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CARBON STOCKS AND CHANGE IN NEW ZEALANDS NATURAL FORESTS

ESTIMATES FROM THE FIRST TWO COMPLETE INVENTORY CYCLES 2002-2007 AND 2007-2014

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Report information sheet

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Executive summary

Natural forests provide a significant percentage of the non-atmospheric carbon that can be found on land. The natural balance of overall stored biomass stocks in undisturbed native forest systems is affected over time by disturbances of various kinds. Such shifts in carbon stocks over time are influenced by the dynamics of growth, recruitment, mortality and decay as a response to such disturbances. For international reporting on carbon stocks and changes it is essential to provide estimates on a national level across all forests. A national forest inventory has been operational since 2002 and is now in its third measurement cycle, although this is still incomplete. Forest plot data for the first two measurement cycles has been processed, quality checked and analysed and for the first time allows the estimation of carbon stocks and changes in New Zealand's natural forests.

The objective of this report is to present the result from an updated analysis of natural forest inventory data for the first measurement cycles (2002 -2007 and 2009-2012).

Key results

The analysis of permanent plots at 1,051 grid locations within mapped pre-1990 natural forest showed that New Zealand's natural forests are in "balance" and show no significant carbon stock changes between the two measurement cycles. The total carbon stocks in natural forests was 226.3 ± 14.0 tC ha^{-1} in the first measurement period, while in the second measurement cycle carbon stocks were 226.0 ± 13.8 tC ha^{-1}. Around 73% of assessed carbon is stored in the living biomass pools, while Dead Wood and Litter contain the remaining 27% of carbon in New Zealand's natural forests. Classifying plots based on their species composition into tall forest and regenerating forest, highlighted that carbon stocks were not significantly different in tall forests between the first and second measurement cycles with 251.5 ± 15.1 tC ha^{-1} and 250.5 ± 14.9 tC ha^{-1} respectively. Carbon stocks in Regenerating forest changed from 52.6 ± 7.5 tC ha^{-1} to 57.6 ± 8.5 tC ha^{-1}. Carbon stock changes were significantly different to zero in Regenerating forest with an increase of 4.8 ± 1.9 tC ha^{-1} or 0.6 ± 0.3 tC ha^{-1}y^{-1}.

A detailed analysis based on the alliances and associations (forest types) of the forest classification (Wiser and De Cáceress 2018) revealed that carbon stock changes are not significant from zero in all tall forest associations except a significant decline (-9.0 ± 7.2 tC ha^{-1}) in Kamahi-podocarp forest, a widely distributed forest association. Associations with Kanuka as part of the regenerating forests showed

significant positive carbon stock changes e.g. Kanuka shrubland sequestered 8.1 ± 5.8 tC ha^{-1} between the measurement cycles (1.2 ± 0.9 tC $ha^{-1}y^{-1}$)

The average AGB carbon stock across all plots is134 tC ha^{-1} which is the level at which growth of living stems is in balance with the loss in mortality. This indicates that nationally our natural forests are in a state of equilibrium. The presence of an equilibrium state suggests that there have not been major external factors impacting on growth or mortality over recent decades or positive and negative effects from such factors occurred at the same level balancing each other out.

Conclusions

Natural forests overall maintain a large pool of land-based carbon but on a national level do not sequester additional carbon and therefore are not a carbon sink. The system is in “balance” at the national level. Viewing regenerating forests alone they have smaller total carbon pools but are sequestering carbon and can therefore be considered a carbon sink while Tall forest with an average AGB carbon stock of 148 tC ha^{-1} is nationally in carbon balance.

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Introduction

Natural forests contain a significant percentage of the non-atmospheric carbon that can be found on land. The natural balance of overall stored biomass stocks in native forest systems is affected over time by disturbances of various kinds. Such shifts in carbon stocks over time are influenced by the dynamics of growth, recruitment, mortality and decay as a response to such disturbances. National Forest inventories (NFIs) with permanent sample plots repeatedly measured over periods of time are able to provide measurements that allow the quantification and modelling of these dynamics and the carbon stocks at certain points in time and their change. The New Zealand pre-1990 natural forest inventory is New Zealand's first plot based national NFI that can provide such data as part of the Land Use and Carbon Analysis System (LUCAS). LUCAS is a cross-government programme administered by the Ministry for the Environment (MfE) which primary purpose is to support New Zealand's international reporting requirements under the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and the Paris Agreement. LUCAS combines the information from NFIs in pre-1990 natural forests, pre-1990 and post-1989 planted forests and post-1989 natural forests and wall-to-wall satellite-based mapping of these land-use types.

An important part of LUCAS is the pre-1990 natural forest inventory as it represents natural forests and shrublands that cover nearly 26% of New Zealand's land area (Stats NZ 2019). The inventory is designed as a network of permanent plots laid out on an 8 x 8 km grid covering the area of pre-1990 indigenous forest and shrubland and provides, beside other metrics such as species composition, unbiased estimates of carbon stocks and stock change in natural forests 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 and an inner 20 m x 20 m square plot (Payton et al., 2004). 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 circular plot and all stems ≥ 2.5 cm DBH and dead wood ≥10 cm diameter are measured in the inner square plot. Repeated measurements of each present tree inside the respective plot area were remeasured between 2009 and 2014 and any ingrowth trees added as well as recent dead trees accounted for as mortality.

Carbon stocks are summarised into four carbon pools:

1) AGB (above ground biomass) in trees ≥ 2.5cm diameter at breast height (DBH, measured at 1.35 m height) and shrubs (AGB),

2) below-ground biomass (BGB),

3) Dead Wood or Coarse Woody Debris (CWD), and

4) Litter, as required for UNFCCC and KP reporting (Intergovernmental Panel on Climate Change 2006, 2014).

Dead Wood arises from the mortality of trees and branches and is defined to be ≥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 models described by Beets et al. (2012).

The first analysis of the inventory based on 1,256 plots measured between 2002 and 2007 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 tC ha^{-1}. The stock in natural forest excluding shrubland was 218 tC ha^{-1}. These estimates did not include below ground CWD.

Robust estimates of changes in carbon pools over time became possible after the completion of the second measurement in 2014. An analysis of stocks and stock changes from 874 grid locations with two measurements was reported in Holdaway et al. (2014) and Holdaway et al. (2017). This analysis indicated that total carbon stock in pre-1990 natural forest measured in 2002-07 (Time 1) averaged 228.7 tC ha$^{–1}$ for the 2002-07 measurement, and 231.5 tC ha$^{–1}$ for the second measurement carried out in 2009-14 (Time 2). The overall average annual net change in carbon stocks across all pre-1990 natural forest was slightly positive (+0.34 tC ha–1 yr–1) although statistically indistinguishable from zero. These estimates also did not include below ground CWD. While the work of Holdaway et al. (2017) was the first published estimate of carbon stocks and their changes in NZ’s natural forests the analysis was based solely on data from the 20 m x 20 m inner plots, and did not include measurements in the 20m radius circular plot (external (EXT) subplot), Apart from not utilising all the available data, for large emergent trees and CWD with diameter ≥ 60 cm, evidence has since emerged that large stems were over-sampled in the 20 m x 20 m plots, meaning that estimates of carbon stocks based only on these plots are too high (Paul et al. 2019). It was therefore considered essential to use all data including measurements from the EXT subplots to provide reliable estimates of carbon stocks and stock changes.

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

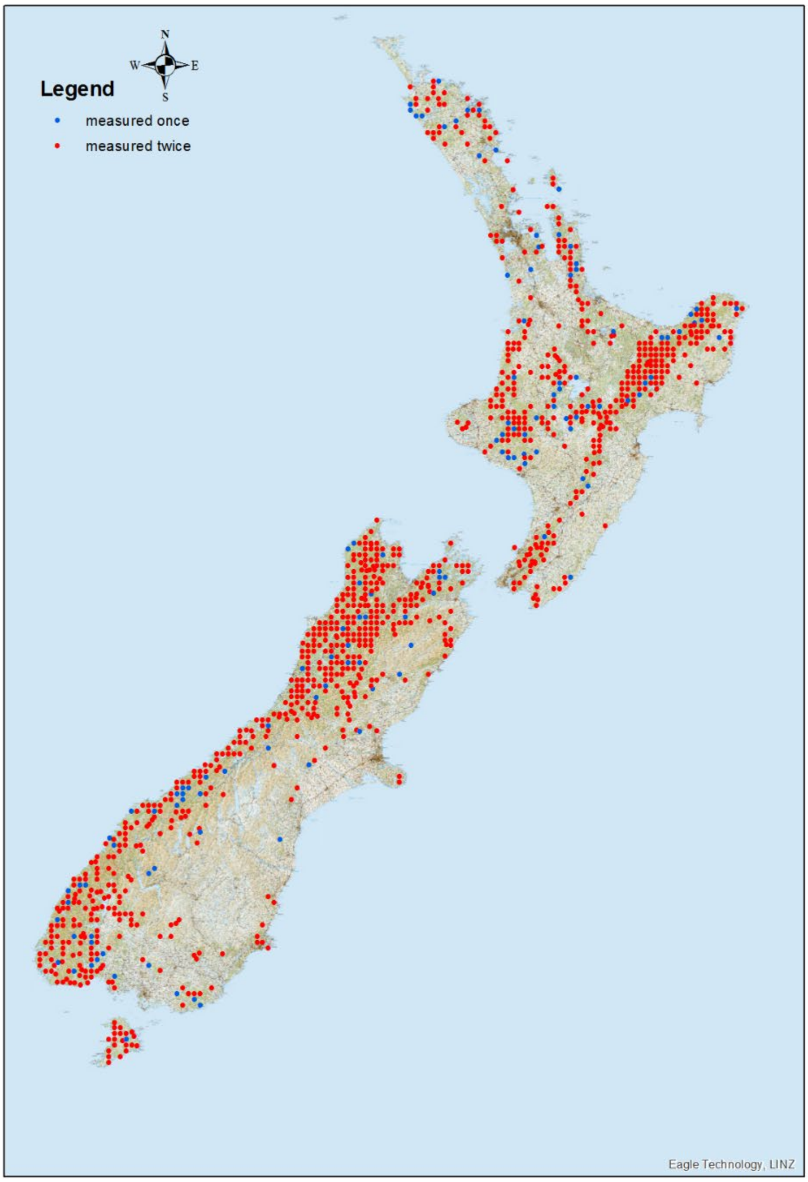
With further improvements in the methods used to estimate CWD carbon through an informed modelling approach (Kimberley et al. 2019), and better representation of belowground carbon (Easdale et al. submitted) plus the addition of additional 44 plots measured during 2013-14 measurement, new and more complete carbon stock and stock change estimates are now provided for New Zealand's pre-1990 natural forest.

Materials and methods

The Natural forest Inventory

The pre-1990 natural forest inventory consists of a network of permanent plots laid out on a 8 x 8 km grid covering the area of pre-1990 indigenous forest and shrubland (Map 1). The inventory is designed to provide unbiased estimates of carbon stocks and stock change in natural forest on a per hectare basis and for the total mapped area of natural forests with known precision (Cochran 1977, Coomes et al. 2002).

Figure 1: NFI plots in natural forests measured twice (red) or once (blue) during the two measurement cycles (2002-07 and 2009-14).



The pre-1990 natural forest inventory is based on the design of a random systematic sampling grid and at each grid location in mapped natural forests based initially on the Land Cover Data Base 1 (LCDB1) and in recent years the Land Use Map (LUM) 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 and a nested inner 20 m x 20 m square plot (Payton et al. 2004a, Ministry for the Environment 2018). 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 20 m radius plot and all stems ≥2.5 cm DBH and dead wood ≥10 cm diameter are measured in the inner 20 m x 20 m plot when plots were first established between 2002 and 2007. While dead wood re-measurements continue to be taken during the second measurement period, we model dead wood carbon stock and changes based on the method outlined in Kimberley et al. (2019).

In each nested plot all stems meeting the DBH size thresholds are tagged permanently allowing the "tracking" of each individual stem through time. It also allows the identification of ingrowth and mortality of live stems between measurements and allows for the precise estimation of changes in stem numbers, growth and related metrics such as biomass and carbon on a stem and plot basis.

Continuous inventory with two full cycles 2002-07 and 2009-14

The current study uses re-measurement data from 925 (77%) of the 1,208 locations categorised as pre-1990 natural forest based on a mapping exercise in 2012 (Land Use Map sourced from the Ministry for the Environment 2014). Of the remaining 283 locations, 115 had been measured in the 2002-07 cycle but were not re-measured in 2009-14 due to budget constraints, 11 had been measured in 2009-14 as new plots added to the inventory based on mapping and 76 had yet to be measured in 2009-14 again due to budget constraints, 80 were inaccessible either due to health and safety risks (33) or because landowners denied the field team access (47). One pine plot (BU14) was not measured, and one plot (DG66) was to be re-established as it was measured using only a 10 x 10 m inner plot. The initial selection of plots for re-measurement was made randomly, however it is unclear whether the 925 plots included in our analysis are a fully representative (unbiased) subset of the 1,208 locations. Seven plots out of the 925 plots did not have any trees (<2.5 cm DBH) and represented low shrubland-grassland ecotones and were assigned zero carbon.

The average time between the first and second measurements across the 925 locations was 7.67 years.

Data quality assurance

Inventory field procedures and data quality audits were carried out during the two inventory periods across a minimum of 7.5% of measured plots annually (varied between 7.5% and 10% of plots between measurement years) and across the full dataset once entered into the database. Through those data quality audits, various data issues were identified using a series of data checking procedures developed using SAS Version 9.3 macros and were rectified accordingly. Data issues found were often transcription errors, missed or erroneous measurements. Overal,11,862 records (3.2%) related to stem diameter and height entries (total 366,568 records) and 1,172 entries (2.4%) related to CWD (total 47,861 records) were corrected.

The stem following method to determine carbon stock change

To estimate changes in the AGB pool each measured stem in the inventory was "followed" over time. This is a more detailed method compared to the common simple differential methods on a plot basis. On a plot basis the "Stem Following" method, can be calculated by summing the stock change for each individual live stem (growth) and subtracting the summed Time 1 carbon for individual stems which died in the period between Time 1 and Time 2. To account for ingrowth and missing measurements e.g. trees measured at Time 2 which were not measured at Time 1 were predicted using the missing value method and used in the calculation of stock change provided that the DBH at Time 2 was above the DBH threshold for being included e.g. 2.5 cm or 60 cm. For example, if a tree in the 20m radius plot was measured with a DBH of 60.5 at Time 2 and the predicted DBH at Time 1 was 59 cm the 59 cm was used at Time 1. Likewise if a tree in the 20m x 20m plot had a DBH of 2.6 cm at Time 2 and the predicted DBH was 2.3 cm at Time 1 (in the internal plot), the 2.3 cm was used at Time 1. To calculate stocks using this method, Time 2 stocks were used as the reference, and Time 1 stocks obtained by subtracting stock change calculated using the "Stem Following" method from this value.

Height estimation

Heights were estimated using height/DBH regression models fitted to height measurements of all live, non-leaning trees and shrubs measured twice (i.e., in both 2002-7 and 2009-14). 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 deriving the height/dbh relationship (Kimberley and Beets 2016). Also as described in Kimberley and Beets (2016) tests suggested different criteria were used to select height trees in each period, and to ensure that height changes represented genuine growth effects, only stems measured in both period were used to develop the models.

The method used the following underlying relationship between height, *H*(m), and DBH, *D* (cm):

[1] $$H = 1.35 + exp(a_i + b_i \times D^{-0.3})$$

which was fitted in its linearized form:

[2] $$ln(H - 1.35) = a_i + \ b_i \times D^{-0.3}$$

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

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

[3] $$Y \ = \ln(H - 1.35) - a_i - b_i \times \ D^{-0.3}$$

A linear regression between Y and $DBH^{-0.3}$ was then fitted for each plot with separate intercepts for each 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] $$(H - 1.35)_{Pred} = exp(Y_{Pred} + a_i + b_i \times D^{-0.3})$$

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 with live, non-leaning trees and shrubs measured twice:

[5] $$R = mean(H - 1.35)/mean(H - 1.35)_{Pred}$$

Individual values of R were calculated for each species with three or more height measurements in a plot and 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] $$H_{pred} = 1.35 + R \times (H - 1.35)_{Pred}$$

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

Live carbon stock calculations based on volume

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 equations in Beets et al. (2012) from DBH (cm) and predicted height (m). Dry weight of stems was then estimated by multiplying the volume by whole stem basic density tabulated by species and ranging from 288 kg m^{-3} to 770 kg m^{-3}. For species with no tabulated density, the mean density of the genus, or failing that of the growth type (canopy tree, subcanopy tree, tree-fern/cabbage tree or shrub) was used. Stem carbon was then estimated by multiplying the dry weight by the carbon fraction, assumed to be 0.51 for gymnosperms and 0.48 for broadleaf and other species. For tree ferns, cabbage trees and palms, carbon was estimated directly from DBH (cm) and predicted height (m) using the equations in Beets et al. (2012).

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 ≥ 5 cm DBH, and monocots (palms and cabbage trees), 0.194 for tree ferns, and 0.245 for gymnosperm trees and shrubs ≥ 5 cm DBH as suggested by Easdale et al. (in prep.).

Coarse woody debris carbon stock calculations

For dead standing tree spars, the original volume of each standing spar (m^3) was firstly predicted from *DBH* and predicted height using the allometric equation for live stems in Beets et al (2012). Because standing dead tree spars are often broken, the volume of the truncated spar was calculated from DBH and measured height. Although inventory data collection protocols (Ministry for the Environment 2018) require that all spars are measured for height, in practice 6% of all spars in the inventory were not measured, and predicted height was used in place of measured height in that case. The volume was calculated using the following taper function developed from sectional measurements of a subset of 115 of the trees used to develop the allometric relationships described by Beets et al. (2012):

[7] $$V_{Spar} = V_{stem} \times (1 - 0.06501 \times X^2 - 2.92127 \times X^3 + 3.37103 \times X^4 - 1.35551 \times X^5 - 0.02924 \times X^{81})$$

where, $X = (H_{Pred} - H)/H_{Pred}$

As Dead Wood is defined as being 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, *H*, and the height corresponding to a stem diameter of 10 cm.

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:

[8] $$V_{Stump} = \pi \times H \times (SED/2)^2$$

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

$$[9] \qquad V_{fallen} = 1/3 \times (\pi \times Length) \times ((LED/2)^2 + LED/2 \times SED/2 + (SED/2)^2)$$

Only pieces with SED ≥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 and stumps using the same decay modifiers and carbon fraction.

Carbon, *C* (kg), of CWD in dead spars, stumps and fallen pieces was estimated using:

$$[10] \qquad C_{CWD} = V_{CWD} \times Density \times Decay\_Modifier \times Carbon\_fraction$$

In this equation, V_{CWD} (m^3) is volume, *Density* (kg/m^3) is basic density of fresh dead material tabulated by species as used for live stems, *Decay_Modifier* is an adjustment accounting for the loss in density of dry matter due to tabulated by decay class (Coomes et al. 2002, Holdaway et al. 2017) assigned by the field team to each piece of CWD (Payton et al. 2004b, Ministry for the Environment 2018), and *Carbon_fraction* is assumed to be 0.50 for all dead material. Where the species was unknown as was often the case, a basic density of 477 kg/m^3 was used, this being the volume-weighted mean of the tabulated density for all dead material of known species in the inventory.

Carbon in stumps and dead standing spars of tree ferns, cabbage trees and palms was estimated directly from measured height and DBH by calculating the carbon in an equivalent live stem using the equation in Beets et al. (2012) and multiplying by the decay modifier.

Recent analysis has demonstrated that the plot measurements of CWD obtained in the inventory tend to significantly understate the true amount of CWD in a plot (Kimberley et al. 2019). This error is thought to be due to a consistent tendency for CWD material to be missed during the measurement process. For example, under current measurement protocols, there is no attempt to measure Decay Class 4 (heavily decayed) material, nor to measure fallen stems and other CWD material buried more than 50% in the forest floor.

As described in Kimberley et al. (2019), it is possible to predict the CWD carbon in 2009-14 by taking the measurement from the 2002-07 cycle as a starting value, adding inputs to the CWD carbon pool from trees that died between measurements, and subtracting the carbon predicted to be lost from decay over the period using the decay models of Garrett et al. (2019). We applied this method to the natural forest inventory, and as expected, it produced a higher estimate of CWD for 2009-14 than the measured value. This is because the modelled losses from decay are too low because of the measured CWD in 2002-07 is underestimated. An adjustment factor was obtained by an iterative procedure such that, when multiplied by the measured CWD in both 2002-07 and 2009-14, the modelled estimate for 2009-14 was the same as the adjusted measurement at that time. The adjustment factor derived using this approach was 1.767. In other words, the corrected estimates of CWD carbon were obtained by increasing the measured values by 76.7%.

Carbon in litter and belowground dead roots

During the first measurement period (MP 1) (2002-2007) carbon in the Litter pool was sampled and analysed for a random sample of plot locations following Davis et al. (2004). This included the three sub-pools of Fine woody debris (<10 cm diameter), litter and fermenting and humus material (FH). While 320 grid locations were sampled only 253 of these were defined through mapping to be in pre-1990 tall and regenerating natural forest. Based on these subsamples of the full inventory mean values of carbon in litter was calculated and assumed constant.

Relationships between the Litter carbon pool and the AGB and CWD carbon pools were explored with the latter tested using various transformations. All relationships were weak although there was a general tendency for Litter carbon to be positively related to AGB carbon. The best relationship found was between between Litter carbon and log(AGB carbon + 1) using a quadratic regression model, although the relationship was weak (R^2=0.06). This model was used to provide a double sampling regression estimate of Litter for the 2002-07 cycle (see, e.g., Cochran (1977)).

Estimates of the carbon in dead roots were not provided in earlier reports of natural forest carbon (e.g., Beets et al. (2009), Holdaway et al. (2014)) and there are no direct measurements of carbon in below-ground dead wood in the inventory. However, for completeness, the current study provides estimates of carbon in this pool from the best information currently available. A study of decay rates in roots of native trees using data from 3 rimu and 2 silver beech trees found roots to decay more quickly than above-ground dead wood (Garrett et al. 2019). 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. 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 below ground decay rate implies that carbon in below ground dead roots will be $0.25 \times 0.76 = 0.19$ times the above ground dead wood carbon. Therefore, in the current study, carbon in below ground dead roots was estimated using 0.19 times the above-ground CWD.

Converting carbon estimates of stems and CWD pieces into per hectare estimates

With the nested plot design used in the inventory, larger diameter stems and dead wood were measured within the 20 m radius circular plots while smaller diameter material was only measured within the inner plots. 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) whereas smaller diameter material was sampled over a plot area averaging only 0.0345 ha, with areas of inner square plots calculated using the Bretschneider formula for the area of a convex quadrilateral (Paul et al. 2019).

All stems, spars and fallen pieces ≥ 60 cm in diameter were assumed to be sampled over the area of the circular plot, with the remaining smaller diameter pieces assumed to be sampled over the inner plot area.

To combine these two types of data into a single per hectare estimate of carbon for the grid location, the weight of carbon (kg) in each tree, spar or piece was divided by the area of the plot over which it was sampled and further divided by 1000 to convert into tC ha^{-1}. These values were summed to provide the total tC ha^{-1} for the grid location. To ensure the strict application of the minimum diameter size for 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 fallen pieces found in the inner plot with LED greater than 60cm 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 areas, and the remainder assumed to be sampled over the inner plot area.

Adjustments for plots measured only once

The inventory includes measurements from 1,051 grid locations. Of these, 1,040 were measured in the 2002-07 inventory cycle and 936 measured in the 2009-14 cycle, and only 925 were measured in both cycles. In previous reports describing the inventory such as Holdaway et al. 2014 and Holdaway et al. 2017, the analysis was restricted to data from plots measured in both cycles. However, in the current study, we believed it desirable to incorporate data from grid locations measured only once in case those measured in both cycles were not fully representative of pre-1990 natural forest. We therefore based the analysis of the inventory on a double sampling framework using regression estimators. With this approach, plots measured in both cycles were used to establish regression models for predicting stocks in the 2009-14 cycle from those in the 2002-2007 cycle. These regression models were used to predict stocks in 2009-14 for plots measured only in the 2002-2007 cycle. Similarly, stocks in plots not measured in the 2002-07 cycle were predicted using stocks measured in the 2009-14 cycle. Also, stock change in plots measured only once were predicted using regressions with stocks as the independent variable. Even 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 which are described later in the report. Finally, the litter pool was only measured in 252 grid locations and only in the 2002-07 cycle. Litter was therefore estimated using regression models using AGB carbon as the independent variable as this variable was more closely related to litter than any other available variable. The double sampling regression estimation procedures used are not described in further detail in this report as they are well described in standard sampling texts such as Cochran (1977). The regression models used in this analysis are listed in Appendix 2.

Errors of estimates

Estimates of uncertainty obtained in forest inventories are usually calculated on the basis of plot-to-plot sampling variation. They thus take into account the natural variability of tree size and distribution within a forest, and also allow for random measurement errors, but take no account of errors in underlying models used to calculate stand metrics. However, carbon estimates from the natural forest inventory involve the use of highly derived models as described above. It is therefore desirable to take into account model prediction errors when calculating uncertainty in this inventory.

Our approach to combine model and sampling uncertainty for carbon estimates is to use simple statistical rules for combining errors such as those suggested by the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change 2014). This approach was adopted in the current study. The calculated best estimates of uncertainty for all models and model elements used for predicting carbon is summarised in Appendix 1.

The other source of uncertainty in carbon stock and stock change predictions is caused by plot-to-plot sampling variation. This variation is mainly caused by differences in vegetation structure and composition, but it also includes effects of measurement error and error resulting from height prediction models. Note that the height models are fitted separately to each plot, and as mean predicted heights of height-measured trees are constrained to equal their actual mean, these models are unlikely to have consistent model prediction error and their variability is therefore taken into account by the sampling uncertainty.

The uncertainty of carbon estimates from plot-to-plot sampling variation was calculated using standard procedures based on the assumption that the grid locations represent a simple random sample of plots from pre-1990 natural forest. As described in the previous section, regression estimators were used to adjust for grid locations measured only once, and the standard rules for estimating uncertainty in regression estimators were therefore used (Cochran 1977).

To combine the sampling uncertainty and model prediction uncertainty, we used IPCC rule 6.4 (see Appendix 1):

$$[11] \qquad U_{total} = \sqrt{(U^2_{sampling} + U^2_{model})}$$

where $U_{sampling}$ and U_{model} are uncertainties (95% confidence intervals) associated with sampling and model prediction errors, and U_{total} is the effect of their combined uncertainty.

Note that when several pools were combined (e.g., when calculating total carbon), the model uncertainty for the combined estimate given in Appendix 1 was used, and the sampling uncertainty was based on the combined pools calculated for each plot. Similarly, when calculating changes in stocks, the stock change was calculated for each grid location, and the sampling uncertainty calculated from these differences.

National estimates of carbon stocks and changes

Carbon stocks are summarised into four carbon pools: 1) Above ground biomass in trees and shrubs ≥ 2.5cm DBH (AGB), 2) below-ground biomass (BGB), 3) Dead Wood or Coarse Woody Debris (CWD), and 4) Litter.

Dead Wood arises from mortality of trees and branches and is defined to be ≥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 models described by Beets et al. (2012).

Estimates of carbon stocks per hectare by pool were obtained for each measurement period using regression estimators. Stock change was calculated using the stem following method, obtaining changes in carbon pools by summing the stock change for each individual stem, and subtracting the carbon for stems which died between measurements.

Stock and stock change estimates were also summarised by vegetation class based on species composition within the plots prepared by Wiser et al. (2016), and summarised using a simplified version of these classes termed ‘tall forest’ and ‘regenerating forest’. Estimates were also summarised by land tenure comparing public conservation land with all other forms of land tenure.

Results

Analysis of inventory data from permanent plots at 1,051 grid locations within New Zealand's pre-1990 natural forest shows that the forest is in a state of carbon balance. Carbon stocks in all biomass pools averaged 226.3 ± 14.0 tC ha^{-1} in the first period and 226.0 ± 13.8 tC ha^{-1} in the second period (Table 1). Around 73 % of assessed carbon is stored in the living biomass (AGB and BGB), while Dead wood and Litter store the remaining 27% of carbon in New Zealand's forests.

Using a classification system based on species composition and structure (Wiser and De Cáceress 2018), plots were split into Tall forest and Regenerating forest types. Carbon pools in Tall forest were nearly four times higher than those in Regenerating forest. Total carbon stocks in Tall forests averaged 251.5 tC ha^{-1} in the first period and 250.5 tC ha^{-1} in the second period compared to 52.6 tC ha^{-1} and 57.6 tC ha^{-1} in Regenerating forest for the same periods.

Table 1. Estimates of carbon stocks (±95%CI based only on sampling variation) based on plots measured twice in pre-1990 natural forest. Estimates are shown for all plots measured twice, and separately for plots classified as Tall Forest and Regenerating Forest on the basis of species composition. Plus-or-minus values are estimated 95% confidence intervals calculated using two methods; the first method is based solely on sampling variation between plots (CI_s); and the second method combines the effects of sampling variation and prediction uncertainty ($CI_{s\&p}$).

Forest type[1]	Pool	Stocks in 2002-07			Stocks in 2009-14		
		tC ha^{-1}	CI_s	$CI_{s\&p}$	tC ha^{-1}	CI_s	$CI_{s\&p}$
All plots (N=1051)	AGB	133.9	±5.2	±8.2	133.5	±5.1	±8.1
	BGB	31.4	±1.2	±2.0	31.3	±1.2	±2.0
	Dead wood	40.1	±2.7	±10.8	40.2	±2.5	±10.8
	Litter[2]	21.0	±3.5	±3.5	21.0	±3.5	±3.5
	All pools	226.3	±8.5	±14.0	226.0	±8.3	±13.8
Tall forest (N=918)	AGB	148.3	±5.3	±8.7	147.4	±5.1	±8.6
	BGB	34.8	±1.3	±2.2	34.5	±1.2	±2.1
	Dead wood	45.3	±2.9	±12.1	45.4	±2.7	±12.1
	Litter	22.7	±4.0	±4.0	23.0	±4.0	±4.0
	All pools	251.5	±8.7	±15.1	250.5	±8.4	±14.9
Regeneratin g forest (N=131)	AGB	31.9	±5.1	±5.3	35.5	±5.9	±6.1
	BGB	7.7	±1.2	±1.3	8.5	±1.4	±1.5
	Dead wood	3.9	±1.9	±2.2	4.4	±2.1	±2.4
	Litter	8.7	±1.7	±1.7	8.7	±1.7	±1.7
	All pools	52.6	±7.1	±7.5	57.6	±8.1	±8.5

[1]Note that two grid locations were not classified into a forest type
[2]Litter was only measured in 2002-07 and was assumed to be unchanged in 2009-14

Over the 7.7 years between the first and second measurement periods covered by the inventory, there was no significant change in total carbon across all plots, with the estimated change over this period being 0.3 ± 1.4 tC ha^{-1} which does not differ significantly from zero (Table 2). However, Tall forests and Regenerating forests which showed very different levels of carbon stocks (Table 1) also showed differences in carbon stock change (Table 2). In Tall forest, stock change was -0.3 ± 1.6 tC ha^{-1}, not significantly different to zero, and indicating that Tall forests are in carbon balance. However, stock change was significantly positive in Regenerating Forest, averaging 4.8 ± 1.9 tC ha^{-1}.

Table 3. Estimates of carbon stock changes for all plots and for tall forest and regenerating forest separately within the pre-1990 natural forest. Carbon stock change is calculated based on stem following method. Plus-or-minus values are estimated 95% confidence intervals calculated using two methods; the first method is based solely on sampling variation between plots (CI_s); and the second method combines the effects of sampling variation and prediction uncertainty ($CI_{s\&p}$).

Forest type	Pool	Change in stocks		
		tC ha^{-1}	CI_s	$CI_{s\&p}$
All plots (N=1051)	AGB	0.1	±1.1	±1.1
	BGB	0.0	±0.3	±0.3
	Dead wood	0.3	±1.3	±1.3
	Litter[1]	-		
	All pools	0.3	±1.4	±1.4
Tall forest (N=918)	AGB	-0.4	±1.2	±1.2
	BGB	-0.1	±0.3	±0.3
	Dead wood	0.2	±1.5	±1.5
	Litter	-		
	All pools	-0.3	±1.6	±1.6
Regenerating forest (N=131)	AGB	3.7	±1.6	±1.6
	BGB	0.9	±0.4	±0.4
	Dead wood	0.6	±0.7	±0.7
	Litter	-		
	All pools	4.8	±1.9	±1.9

[1]Litter was only measured in the 2002-07 cycle and it is therefore not possible to estimate its change.

Carbon stocks by land tenure are shown in Table 3. Differences between land tenure are evident with lower average carbon stocks of 159.1 tC ha^{-1} on non-public conservation during the first measurement and 161.6 tC ha^{-1} during the first re-measurement compared to higher stocks on public land of 251.8 tC ha^{-1} and 250.5 tC ha^{-1} respectively.

A further breakdown into forest alliances and associations (Wiser and De Cáceress 2018) is shown in Table 4. The highest carbon stocks were found in silver beech-red beech-kamahi forests (353.3 tC ha^{-1}) belonging to the beech-broadleaved forest alliance (308.4 tC ha^{-1}) followed by the association silver beech-red beech-black/mountain beech forest (315.7 tC ha^{-1}), which belong to the beech-forest alliance (232.7 tC ha^{-1}). Forest alliances with higher podocarp abundance such as Beech-Broadleaved-Podocarp forest and Broadleaved-Podocarp Forests had overall lower carbon stocks (259.1 tC ha^{-1} and 220.3 tC ha^{-1} respectively).

Table 3. Estimates of carbon stocks for each cycle for plots within public conservation land and other forms of land tenure. Plus-or-minus values are estimated 95% confidence intervals calculated using two methods; the first method is based solely on sampling variation between plots (CI_s); and the second method combines the effects of sampling variation and prediction uncertainty ($CI_{s\&p}$).

Tenure	Pool	Stocks in 2002-07			Stocks in 2009-14		
		tC ha^{-1}	CI_s	$CI_{s\&p}$	tC ha^{-1}	CI_s	$CI_{s\&p}$
Public conservation land (N=672)	AGB	148.7	±6.2	±9.3	147.6	±6.1	±9.2
	BGB	34.9	±1.5	±2.3	34.6	±1.4	±2.3
	Dead wood	45.4	±3.2	±12.2	45.6	±3.1	±12.3
	Litter	22.7	±5.0	±5.0	22.7	±5.0	±5.0
	All pools	251.8	±10.3	±16.1	250.5	±10.3	±16.0
Other forms of land tenure (N=251)	AGB	95.1	±9.8	±10.8	97.0	±9.6	±10.6
	BGB	22.3	±2.3	±2.6	22.7	±2.3	±2.5
	Dead wood	25.2	±4.3	±7.9	25.4	±4.4	±7.9
	Litter	16.5	±6.8	±6.8	16.5	±6.8	±6.8
	All pools	159.1	±15.9	±17.7	161.6	±15.7	±17.6

Table 4. Estimates of total carbon stocks for each cycle by forest type (Forest alliance and associations) as defined by Wiser et al. (2016). Plus-or-minus values are estimated 95% confidence intervals calculated using two methods; the first method is based solely on sampling variation between plots (CI_s); and the second method combines the effects of sampling variation and prediction uncertainty ($CI_{s\&p}$).

Forest type	N	Stocks in 2002-07			Stocks in 2009-14		
		tC ha^{-1}	CI_s	$CI_{s\&p}$	tC ha^{-1}	CI_s	$CI_{s\&p}$
Beech-Broadleaved Forest							
Kāmahi-hardwood forest	75	305.1	±25.6	±29.7	306.4	±25.0	±29.3
Silver beech-broadleaf forest	70	265.2	±23.2	±26.6	266.7	±24.6	±27.8
Silver beech-red beech-kāmahi forest	73	353.3	±30.8	±35.5	351.9	±25.4	±30.9
Subtotal	218	308.4	±15.7	±21.9	308.9	±14.6	±21.1
Beech-Broadleaved-Podocarp Forest							
Kāmahi-Southern rata forest and tall shrubland	39	194.0	±37.6	±38.8	194.3	±35.5	±36.7
Pepperwood-hardwood forest and successional shrubland	50	286.8	±35.8	±38.5	286.8	±37.1	±39.8
Kāmahi forest	59	312.7	±29.7	±33.5	308.3	±28.2	±32
Kāmahi-silver fern forest	42	211.2	±29.4	±31.1	208.3	±28.2	±29.9
Subtotal	190	259.1	±17.1	±21.3	257.1	±17.0	±21.2
Beech Forest							
Black/mountain beech forest (subalpine)	28	190.8	±20.9	±22.9	196.0	±22.3	±24.2
Black/mountain beech-silver beech forest/subalpine shrubland	54	225.1	±41.2	±42.6	224.0	±41.2	±42.6
Black/mountain beech forest	34	182.7	±30.5	±31.8	186.6	±33.5	±34.7
Silver beech-red beech-black/mountain beech forest	28	315.7	±36.7	±39.9	315.4	±37.9	±41.0
Silver beech forest with mountain lacebark and weeping matipo	11	214.9	±103.7	±104.2	216.0	±122.4	±122.8
Hard beech-kāmahi forest	21	287.9	±238.8	±239.3	282.5	±239	±239.4
Subtotal	176	232.7	±19.4	±22.5	233.3	±19.6	±22.6
Broadleaved-Podocarp Forest (including kauri)							
Kāmahi-podocarp forest	86	294.1	±53.6	±55.5	285.1	±53.0	±54.8
Mahoe forest	61	179.5	±34.7	±35.8	181.9	±28.2	±29.5
Tawa forest	82	246.2	±32.6	±34.8	244.6	±32.6	±34.7
Silver fern-mahoe forest	64	152.1	±19.6	±20.9	151.1	±19.3	±20.6
Pepperwood-fuchsia-broadleaf forest	22	148.0	±45.6	±46.2	148.7	±38.1	±38.8
Mataī forest	7	188.4	±153.6	±153.9	195.1	±154.8	±155.0
Towai-tawa forest	9	241.1	±326.1	±326.3	242.1	±325.1	±325.3
Subtotal	331	220.3	±15.5	±18.9	218.0	±14.7	±18.2
Shrublands							
Kānuka shrubland with Coprosma and prickly mingimingi	24	83.6	±18.1	±18.5	91.8	±21.7	±22.1
Grey scrub with kānuka	30	33.5	±11.3	±11.4	36.9	±13	±13.1
Mānuka shrubland	5	26.9	±174.2	±174.2	27.0	±174.1	±174.1
Matagouri shrubland[1]	1	11.9			13.0		
Turpentine scrub-*Gaultheria* montane shrubland	9	7.4	±82.6	±82.6	7.3	±82.9	±82.9
Gorse shrubland with cabbage trees[1]	5	24.1			14.9		
Subtotal	74	45.3	±9.6	±9.8	48.8	±11.0	±11.2
Other							
Kānuka forest and tall shrubland	57	62.1	±10.5	±10.9	69.0	±11.6	±12
Mountain neinei-Inanga low forest and subalpine shrubland[1]	3	184.0			186.7		
Total	1051	226.3	±8.5	±14	226.0	±8.3	±13.8

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

Carbon stock changes by land tenure are shown in Table 5. While carbon stock changes in natural forest on public land showed no significant change in carbon stocks (not significantly different from zero) with 37 plots (5%) of public land plots classified as Regenerating forest. Natural forest on private land showed a significant positive change in carbon stocks (3.1 tC ha^{-1}) between the two inventory periods with 85 plots or 33% of plots on private land classified as Regenerating forest.

Stock changes by forest alliance and associations are shown in Table 6. There were a few statistically significant differences in stock changes evident between forest associations. The only tall forest association with a significant change in carbon stocks is Kamahi-podocarp-forest in the broadleaved-Podocarp Forest Alliance with a significant decline in carbon stocks (-9.0 ± 7.2 tC ha^{-1}). Most other "Tall" forest alliances show small changes in carbon stocks that were not significantly different from zero, suggesting that tall forest alliances in general are in balance. In contrast, the shrubland alliance and Kanuka forest association sensu Wiser (2016) showed significant positive carbon stock changes of 3.5 tC ha^{-1} and 6.7 tC ha^{-1} respectively.

Table 5. Estimates of carbon stock changes for all plots and for tall forest and regenerating forest separately within the pre-1990 natural forest. Carbon stock change is calculated based on stem following method. Plus-or-minus values are estimated 95% confidence intervals calculated using two methods; the first method is based solely on sampling variation between plots (CI_s); and the second method combines the effects of sampling variation and prediction uncertainty ($CI_{s\&p}$).

	Pool	Change in stocks		
		tC ha^{-1}	CI_s	$CI_{s\&p}$
Public conservation land (N=672)	AGB	-0.8	±1.3	±1.3
	BGB	-0.2	±0.3	±0.3
	Dead wood	0.2	±1.6	±1.6
	Litter	-		
	All pools	-0.7	±1.8	±1.8
Other forms of land tenure (N=251)	AGB	2.4	±2.0	±2.0
	BGB	0.6	±0.5	±0.5
	Dead wood	0.2	±2.0	±2.0
	Litter	-		
	All pools	3.1	±2.1	±2.1

Table 9. Estimates of total carbon stock changes (±95%CI) calculated using the "Stem Following" method in forest types as defined by Wiser et al. (2016). Changes in stock values in bold differ significantly from zero. Plus-or-minus values are estimated 95% confidence intervals calculated using two methods; the first method is based solely on sampling variation between plots (CI_s); and the second method combines the effects of sampling variation and prediction uncertainty ($CI_{s\&p}$).

Forest type	N	Change in stocks		
		tC ha^{-1}	CI_s	$CI_{s\&p}$
Beech-Broadleaved Forest				
Kāmahi–hardwood forest	75	2.4	±7.1	±7.1
Silver beech–broadleaf forest	70	1.1	±4.7	±4.7
Silver beech-red beech-kāmahi forest	73	0.7	±7.5	±7.5
Subtotal	218	1.4	±3.8	±3.8
Beech-Broadleaved-Podocarp Forest				
Kāmahi – Southern rata forest and tall shrubland	39	-0.2	±3.7	±3.7
Pepperwood–hardwood forest and successional shrubland	50	1.0	±7.8	±7.8
Kāmahi forest	59	-2.3	±6.4	±6.4
Kāmahi - silver fern forest	42	-2.1	±6.8	±6.8
Subtotal	190	-1.0	±3.2	±3.2
Beech Forest				
Black/mountain beech forest (subalpine)	28	4.9	±5.2	±5.2
Black/mountain beech - silver beech forest/subalpine shrubland	54	-0.3	±4.4	±4.4
Black/mountain beech forest	34	3.5	±6.5	±6.5
Silver beech – red beech – black/mountain beech forest	28	1.7	±9.1	±9.1
Silver beech forest with mountain lacebark and weeping matipo	11	1.7	±9.4	±9.4
Hard beech – kāmahi forest	21	-3.3	±9.8	±9.8
Subtotal	176	1.3	±2.8	±2.8
Broadleaved-Podocarp Forest (including kauri)				
Kāmahi-podocarp forest	86	**-9.0**	**±7.1**	**±7.2**
Mahoe forest	61	2.3	±4.8	±4.8
Tawa forest	82	-0.2	±5.0	±5.0
Silver fern - mahoe forest	64	-1.3	±6.8	±6.8
Pepperwood – fuchsia – broadleaf forest	22	1.8	±10.1	±10.1
Mataī forest	7	6.5	±24.0	±24.0
Towai – tawa forest	9	0.9	±25.5	±25.5
Subtotal	331	-2.0	±2.9	±2.9
Shrublands				
Kānuka shrubland with Coprosma and prickly mingimingi	24	**8.1**	**±5.7**	**±5.8**
Grey scrub with kānuka	30	**3.3**	**±2.8**	**±2.8**
Mānuka shrubland	5	0.0	±3.6	±3.6
Matagouri shrubland	1	1.0		
Turpentine scrub–*Gaultheria* montane shrubland	9	0.6	±1.4	±1.4
Gorse shrubland with cabbage trees	5	-9.2	±16.0	±16.0
Subtotal	74	**3.5**	**±2.5**	**±2.5**
Other				
Kānuka forest and tall shrubland	57	**6.7**	**±2.9**	**±2.9**
Mountain neinei – Inanga low forest and subalpine shrubland	3	4.2	±32.1	±32.1
Other (undefined)				
Total	1051	0.3	±1.4	±1.4

Net change in above ground live carbon can be partitioned into gross increment and mortality. The net change in carbon is the sum of these two components. The gross increment and mortality in above ground biomass were calculated overall, and for Tall and Regenerating forest types (Table 7). This shows that the increase in carbon in growing live stems is higher in Tall forest than in Regenerating forest, averaging 1.29 tC ha^{-1} yr^{-1} in Tall forest and only 1.05 tC ha^{-1} yr^{-1} in Regenerating forest. However, losses in carbon from mortality are much higher in Tall forest than Regenerating forest, more than offsetting the higher gain in carbon from growing trees. It is because of the much lower level of mortality that Regenerating forest shows a net gain in carbon.

Table 7. Estimates of annual AGB increase in carbon from growth of living trees, losses from tree mortality, and net change (±95%CI) for all pre-1990 forest, and for tall forest and regenerating forest, based on plots measured in both cycles of the inventory (n = 925).

Forest type	Increase in AGB carbon from tree growth	Loss in AGB carbon from mortality	Net change in AGB carbon
		tC ha^{-1} yr^{-1}	
All plots	1.26 ± 0.08	-1.25 ± 0.12	0.00 ± 0.17
Tall forest	1.29 ± 0.09	-1.36 ± 0.14	-0.10 ± 0.20
Regenerating forest	1.05 ± 0.20	-0.56 ± 0.12	0.65 ± 0.26

This result is not unexpected. Mortality in regenerating forest stands is generally lower than in more mature stands due to the lower level of competition between trees. This can be shown by plotting the relationships between gross increment, mortality and net change in carbon against carbon stocks (Fig. 2). It can be seen that the gross increment in AGB carbon increases rapidly with increasing stocks, but levels off once the AGB stocks reach about 100 tC ha^{-1}. Above this level of stocks, the annual increase in carbon produced by growing stems is remarkably constant, averaging about 1.4 tC ha^{-1} yr^{-1}. Annual losses in AGB carbon from mortality are very low when AGB stocks are low, but increase steadily with increasing stocks due to increasing competition between trees.

The net annual change in AGB carbon is the sum of the gross increment and mortality. At AGB stocks below 100 tC ha^{-1}, growth exceeds mortality, and the net change is significantly positive. When AGB stocks are between 100 and 150 tC ha^{-1}, growth and mortality are in balance, and the net change does not differ significantly from zero. However, when stocks are higher than 150 tC ha^{-1}, mortality exceeds growth and the net change is significantly negative. This means that on average, plots with AGB carbon stocks above 150 tC ha^{-1} are more likely than not to lose carbon.

The relationships shown in Fig. 2 explain why Regenerating forest, which has a net AGB carbon stock averaging only 31.9 tC ha^{-1}, is gaining carbon, while Tall forest, which has a net AGB carbon stock averaging 148.3 tC ha^{-1} is in carbon balance.

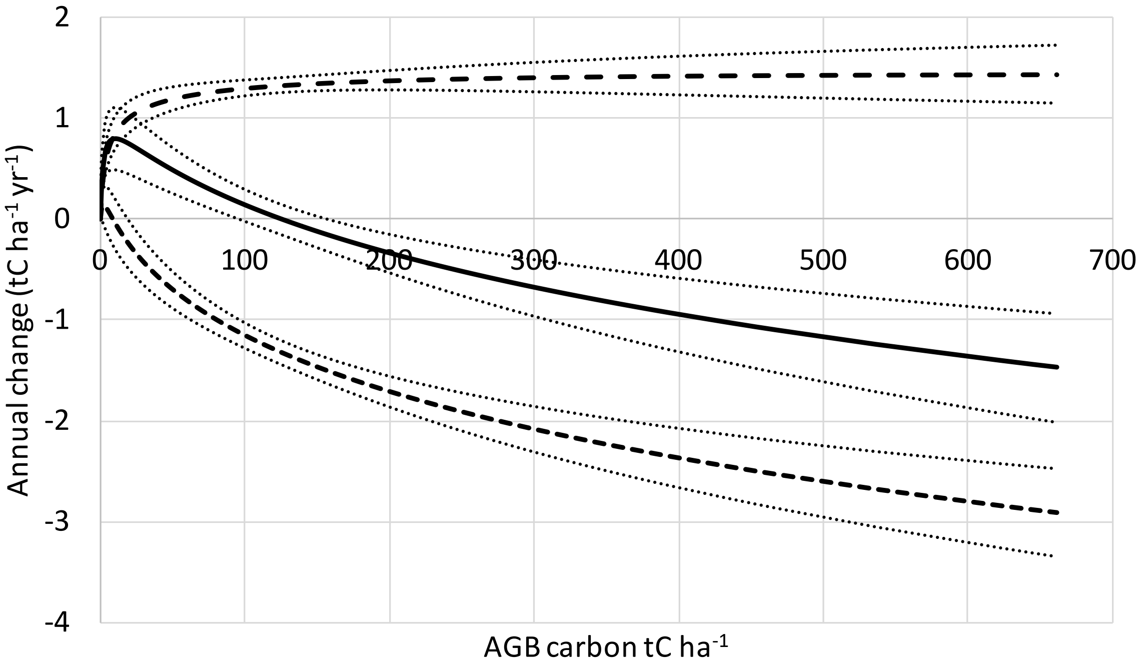


Figure 2. Regression models showing how annual increase in AGB carbon from growing stems (top dashed line with longer dashes), annual losses in AGB carbon from mortality (lower dashed line with shorter dashes), and the annual net change in AGB carbon (solid line), is related to mean AGB carbon stocks in New Zealand's pre-1990 natural forest. For each regression model, 95% confidence intervals are shown by dotted lines above and below the prediction line.

Discussion

The carbon stocks and stock changes between the first two inventory periods presented in this report are New Zealand's first estimates of their kind for the vast expanse of natural forests in the country. They are based on a proven systematic sampling design with random starting location and an appropriate permanent plot design, and include a sophisticated modelling approach to improve the prediction of CWD.

Most national forest inventories are designed as representative, often random or grid-based, sampling designs covering for the forested extent 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. 2009). To achieve full representativeness, all grid-points should be sampled during an inventory period. If this does not occur, for example if some plots are not measured due to financial budget constraints, the underlying selection of measured plots needs to be random or use some other method to ensure that estimates are unbiased. This occurred in New Zealand's natural forest where some plots were not sampled in the second cycle. However, we were able to use information from the 115 locations measured only in the first cycle but not in the second, and the 11 locations measured in the second but not in the first cycle. This was achieved using a double sampling regression estimation approach. This means that information from 1,051 locations representing 87% of the of the 1,208 grid locations in pre-1990 natural forest was used in the analysis.

Because not all grid locations were included in the study, it is possible that our estimates of carbon stocks and stock changes have some degree of bias. This would be the case if carbon stocks and stock changes in the 13% of locations not included in the study differ appreciably from the national averages. To consider whether this might be so, we here examine the reasons why these locations were not included in the study. Some 3% of locations could not be sampled due to their inaccessibility (e.g., due to steep terrain), and although it is likely that carbon stocks at such locations will differ from the national average, their effect can only be minor given the small numbers of locations involved. Similarly, access was denied at only 4% of locations, and the effect of this omission is also likely to be minor. A potentially greater effect could result from the 6% of locations which have not yet been measured. These are mostly grid locations which were not initially classified as natural forest and it is likely that their carbon status differs from the national average. As measurements from these locations become available in future years, this source of error will gradually be eliminated, but our estimates could certainly have some level of bias due to the omission of such plots in the current study.

Returning to the 9% of locations that were measured in the first period but not re-measured during the second period due to budgetary constraints. We can be fairly sure that this omission could have potentially biased the overall results as the re-measurement programme during the second period was deliberately devised so that all 'shrub' plots were included in the second measurement period. Therefore, the plots that were not measured are not a random or representative sample of all locations. In practice, however, the mean carbon in plots that were only measured in the first cycle of the inventory was actually slightly higher than the average (total carbon of 232.3 tC ha^{-1} vs 226.3 tC ha^{-1}), so it is unlikely their omission would have led to a significant level of bias. However, because information from plots measured only once was utilised in our regression estimation approach, we believe that any bias arising from the omission of these plots from the second measurement cycle is likely to be minimal.

Plot-design can play a crucial role in inventory sampling. The initial design of the New Zealand natural forest (Coomes et al. 2002) critically accounts for the wider spatial distribution of large trees by including a larger sample plot (20m radius) to capture these trees accurately. While Holdaway et al. (2017) used only 20 m x 20 m plots the current analysis includes the larger 20m radius tree data to avoid a bias associated with the 20 m x 20 m square plots (Paul et al. 2019). While our estimates of the total carbon stock in natural forest are similar to that of Holdaway et al. (2014) the estimates of carbon by pool differ significantly from the Holdaway study partly due to the use of the complete nested plot. Our estimates of carbon in the AGB and BGB pools are lower and these lower estimates of AGB and BGB carbon are due to the inclusion of the larger 20m radius tree data as this eliminated the known bias caused by an over-representation of large stems in inner 20 m × 20 m plots (Paul et al. 2019).

Estimates of carbon in the below-ground dead wood pool were not provided in previous studies providing total biomass for New Zealand’s forests. Therefore our CWD estimates are higher than those of Holdaway et al. (2014) or Kimberley and Beets (2016b) as we now include below-ground CWD. More importantly, we also use an adjustment to account for a consistent tendency for CWD to be underestimated using current measurement protocols (Kimberley et al. 2019). Our estimate for Litter is also higher than estimates in Holdaway et al. (2014). The reason for this is unclear although our estimate for this pool is very similar to the original estimate of Beets et al. (2009) who first described the Litter data used in all subsequent studies.

Our approach of estimating actual carbon stock change by using the stem following method is also an improvement over methods in previous studies using the simple difference method. Simply speaking the difference method does not distinguish between the difference of an ingrowth stem meeting a measurement threshold over time and the true growth of an ingrowth stem between measurements. While the difference method estimates stock change between two measurement periods as the difference between the two calculated stocks e.g. a stem at time 2 with 2.6 cm will be assigned a zero stock at time 1 and the difference is an overpredicted stock change compared to the true carbon stock change during the time between measurements. Our stem following method provide a more precise approach avoiding such overprediction by calculating carbon stocks by summing the stock change for each individual live stem, and subtracting the Time 1 carbon for stems which died between measurements. For this method, trees measured at Time 2 which were not measured at Time 1 were always predicted using the missing value method and used in the calculation of stock change provided that the DBH at Time 2 was above the threshold. For example, if the DBH at Time 2 was 60.5 cm and the predicted DBH at Time 1 was 59 cm (in the EXT so not measured), the 59 cm was used at Time 1. Likewise, if the DBH at Time 2 was 2.6 cm and the predicted DBH was 2.3 cm at Time 1 (in the internal plot), the 2.3 cm was used at Time 1. To calculate stocks using this method, Time 2 stocks were used as the reference, and Time 1 stocks obtained by subtracting stock change calculated using the “Stem Following” method from this value which provides a better approximation of true carbon stock change than an over-prediction based on zero carbon in Time 1.

Although carbon stocks across the entire natural forest are approximately in balance, total carbon in Regenerating forest has increase by an average of 4.8 tC ha^{-1} during the study period, and there is some indication of a decline in carbon stocks in the Tall forest by an average of 0.43 tC ha^{-1} for the same period. The estimate of change for Regenerating forests is statistically highly significant, although the estimate for Tall forest is not significant at the 5% level of significance. Our estimate of the increase in carbon stocks in Regenerating forest is lower than that of Holdaway et al. (2014) (1.39 tC ha^{-1} yr^{-1}), which is largely due to the use of the revised forest type classification system of Wiser (2016). Holdaway et al. (2014) used a classification provided by Wiser et al. (2013). If the Wiser (2016) classification is applied to the Holdaway et al (2014) stock estimates, their estimate of annual change reduces to 1.1 tC ha^{-1} yr^{-1}. Holdaway et al. (2014) also included carbon calculated using the "Shrub" measurement method which we did not include in our study. Carbon estimated using the shrub method contributed 0.18 tC ha^{-1} yr^{-1} to the change between the two measurement periods for Regenerating forest. Although these two effects largely explain the difference between the overall mean estimates of carbon stock change between our study and Holdaway et al. (2014) in Regenerating forest, at the individual plot level, there were substantial differences in carbon change estimates between the two studies as a result of the error checking and correction procedures implemented in our study.

The regression models shown in Fig.2 demonstrate that the difference in carbon sequestration between Regenerating and Tall forest naturally follows from their different stages of forest development and succession. Figure 2 also shows why New Zealand's natural forests are in carbon balance. The average AGB carbon stock across all plots in the inventory is 134 tC ha^{-1} which is the level at which gain in carbon from growth of living stems is precisely in balance with the loss in carbon from mortality. This result is not a coincidence but rather, it is what is expected in a forest ecosystem not subject to major external disturbance which is therefore in a natural state of equilibrium. This result suggests that there have been no major external factors impacting on forest growth or mortality in New Zealand's natural forests over recent decades. Or, if there have been any such factors affecting the forest, there must have been an equivalent level of positive and negative effects.

Our study further refines the methods of estimating carbon in natural forest described in earlier reports. An important development is the inclusion of an estimate of carbon in below ground CWD which was not included in any earlier study, and an adjustment to allow for underestimation in the measurement of CWD carbon. Finally, the uncertainties of estimates of stocks and stock changes provided in this report now take account of both model prediction error and uncertainty associated with sampling variation between plots.

Conclusions

Natural forests overall maintain a large pool of land-based carbon but on a national level do not sequester additional carbon and therefore are not a carbon sink. The system is in “balance” at the national level with the average AGB carbon stock in Natural forests across all plots being 134 tC ha^{-1} which is the level at which growth of living stems is in balance with the loss in mortality. The presence of an equilibrium state suggests that there have not been major external factors impacting on growth or mortality over recent decades. Another explanation is that positive and negative effects from external factors occurred at the same level and therefore balancing each other out.

Viewing regenerating forests alone they have smaller total carbon pools but are sequestering carbon and can therefore be considered a carbon sink, while Tall forests with an average AGB carbon stock of 148 tC ha^{-1} is in carbon balance.

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References

Beets, P. N., M. O. Kimberley, C. J. Goulding, L. G. Garrett, G. R. Oliver, and T. S. H. Paul. 2009. Natural forest plot data analysis: Carbon stock analyses and re-measurement strategy. 43782. Scion, Rotorua, New Zealand.

Beets, P. N., M. O. Kimberley, G. R. Oliver, S. H. Pearce, J. D. Graham, and A. Brandon. 2012. Allometric Equations for Estimating Carbon Stocks in Natural Forest in New Zealand. Forests **3**:818-839.

Cochran, W. G. 1977. Sampling techniques. 3rd Edition edition. Wiley & Sons.

Coomes, D. A., R. B. Allen, N. A. Scott, C. Goulding, and P. Beets. 2002. Designing systems to monitor carbon stocks in forests and shrublands. Forest Ecology and Management **164**:89-108.

Davis, M. R., R. H. Wilde, L. G. Garrett, and G. R. Oliver. 2004. New Zealand carbon monitoring system: Soil data collection manual. Caxton Press, Christchurch, New Zealand.

Easdale, T. A., S. J. Richardson, M. Marden, J. England, J. Gayoso-Aguilar, Javier Guerra-Carcamo, J. McCarthy, K. Paul, L. Schwendenmann, and A. Brandon. submitted. Root biomass allocation in southern temperate forests. Forest Ecol Manage.

Garrett, L. G., M. O. Kimberley, G. R. Oliver, M. Parks, S. H. Pearce, P. N. Beets, and T. S. H. Paul. 2019. Decay rates of above- and below-ground coarse woody debris of common tree species in New Zealand's natural forest. Forest Ecology and Management **438**:96-102.

Holdaway, R. J., T. A. Easdale, F. E. Carswell, S. J. Richardson, D. A. Peltzer, N. W. H. Mason, A. M. Brandon, and D. A. Coomes. 2017. Nationally Representative Plot Network Reveals Contrasting Drivers of Net Biomass Change in Secondary and Old-Growth Forests. Ecosystems **20**:944-959.

Holdaway, R. J., T. A. Easdale, N. W. H. Mason, and F. Carswell. 2014. LUCAS Natural Forest Carbon Analysis. Landcare Research, Lincoln.

Intergovernmental Panel on Climate Change. 2006. 2006 IPCC guidelines for national greenhouse gas inventories. Institute for Global Environmental Strategies, Hayama, Japan.

Intergovernmental Panel on Climate Change. 2014. 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol.*in* T. Hiraishi, T. Krug, K. Tanabe, N. Srivastava, J. Baasansuren, M. Fukuda, and T. G. Troxler, editors. IPCC, Switzerland.

Kimberley, M. O., and P. N. Beets. 2016. Methods of estimating height increments in the natural forest inventory. Contract report prepared for the Ministry for the Environment by Scion. , Wellington: Ministry for the Environment.

Kimberley, M. O., P. N. Beets, and T. S. H. Paul. 2019. Comparison of measured and modelled change in coarse woody debris carbon stocks in New Zealand's natural forest. Forest Ecology and Management **434**:18-28.

Ministry for the Environment. 2018. Land Use and Carbon Analysis System: Natural Forest Data Collection Manual Version 2.8.*in* M. f. t. Environment, editor., Wellington.

Paul, T. S. H., M. O. Kimberley, and P. N. Beets. 2019. Thinking outside the square: Evidence that plot shape and layout in forest inventories can bias estimates of stand metrics. Methods in Ecology and Evolution **10**:381-388.

Payton, I. J., C. L. Newell, and P. N. Beets. 2004a. New Zealand Carbon Monitoring System: Indigenous forest and shrubland data collection manual. Caxton Press, New Zealand.

Payton, I. J., C. L. Newell, and P. N. Beets. 2004b. New Zealand carbon monitoring system: Indigenous forest and shrubland data collection manual. Ministry for the Environment, Christchurch, New Zealand.

Stats NZ. 2019. Forests and Forest Products.

Tomppo, E., T. Gschwantner, D. Lawrence, and R. E. McRoberts. 2010. National forest inventories: Pathways for common reporting. Springer, New York, NY.

Tomppo, E., T. Gschwantner, M. Lawrence, and R. E. McRoberts. 2009. National forest inventories. Business Media, Dordrecht.

Wiser, S. 2016. Vegetation classification of all measurements of the LUCAS natural forest plots. Contract report prepared for the Ministry for the Environment. . Ministry for the Environment, Wellington.

Wiser, S. K., and M. De Cáceress. 2018. New Zealand's plot-based classification of vegetation. Phytocoenologia **48**:153-161.

Appendix 1. Model prediction errors

The Intergovernmental Panel on Climate Change provides a number of rules for combining uncertainties of model predictions (Intergovernmental Panel on Climate Change 2014). These rules assume a number of quantities x_1, x_2, … have % uncertainties U_1, U_2,… Uncertainties are defined to be half the total width of the 95% confidence interval of the quantity expressed as a percentage.

If the quantities are combined by addition, i.e., $x_{total} = x_1 + x_2 + \ldots$, the rule to calculate the % uncertainty of x_{total} assuming the uncertainties are independent is:

Rule 6.3: $$U_{total} = \frac{\sqrt{(U_1 x_1)^2 + (U_2 x_2)^2 + \ldots}}{x_1 + x_2 + \ldots}$$

If the quantities are combined by multiplication, i.e., $x_{total} = x_1 \times x_2 \times \ldots$, the rule to calculate the % uncertainty of x_{total} is:

Rule 6.4: $$U_{total} = \sqrt{U_1^2 + U_2^2 + \ldots}$$

Best estimates of uncertainties were obtained for all the models used for predicting carbon as summarised in Table 1.

Table 1. Uncertainties for various models and model elements used in estimating carbon in natural forests.

	Model element	Typical value	Uncertainty (95% CI expressed as a percentage)	Source
1	Stem volume	5.59 m^3	±3.5%	95% CI of prediction from allometric regression model
2	Outerwood density	450 kg m^{-3}	±1.5%	95% CI of red beech mean OW density from density database
3	Stem density / Outerwood density ratio	0.905	±2.0%	95% CI of estimate
4	Whole stem density	450 kg m^{-3}	±2.5%	Apply Rule 6.4 to rows 2 & 3
5	Carbon fraction	0.5	±2.0%	Estimate
6	Stem carbon	1,300 kg	±4.7%	Apply Rule 6.4 to rows 1, 4 & 5
7	Branch carbon	257 kg	±16.7%	95% CI of prediction from allometric regression model
8	Foliage carbon	29 kg	±29.1%	95% CI of prediction from allometric regression model
9	AGB carbon	1,586 kg	±4.7%	Apply Rule 6.3 to rows 6, 7 & 8
10	AGB carbon per ha	134 tC ha^{-1}	±4.7%	Same as row 9
11	Change in AGB carbon per ha	0 tC ha^{-1} yr^{-1}	±4.7%	Same as row 10
12	Root/Shoot ratio	0.25	±2.0%	Estimate
13	BGB carbon	397 kg	±5.1%	Apply Rule 6.4 to rows 9 & 12
14	BGB carbon per ha	31 tC ha^{-1}	±5.1%	Same as row 13
15	Change in BGB carbon per ha	0 TC ha^{-1} yr^{-1}	±5.1%	Same as row 14
16	1+Root/Shoot ratio	1.25	±0.4%	Based on row 12
17	AGB+BGB carbon	1,983 kg	±4.7%	Apply Rule 6.4 to rows 9 & 16
18	AGB+BGB carbon per ha	165 tC ha^{-1}	±4.7%	Same as row 17
19	Change in AGB+BGB carbon per ha	0 tC ha^{-1} yr^{-1}	±4.7%	Same as row 18
20	Volume of spars & CWD pieces	1 m^3	±7%	Use twice the uncertainty of live stem volume (row 1)
21	CWD Density	450 kg m^{-3}	±5%	Use twice the uncertainty of live stem density (row 4)
22	Decay modifier	0.6	±20%	Estimate
23	Factor accounting for underestimation of CWD	1.767	±14%	Estimate based on range 1.5 to 2.0
24	AG CWD carbon	216 kg	±26%	Apply Rule 6.4 to rows 5, 20, 21, 22 & 23
25	BG CWD / AG CWD ratio	0.19	±15%	Estimate
26	BG CWD carbon	41 kg	±30%	Apply Rule 6.4 to rows 24 & 25
27	1 + BG CWD / AG CWD ratio	1.19	±2.4%	Based on row 25
28	CWD carbon	257 kg	±26%	Apply Rule 6.4 to rows 24 & 27
29	CWD carbon per ha	34 tC ha^{-1}	±26%	Same as row 28
30	Change in CWD carbon per ha	0 tC $h1^{-1}$ yr^{-1}	±26%	Same as row 29
31	Total carbon per ha in all pools excluding litter	219 tC ha^{-1}	±5.4%	Apply Rule 6.3 to rows 18, 29
32	Change in carbon per ha excluding litter	0 tC ha^{-1} yr^{-1}	±5.4%	Same as row 31
33	Litter carbon per ha	20 tC ha^{-1}	±0%	Measured directly, not modelled

Appendix 2. Regression models used in the analysis of pre-1990 natural forest.

y	x	Model	R^2
AGB1 (tC ha^{-1})	AGB2 (tC ha^{-1})	y=0.6676+0.9976*x	0.955
AGB2 (tC ha^{-1})	AGB1 (tC ha^{-1})	y=5.3713+0.9573*x	0.955
BGB1 (tC ha^{-1})	BGB2 (tC ha^{-1})	y=0.1560+0.9978*x	0.955
BGB2 (tC ha^{-1})	BGB1 (tC ha^{-1})	y=1.2499+0.9575*x	0.955
CWD1 (tC ha^{-1})	CWD2 (tC ha^{-1})	y=4.5263+0.8816*x	0.767
CWD2 (tC ha^{-1})	CWD1 (tC ha^{-1})	y=5.4053+0.8698*x	0.767
AGB1+BGB1+CWD1 (tC ha^{-1})	AGB2+BGB2+CWD2 (tC ha^{-1})	y=-0.0889+1.0006*x	0.966
AGB2+BGB2+CWD2 (tC ha^{-1})	AGB1+BGB1+CWD1 (tC ha^{-1})	y=6.9065+0.9653*x	0.966
Litter (tC ha^{-1})	AGB1 (tC ha^{-1})	$y=3.2722+0.1812*x-00002609*x^2$	0.080
AGB2-AGB1	AGB1	$y=4.9629*\ln(x+1)-1.0231*\ln(x+1)^2$	0.031
BGB2-BGB1	BGB1	$y=1.3552*\ln(x+1)-0.3907*\ln(x+1)^2$	0.033
CWD2-CWD1	CWD1	$y=7.6467*\ln(x+1)-2.0380*\ln(x+1)^2$	0.073
(AGB2+BGB2+CWD2)- (AGB1+BGB1+CWD1)	AGB1+BGB1+CWD1	$y=5.4427*\ln(x+1)-1.0253*\ln(x+1)^2$	0.023