	26/24/15	28.54	*11.86*	35.58	*14.25*	28.27	*12.40*
S3 Mānuka shrubland	6/6/3	41.54	*131.25*	49.89	*137.32*	35.61	*131.26*
S4Matagouri shrubland[1]	1/1/1	7.67		10.06		11.36	
S5Turpentine scrub-*Gaultheria* montane shrubland	7/7/7	6.56	*54.97*	11.08	*55.86*	10.02	*55.12*
S6Gorse shrubland with cabbage trees	5/5/3	19.22	*16.26*	11.72	*12.07*	16.44	*7.31*
Subtotal	67/64/43	41.14	*10.38*	47.48	*12.17*	41.42	*11.63*
Other							
OF1Kānuka forest and tall shrubland	54/49/36	64.03	*11.57*	73.35	*13.80*	90.68	*20.32*
PF1S13&14Mountain neinei-Inanga low forest and subalpine shrubland[1]	2/3/4	199.78		161.98		152.67	
Total[2]	1027/921/641	226.54	*13.67*	229.81	*14.01*	223.39	*14.74*

[1] Too few observations to calculate 95% confidence intervals

[2] 20 grid locations were not classified into a forest alliance; out of these 18 were only measured in the 3rd cycle and 2 measured in the last two cycles

Table 15: Estimates of carbon stocks in C1 and C3 based on plots measured in pre-1990 natural forest that also allowed the calculation of carbon stock changes between these inventory cycles based on actual measurements. Number of plots measured are given for each forest type. Estimates are shown for all forests, and for tall forest and regenerating forest based on the LandCoverDatabase Version 5 (Easdale et al. 2020). Plus-or-minus values are estimated 95% confidence intervals calculated by combining the effects of sampling variation and model prediction error (CI$_{s\&p}$).

Forest group[1]	Pool	Stocks Cycle 1		Stocks Cycle 3	
		tC ha^{-1}	±CI $_{s\&p}$	tC ha^{-1}	±CI $_{s\&p}$
All plots	AGB	136.88	9.81	135.59	8.97
	BGB	32.11	2.25	31.80	2.20
	Dead wood	41.06	11.10	40.76	10.94
	Litter[2]	21.29	4.28	21.29	4.28
	All pools	231.25	15.55	229.35	15.25
Number of plots		603		603	
Tall forest	AGB	147.01	9.57	144.90	9.36
	BGB	34.47	2.35	33.97	2.30
	Dead wood	43.13	11.91	43.92	11.76
	Litter[2]	22.50	4.36	22.50	4.36
	All pools	247.68	16.20	244.85	15.90
Number of plots		545		545	
Regenerating forest	AGB	41.73	11.10	48.10	11.47
	BGB	9.91	2.61	11.39	2.69
	Dead wood	12.21	8.73	11.12	7.89
	Litter[2]	9.87	18.29	9.87	18.29
	All pools	78.78	26.02	85.54	25.18
Number of plots		58		58	