# Carbon stock changes in New Zealand's pre-1990 planted forests based on a periodic ground inventory

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## REPORT INFORMATION SHEET

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# EXECUTIVE SUMMARY

## Objectives

The Objective of this study was to analyse pre-1990 planted forest data collected in New Zealand in 2010 and 2015, and provide the Ministry for the Environment with a precise estimate of carbon sequestration per hectare over the 2010-2015 period and a net-stocked area based national carbon yield table. The use of a double sampling approach based on LiDAR only plots to improve the representativeness of the yield table was also undertaken.

## Key Results

With the completion of the first re-measurement of the pre-1990 planted forest inventory in October 2015, New Zealand now has data to estimate carbon stocks and sequestration rates for a five-year period. A total of 202 plots (including three abandoned sites treated as non-stocked plots; five with multiple croptypes, three in riparian zones, three in native vegetation, two in pasture, two across roads, two in wilding pines and two that could not be processed) on an 8 km square grid were mapped as pre-1990 planted forest and measured twice. 187 plots were included in the analysis of crop-related carbon stock calculations on stocked land. 160 plots were used to construct the national yield table as plots too young or recently harvested were excluded.

Plot data were checked and imported into the permanent sample plot system at Scion, which allows the checking and tracking of tree growth over multiple measurements. Once the data were checked and corrected, they were processed using the Forest Carbon Predictor (FCP Version 4.12).

To make use of all measured plots to create a general national pre-1990 planted forest yield table in the inventory we used a double sampling approach that enabled us to use both remeasured plots and those measured only once due to their recent harvest or recent planting.

Pre-1990 planted forests are estimated to have lost -8.32 t C/ha during the period 2010 – 2015 (Table 1) indicating a period where pre-1990 planted forests showed a carbon loss. The loss in carbon occurred mainly in the AGB (-11.31 t C/ha) and BGB (-2.39 t C/ha) pools. The slight increase in dead wood (3.25 t C/ha) and the Litter pool (2.13 t C/ha) counteracted the loss to some extent (Table 1).

**Table 1:** Total carbon stocks and sequestration (t/ha) by pool in New Zealand pre-1990 planted forest based on 2015 measurement (crop-carbon).

| Component | Carbon stocks 1st Jan 2010 | | Carbon stocks 31st Dec 2014 | | Carbon sequestration 2010-2014 | |
|---|---|---|---|---|---|---|
| | Estimate C t/ha | 95% CI | Estimate C t/ha | 95% CI | Estimate ΔC t/ha | 95% CI |
| Total | 139.04 | ±11.3 | 130.72 | ±11.4 | -8.32 | ±11.1 |
| AGB | 80.49 | ±11.2 | 69.17 | ±11.0 | -11.31 | ±13.1 |
| BGB | 17.21 | ±2.4 | 14.82 | ±2.4 | -2.39 | ±2.8 |
| DW | 23.29 | ±3.4 | 26.55 | ±3.6 | 3.25 | ±4.7 |
| Litter | 18.06 | ±1.8 | 20.18 | ±1.9 | 2.13 | ±2.4 |

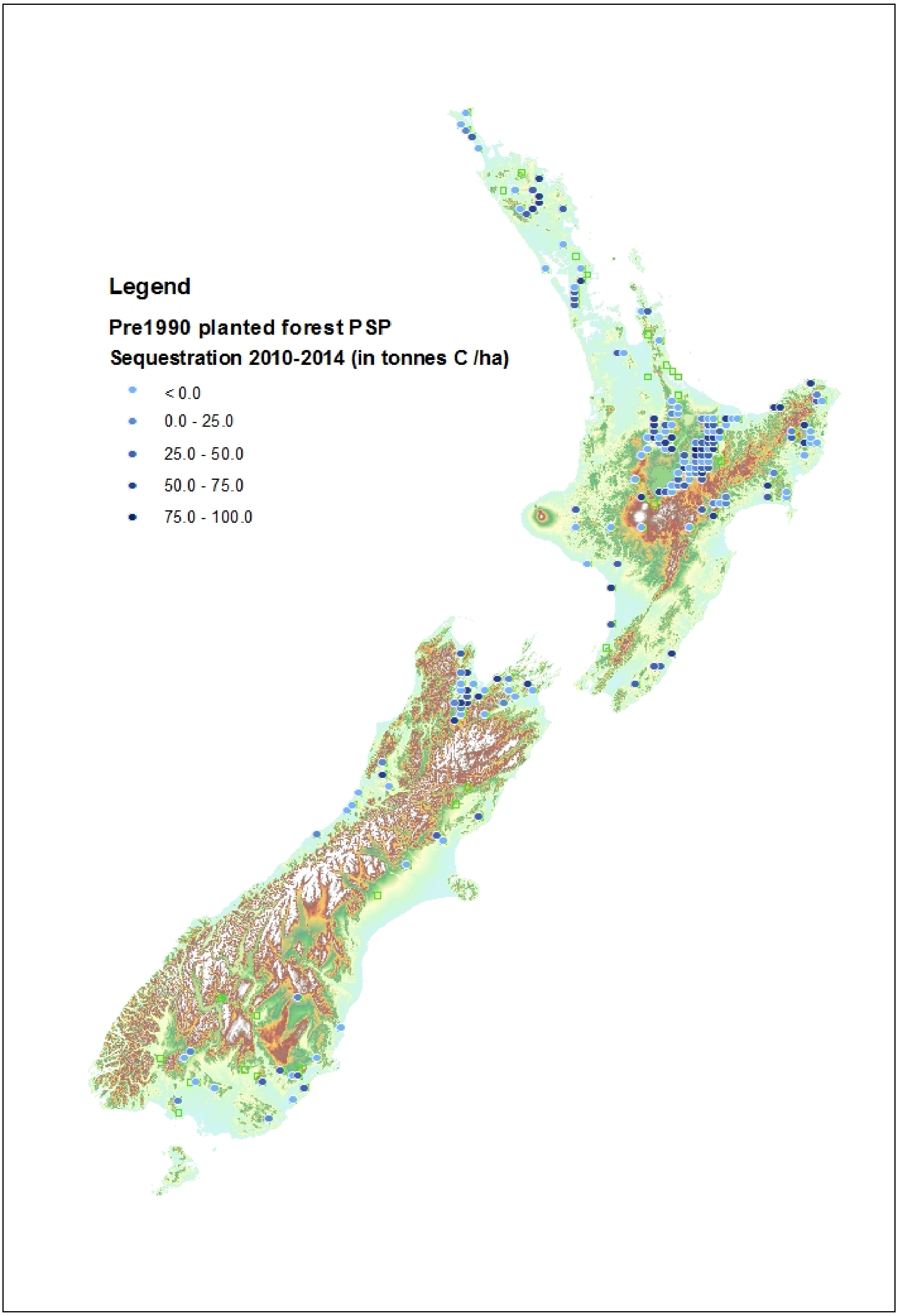
The development of a LiDAR-adjusted yield table used a new and improved method to include LiDAR-only plots. This created a pre-1990 yield table utilizing roughly twice the number of LiDAR-only plots than if solely ground-only plots were included. The yield table was adjusted upward by 1.18% based on this double sampling approach.

## Conclusions and further work

This report provides the first estimate of carbon sequestration in New Zealand's pre-1990 planted forests based on two consecutive and complete ground inventory plot datasets. Previous estimates were based on projections made from the a single measurements in 2010. By providing the associated yield table for pre-1990 planted forests this work contributes to New Zealand's ability to meet its international reporting requirements.

With the development of the ground based inventory designed for periodic re-measurements, New Zealand now has a system in place comparable to other countries with extensive forest inventories. In addition to carbon reporting, this will provide additional information on the state of New Zealand's plantation forests for other national and international reporting requirements such as national environmental reporting or Montreal process reporting.

**Map 1:** Locations of all pre-1990 planted forest plots across New Zealand



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# Introduction

New Zealand is a signatory to the Kyoto Protocol and the United Nations Framework Convention on Climate Change (UNFCCC). It has taken an unconditional target under the UNFCCC to reduce emissions to 5 per cent below 1990 levels over the period between 2013 and 2020. New Zealand prepares an annual inventory report of its greenhouse gases for reporting under the UNFCCC and the Kyoto Protocol (e.g. Anon 2016). New Zealand's gross greenhouse gas emissions (excluding emissions and removals from forests) had increased from 1990 levels by 15,276 kt CO2-e (23.2 per cent) in 2014 (Anon 2016). The main contributors to this increase in emissions were road transport, manufacturing and construction, and enteric fermentation in the agriculture sector. New Zealand will apply Kyoto Protocol rules in accounting for its 2020 target. Under these rules carbon units are issued or cancelled for the net change in carbon stocks that occurs through direct human-induced activities arising from afforestation, reforestation and deforestation (Anon 2016). For the 2013-2020 period, it is now mandatory to also include activities covered under forest management (which includes the management of forests established prior to 1990) under the Kyoto Protocol. New Zealand will account for these forests against a forest management reference level where a departure from a business-as-usual projection results in a credit (which is capped at 3.5% of base year emissions) or a liability (which is unlimited) (Anon 2016). Tracking carbon stock change in all forests is expected to be an important part of New Zealand's post-2020 agreement.

To estimate carbon stocks and stock changes in its pre-1990 planted forest, New Zealand has implemented its Land Use and Carbon Accounting System (LUCAS), managed by the Ministry for the Environment. The forest area is defined by a GIS-based, wall-to-wall map created using historical aerial photographs and satellite images. Mean per hectare carbon stocks and sequestration in the pre-1990 planted forests are estimated by using a double sampling approach in a network of ground-based permanent sample plots measured in 2010 and 2015. This allowed the calculation of carbon at both times (phase 1) or only once (phase 2) in cases where plots were at a very young age or they were an addition in 2015. At the start of the development of LUCAS, no formal ongoing national forest inventory (NFI) that completely covered the total New Zealand's forest area existed (Beets *et al* 2010). A voluntary annual postal survey of the larger planted forest owners is carried out by the Ministry for Primary Industries that collates information on planted forest areas by age classes in a National Exotic Forest Description (NEFD), Anon (2015b). Periodically, yield tables (merchantable volume by age) are derived for the major production tree species and silvicultural regime combinations by surveying the corporate forest owners who manage approximately two thirds of the total area. The accuracy of the results of these surveys is weakest for the non-professionally managed small forests and woodlots that comprise the bulk of the post-1989 planted forests, and the survey would not meet the IPCC guidelines ( for reporting under the Kyoto Protocol (IPCC 2003; IPCC 2013). For pre-1990 planted forests good NEFD data is present. However an independent national assessment of carbon stocks and their change over time will avoid any potential bias or data issues that might arise from the multitude of datasets that are usually collated from various forest owners and management companies under the survey frame of the NEFD.

Under the Kyoto Protocol, the carbon stock changes for LULUCF activities need to be estimated in an unbiased, transparent, and consistent manner, where uncertainties are determined and reduced over time (IPCC 2003, IPCC 2013). Net carbon stock change in the pre-1990 planted forests over the period 1st Jan 2010 to 30th Dec 2014 is described in this report. Ongoing improvements to the inventory reporting, as required under the Kyoto Protocol, imply that all inventory data is subject to change and this report compares the current estimates with previous estimates based on the first CP period as a reference period. The report describes the large-scale national pre-1990 planted forest inventory system based on current ground plots and the calculation of carbon stock changes. It presents estimates of per hectare carbon stocks for 2010 and 2014 and the carbon sequestration rate per hectare during this time period. All plots represent the current spatial extension of pre-1990 planted forests estimated by the Ministry for the Environment (Anon. 2016b). Mapping procedures used to determine the pre-1990 planted forest area in New Zealand or the estimation of soil carbon are not covered and beyond the scope of this report as this work has been undertaken separately.

The report also describes the creation of a national average yield table based on the inventory data. This yield table is currently used to estimate carbon stock changes in planted forests over time and is a critical input to the LUCAS Calculation and Reporting Application. A double sampling approach is used to create an adjusted yield table based on individual plot yield tables calculated from one or two measurements, through area based (net stocked) weighting. In addition LiDAR only plots were used to adjust the national yield table based on the relationship between LiDAR metrics and carbon stocks at each age.

# Materials and Methods

Under the Kyoto Protocol, New Zealand has defined its forests as vegetation having the ability to attain at least 5 m in height *in situ* with at least 30% canopy cover on a minimum area of 1 ha and a width greater than 30 m. Urban trees, shelterbelts, orchards and horticultural trees are not included in the forest definition.

Five carbon pools and their change must be reported for the pre-1990 planted forests:

- Above-ground live biomass (AGB), living stems, branches, foliage,
- Below-ground live biomass (BGL), living roots,
- Dead wood (DW) not contained in the litter, either standing, lying on the ground, or in the soil,
- Litter (Fine Litter, FL) litter, fumic, and humic layers ,
- Soil organic carbon to a specified depth.

The soil organic carbon pool is currently estimated by a separate, independent system within LUCAS. To estimate carbon stocks per hectare in the other four pools, trees and stand parameters are measured in the ground plot network. The data are processed using a forest carbon modelling system called the Forest Carbon Predictor (FCP Version 4.12). The first measurement of permanent sample plots in pre-1990 planted forest was carried out during the winter of 2010 with the original objectives of estimating carbon stocks for deforestation under the Kyoto Protocol and stock change from 1990 for UNFCCC reporting. Re-measurement of these plots and the additional plots recently identified from completed forest mapping was carried out during the winter of 2015. The objectives have been expanded for the re-measure as under the Kyoto Protocol the reporting of forest management is now mandatory from 2013-2020. New Zealand has chosen to report on forest management against a projected business-as-usual forest management reference level for the period. As further explained below, a double sampling approach using a ratio estimator was used to combine both the re-measured plots and plots with only one measurement.

## Sampling design

New Zealand's pre-1990 planted forests are scattered over a total land area of 27 million hectares and a North to South distance of 1600 km. They make up a small proportion of the total land area (less than 6%). Due to the highly scattered and fragmented spatial distribution of these forests the logistics and the positioning of plots requires a significant amount of time. As *Pinus radiata (D.Don.)* responds vigorously to the absence of side competition, with increased stem diameter growth, large branch and crown development and poor stem-form, boundary effects are important. The sampling was therefore designed on the basis of using hidden permanent plots that would include edge situations (Bechtold and Patterson, 2005, Hahn *et al*. 1995, Scott 1993, Van Deusen, 2004). The field procedures were refined over time to improve the sampling efficiency of the inventory. The use of permanent sampling plots provides easily usable trend data and is a recognised way to gather valuable data for objectives often not anticipated at an earlier stage in research and policy (Bakker *et al.* 1996, Coomes *et al.* 2002, Köhl and Scott, 2000, Overton and Stehman, 1996). The plots were "hidden", with a buried centre post and temporary tree markings used, to avoid any subsequent operational treatments that differed from the surrounding stand. The chosen plot size of 0.06 ha is a compromise between the most efficient plot size for ground measurements and "usability" in a double sampling approach using LiDAR.

To sample pre-1990 planted forests representatively across the country an 8km x 8km sample grid (Origin: NZTM coordinates 1066468E and 4730785N) was employed. The chosen grid density was assumed to provide a sufficient number of ground plots to reach an acceptable sampling PLE for the estimation of carbon stocks.

## Field procedures

Field protocols for the plot measurements are described in detail in Herries *et al*. (2012). Where applicable, the plot diameter was adjusted to give the required horizontal area on sloping land. The distance and bearing from the plot centre to each stem located within the radius of the circular plot were measured to enable relocation on remeasure. An "accounting method" was used for the estimation of woody debris originating from within the plot to account for stems that had fallen partially outside the plot boundary (e.g. as a result of a thinning operation). Woody debris that had fallen inside the plot that were clearly identified as originating from trees outside the plot boundary were excluded. In later inventory years, this procedure was simplified to recording stump diameters and stump counts to estimate thinning residues originating from within the plot (described further below).

Within a plot, all trees greater than 2.5 cm diameter at breast height (DBH)[1] were identified by species and their DBH measured. The heights of up to 16 trees per species were measured with a vertex hypsometer, sufficient to construct plot-specific height/DBH functions. Pruned height, the height from ground to the point on the stem of the lowest remaining branch, was measured on the sub-sample of the trees measured for height in the 2010 inventory and recorded as a pruning class for the remainder of the trees in a plot. During the 2015 inventory pruned heights were measured for all trees. Felled trees either from non-commercial thinning operations ("thinning to waste") or from production thinnings (stems removed from the stand) were captured via stump counts and stump diameter measurements related to each identified thinning event, whose year of occurrence was estimated via tree ring counts or company records. The number of felled trees was used in combination with standing live trees and management records to estimate the initial stocking at time of planting and the timing and intensity of past pruning and thinning operations. Needle retention, defined as the average of the number of needle age classes remaining on the height sample trees, was assessed in the 2010 inventory for *P. radiata* only and in the 2015 inventory for *P. radiata* and *Pseudotsuga menziesii (Mirb.)Franco* the second most common plantation tree species in New Zealand. The dead wood and fine litter carbon pools were calculated from the summarized plot tree data and the events responsible for increases in these pools (e.g. thinning and pruning events) via a partitioning routine in FCP Version 4.12.

Twenty soil samples were taken from the upper 5 cm of the mineral soil in each plot and bulked to determine carbon and nitrogen concentrations (g/100 g soil) in the laboratory. This estimate of soil carbon/nitrogen ratio was used as a measure of site fertility and as a variable to estimate stem wood density in each plot.

Native and exotic shrubs and trees in the under-storey or in canopy gaps within the forest were measured if their stems were greater than 2.5 cm DBH and sampled for height as described above for crop trees.

## Carbon stock calculations for planted trees

Plot data were checked and imported into the permanent sample plot (PSP) system at Scion, that allows the checking and tracking of tree growth over multiple measurements (see appendix for detailed corrections).

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[1] In New Zealand, the breast height of exotic planted trees is defined as 1.4 m above firm ground, after vegetation has been removed, on the uphill side of the stem when on sloping terrain, Goulding (2005).

Carbon stocks in the live and dead pools of the planted trees (excluding soil organic carbon and under-storey vegetation) were estimated from the plot measurements using the validated FCP Version 4.12 (Beets *et al.* 2011). This system provides estimates of carbon in the above-ground live biomass, below-ground live biomass, dead wood and litter pools from the plot data at the time of measurement and predictions at other ages over multiple rotations. The system has been recently upgraded to the 4.12 version as part of a long term research programme, and now includes routines for *Ps. menziesii* (the 500 Index model, Knowles 2005) and adjustment factors accounting for different species dependent wood densities (e.g., *Ps. menziesii*). The system integrates:

- the 300 Index Growth Model for *P. radiata*, and the 500 Index Growth Model for *Ps. menziesii*
- stem wood density models for *P. radiata* and *Ps. menziesii*, and
- the C_Change compartment model.

The 300 Index Growth Model (Kimberley *et al.*, 2005) and 500 Index Model both predict the total volume under bark in live and dead stems for each age from the time of planting to harvest age. The models are conditioned in such a way that the estimates of basal area and mean top height are the same as the estimates made at the time of the plot measurement using the standard mensuration methods in New Zealand (Gordon and van der Colff, 2005, Goulding, 2005). The predicted volumes at any age take into account the silvicultural history of the stand (initial stocking and the timing and intensity of pruning, thinning and harvesting operations). Both models have been extensively validated for operational use by the New Zealand forest industry and by research cooperatives.

For *P. radiata*, the oven-dry wood density of annual growth sheaths of the stem is estimated using a wood density model (Beets *et al*., 2007a). This model is a function of the carbon/nitrogen ratio in the top 5cm of mineral soil (a surrogate for fertility) obtained from the soil samples taken at each measurement site, the mean annual air temperature obtained from climate surfaces and the stocking over time estimated by the growth model. Annual total stem volume under bark increment calculated by the 300 Index model is multiplied by the wood density of annual growth increments to predict the annual increments in stem wood dry matter from time of planting. A similar model has recently been developed for *Ps. menziesii* and is included in FCP Version 4.12.

The C_Change model uses the predicted increment in stem wood dry matter to estimate dry matter increment in stem bark, branches, reproductive parts and needles using tree age-specific increment partitioning factors given in Beets *et al.*, (1999) based on earlier work by Madgwick *et al.* (1977); Beets and Pollock (1987) and Beets and Whitehead (1996).

The predicted dry matter partitioned to component Y at stand age t is given by

(1) $Y(t) = (A-D)/(1.0+(t/C)^{B}) + D$

where coefficients A, B, C and D are specific to the four components of needles, stemwood plus bark, stemwood and reproductive parts.

Allocation of dry matter to branches is by difference (i.e., total above-ground production minus needle, stem, and reproductive growth). Coarse and fine (< 2mm diameter) root increments are estimated using increment expansion factors based on root/shoot biomass ratios in Beets *et al.*, (2007b). The model estimates the allocation of dry matter into the needle litter from the live crown biomass using the estimates of needle retention made by the field crews at the time of measurement. Changes in live biomass and dead organic matter pools due to annual tree growth and mortality, including natural stem and crown mortality and as a result of silvicultural activities are determined by historical silvicultural information, field measurements and observations, and the yield predictions from the 300 Index model. Losses of dry matter from dead organic matter pools due to decay are estimated using temperature dependent decay functions for dead wood and litter (Garrett *et al.* 2010). Biomass extracted off-site following harvest operations is based on merchantability parameters (70% of total stem volume following production thinning and 85% of total stem volume following clearfelling), and is treated as an instant emission. Residues are decayed using component-specific decay functions (Garrett *et al.* 2010). Dry matter is converted to carbon currently using a country specific conversion factor of 0.50, which is currently under review. The system reports carbon stocks in above ground live biomass, below ground live biomass, dead wood, and litter pools from the planted trees over multiple rotations, with pools defined as:

- Above-ground live biomass: includes living stems, live and attached dead branches, cones, needles;
- Below-ground live biomass: includes living fine and coarse roots;

- Dead wood: includes total standing dead stems and logs lying on the ground (no minimum diameter limit), and dead coarse roots;
- Litter: includes needle and branch litter and cones on the ground at various stages of decomposition (dead fine roots are assumed to be measured as part of the soil organic matter pool).

## Carbon stocks for non-planted shrubs and trees

The carbon stocks in large shrubs and naturally regenerated ("non-crop") native or exotic trees with a stem DBH ≥ 2.5cm, and their associated dead organic matter, were estimated using allometric equations based on the DBH and height of the individual plant. Within each ground plot a sample of heights was taken in order to develop coefficients for a height / DBH function for use on stems with only a DBH measurement. Height measurements for species other than tree ferns were plotted against DBH by species to check for errors and outliers. A total of 5003 shrubs and trees from the 2015 inventory period with both height and DBH measurements were used to develop species- and plot-specific height diameter functions.

The following height function performed best

(2) $H = 1.4 + \exp\left(a + bD^{c}\right)$

Where: $H$ is height (m),
$D$ is DBH (cm)
$a$ = intercept parameter
$b$ = slope parameter
$c$ = -0.3

This function can be converted into a linear form by log-transforming both sides of the equation. When this linearized form was fitted to the data as a regression model, tests showed that both the intercept parameter (*a*) and the slope parameter (*b*) varied significantly between both plots and species. This suggests that ideally, separate regressions should be fitted for each species within a plot. However, sample sizes of individual species within a typical plot are generally too small to allow this approach to be followed. It was therefore decided to adopt a two-step approach. Firstly, parameter adjustments for each species were incorporated into Model (3) based on an analysis of the entire dataset. Secondly, to predict heights within an individual plot, the height measurements were transformed using these species-level adjustments enabling the model to be fitted as a simple linear regression to the height measurements in the plot. This model was used to predict heights of all trees and shrubs in the plot.

To obtain species-specific parameter adjustments, the following form of the model was fitted using height and DBH measurements of all the live, non-leaning trees and shrubs in the dataset excluding tree ferns and vines:

$$(3) \quad \ln\left(H_{ij} - 1.4\right) = a + a_i + \left(b + b_i\right)D^{-0.3} + e_{ij}$$

where $H_{ij}$ and $D_{ij}$ are height and diameter of the j$^{\text{th}}$ tree or shrub of the i$^{\text{th}}$ species, $a$ and $b$ are global parameters, $a_i$ and $b_i$ are species-specific adjustments fitted as random effects, and $e_{ij}$ is a random error term. This model was fitted as a random coefficient model using the SAS Version 9.2 MIXED procedure. For simplicity, plot effects were not included in this model.

To apply the model to a particular plot, the following procedure is used:

1. All height measurements of live, non-leaning trees and shrubs are transformed using $y_{ij} = \ln\left(H_{ij} - 1.4 - a_i - b_i D_{ij}^{-0.3}\right)$, where $y_{ij}$ is the transformed value and $H_{ij}$ and $D_{ij}$ are height and diameter of the $j^{\text{th}}$ tree or shrub of the $i^{\text{th}}$ species in the plot, and where $a_i$ and $b_j$ are the tabulated adjustments for the $i^{\text{th}}$ species. This transformation brings heights of all species onto a common diameter relationship.
2. A linear regression between $y_{ij}$ and $D_{ij}^{-0.3}$ is then fitted for the plot, and predicted values $\hat{y}$ of $y$ obtained from this regression for all trees and shrubs not measured for height, and for leaning trees.
3. The transformation is then reversed to provide predictions of $H$-1.4 using $\exp\left(\hat{y}\right) + a_i + b_i D^{-0.3}$.
4. Finally, because the back-transformed estimates are generally biased, a bias-correction procedure is applied. To obtain this correction, the ratio $R = mean\left(H - 1.4\right) / mean\left(\exp\left(\hat{y}\right) + a_i + b_i D^{-0.3}\right)$ is calculated using the trees and shrubs measured for height. The ratio $R$ is used to correct for bias, with the final predicted height being $\hat{H} = 1.4 + R\left(\exp\left(\hat{y}\right) + a_i + b_i D^{-0.3}\right)$. Individual values of $R$ are calculated for each species with 3 or more height measurements in the plot. For species with fewer than 3 height measurements, the mean value of $R$ across all species is used.

Stem volume including bark ($V_{stem}$, m$^3$) of all species except tree-ferns was calculated from an allometric equation derived from the DBH, height and stem sectional measurements of 141 native trees of a range of species, found in Beets *et al.* (2009):

(4) $$V_{stem} = 4.83 \times 10^{-5} (D^2 H)^{0.978}$$

Stem carbon ($C_{stem}$, kg) was estimated from volume and stem-wood density, assuming that carbon comprises half of the dry biomass:

(5) $$C_{stem} = W_{stem} \times V_{stem} / 2$$

where $W_{stem}$ (kg m$^{-3}$) is whole-stem, dry-matter wood-density, tabulated by species. For species with no tabulated wood-density, mean wood-density of the genus, or failing that, of the plant type was used.

Carbon (kg) contained in branches ($C_{branch}$) and foliage ($C_{foliage}$) was estimated from DBH (cm) using the equations of Beets *et al*. (2009):

(6) $$C_{branch} = 0.0175 \times D^{2.2}$$

(7) $$C_{foliage} = 0.0171 \times D^{1.75}$$

These estimates were combined to calculate total above ground carbon:

(8) $$C_{live} = C_{stem} + C_{branch} + C_{foliage}$$

Tree fern species show no reliable height/DBH relationship. The average height of individuals measured for height was calculated by species and plot, and carbon estimated from DBH (cm) and height (m). Differences between species functions were statistically significant, but these were small and resulted from stem density differences. The fibrous nature of tree ferns prevents the use of cores. Above ground carbon of the stem and the fronds was therefore estimated from a single equation for all species, found in Beets *et al.* (2009)

(9) $$C_{treefern} = 0.00270 \times (D^2 H)^{1.19}$$

The carbon estimates were summed for all live plants in the plot and the above ground live carbon stock (t/ha) expressed on a unit area basis using the appropriate plot area. Where the plant was dead, the stem carbon was estimated as for live stems and then modified by a multiplier specific to the decay class recorded in the field (Table 2). The branch and foliage carbon in dead trees were assumed to be zero.

**Table 2:** Decay classes and corresponding multipliers for estimating carbon in dead shrubs and non-crop trees

| Planted forest decay class | Multiplier (unknown species) |
|---|---|
| 1 | 1 |
| 2 | 0.82 |
| 3 | 0.66 |
| 4 | 0.47 |
| 5 | Fully decayed |

## Carbon sequestration rates for planted trees

For plots established and measured in 2010 and again in 2015, estimates of carbon stocks in planted trees as at 1st of January 2010 (estimated from the first measurement and corrections of previous errors) and 31st of December 2014 (estimated from the later measurement) could be obtained using FCP Version 4.12. As these estimates required only minimal back-casting of 0.5 years with known history[2] from the measurement date using the FCP models, we can assume they closely represent the true stocks at the beginning and end of this period. We therefore refer to sequestration calculated from these stocks as 'actual' sequestration. However, for plots with only one set of tree data present that allows carbon modelling (e.g. too young in 2010, harvested in 2015 or new plot in 2015) sequestration was estimated using the FCP predicted stocks only with one measurement. For replanted or harvested plots we used the harvested stand age to calculate any remaining carbon stocks.

The basic double sampling ratio estimator was used to account for 'partial plots' in the inventory, i.e., plots which straddled a mapped boundary and which were therefore smaller in area than complete 0.06 ha circular plots. As described in earlier reports, in inventories containing partial plots, the per hectare sequestration is best estimated by dividing the sequestration totalled across all plots by the total area of all plots.

The ratio estimator that achieves this is given by:

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[2] Forecasting is much more uncertain as future management events are not known.

(1) $$R = \frac{\sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i}$$

Where:

*R* is the ratio estimate of mean carbon per hectare
$y_i$ is the carbon stock in all plots for site *i* in tonnes
$x_i$ is the mapped area of post-1989 forest for all plots on a site *i* in hectares
*n* is the number of sites (plots summed at the site level to account for the dependency between plots on a site)

An estimate of the variance of this estimator is as follows:

(2) $$V(R) = \frac{1}{n(n-1)\left(\sum_{i=1}^{n} x_i / n\right)^2}\left(\sum_{i=1}^{n} y_i^2 + R^2\sum_{i=1}^{n} x_i^2 - 2R\sum_{i=1}^{n} y_i x_i\right)$$

## Yield table estimation based on two measurements

Yield tables were constructed for the net stocked area of pre-1990 planted forest. The plots used in this analysis were the same as those used to estimate carbon sequestration, with the exception that plots that had been recently harvested or planted were excluded as it was considered that these plots provided no useful data for developing yield tables.

The procedure for obtaining yield tables is described as follows. Firstly, yield tables were generated for each plot and measurement using FCP 4.12. These tables consisted of annual estimates of carbon per-hectare in the planted trees for each pool. Where more than one crop was measured in a plot, FCP was run separately for each crop, and the summed carbon values across all crops obtained for each age.

For plots measured twice (n = 127), there were two yield tables, one based on each measurement. A single 'best' yield table estimate was constructed for each plot using the following procedure:

- For ages less than the first measurement age, the yield table derived from the first measurement was used: $y_{best}=y_1$, where $y_1$ is yield based on the first measurement.
- For ages greater than the second measurement age, the yield table derived from the second measurement was used: $y_{best}=y_2$, where $y_2$ is yield based on the second measurement.

- For ages between the first and second measurement, an interpolated value was calculated from the two tables: $y_{best}=y_1\times(t-t_1)/(t_2-t_1)+y_2\times(t_2-t)/(t_2-t_1)$, where $t$ is age, and $t_1$ and $t_2$ are ages of first and second measurements.

Ratio estimators were used to obtain yield tables for the "Measured Twice" stratum. For each plot and age, carbon per plot (tonnes) was calculated by multiplying carbon per-hectare by net stocked area. Using the twice measured plots, the following ratio was used to correct for possible bias: $R_1=\Sigma y_{best}/\Sigma y_1$. A second ratio was then calculated using all plots (e.g. those with one measurement) $R_2=\Sigma y_1/\Sigma plotarea$, where *plotarea* is the net stocked area of the plot. The ratio estimator was calculated as the product $R_1\times R_2$. This procedure was similar to that used for estimating sequestration as described in the previous section.

The procedure for obtaining yield tables for those plots only measured once was identical to those used in the "Measured Twice" stratum except that $y_2$ was substituted for $y_1$ in the calculations of $R_1$ and $R_2$. $R_1$ was calculated using plots measured twice, which assumes that the correction for possible bias was the same in both strata, and the summation used in $R_2$ was over the "Measured Once" stratum.

## Lidar used for data verification

LiDAR height measurements are expected to be highly correlated with ground measurements of tree height. This means that the LiDAR data can be used to verify the ground data and vice-versa. However, we identified 21 plots where the LiDAR height metrics were incompatible with ground height measurements. These plots had LiDAR characteristics of a harvested site with very low percentages of returns above 0.5 but ground measurements described tall high volume forest stands. These plots were at this stage excluded from the subsequent analysis. After excluding these outliers, the R2 for a regression between the LiDAR metric, P95ht, and mean top height (MTH) calculated from ground measurements was 99% (Figure 1).

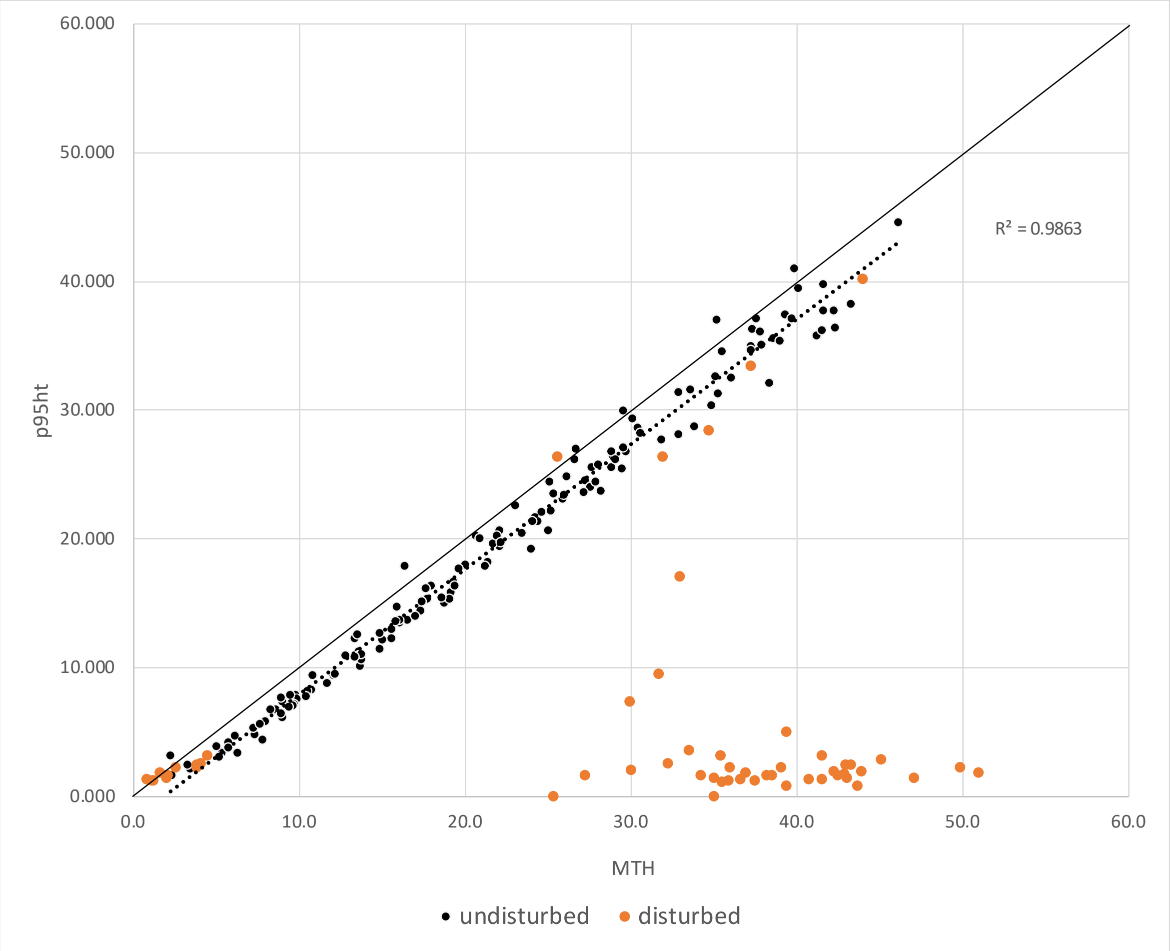

**Figure 1:** Relationship between MTH (ground plot assessment) and p95ht for 2015 measured plots, sites disturbed are shown in orange and were not included in regression. (n = 194)

## LiDAR adjustment for net-stocked area carbon yield table

LiDAR plots have previously been used to improve estimates of carbon stocks in forest inventories using double sampling designs. The pre-1990 inventory is such a design, consisting of Phase 1 plots located on an 8-km grid in which both ground measurements and LiDAR data were collected, and Phase 2 plots spaced at 1 km intervals along 8-km-long North-South transects centred on each Phase 1 plot, with LiDAR data only collected from these Phase 2 plots. The design is described fully in Beets et al. (2012).

When predicting carbon stocks via double sampling forest inventories, regression models are derived from the Phase 1 plots for predicting carbon stocks from LiDAR metrics, and these are used to predict carbon in the Phase 2 plots, thus improving the precision of the carbon estimates obtained from the inventory due to the usually far greater sample number compared to ground-plot only inventories. Typically, regression models used for predicting carbon stocks have $R^2$ values in the range 0.7-0.8, and can thus achieve good improvements in precision of carbon stock estimates.

However, the current analysis is concerned not with estimating carbon stocks at a given point in time but rather with the development of an average yield table providing carbon stocks annually by age within the pre-1990 forest. In isolation, LiDAR metrics would provide little information for predicting carbon yield at a given age. However, if the age of a LiDAR plot is known, the LiDAR metrics can potentially provide useful information on the rate of carbon sequestration, and thus be used to improve the yield table. Therefore, in the current study, the ages of Phase 2 plots were obtained from forest stand record systems. This meant that the LiDAR metrics from the Phase 2 plots could be used to adjust the yield table derived from the Phase 1 ground plots.

Unfortunately stand age could not be established for all known Phase 2 plots, and some ages proved to be unreliable when we assessed the dataset (Figure 2). As mentioned a rigorous checking procedure was followed to eliminate plots with unreliable ages based on LiDAR estimated heights and provided stand ages. Furthermore, as also described above, not all Phase 1 plots were suitable for developing the yield table due to recent harvesting or for other reasons. The procedure adopted in this study required that Phase 2 plots could only be used when their associated Phase 1 plot (i.e., the centre plot of the 8-km transect) was used in developing the yield table. In all, 143 Phase 1 plots were used in the analysis. The two end plots in each transect (if they existed) straddled adjacent transects, and were assigned a weighting of 0.5. Counting these end plots as half plots, 351 Phase 2 plots with reliable ages were available for the analysis.

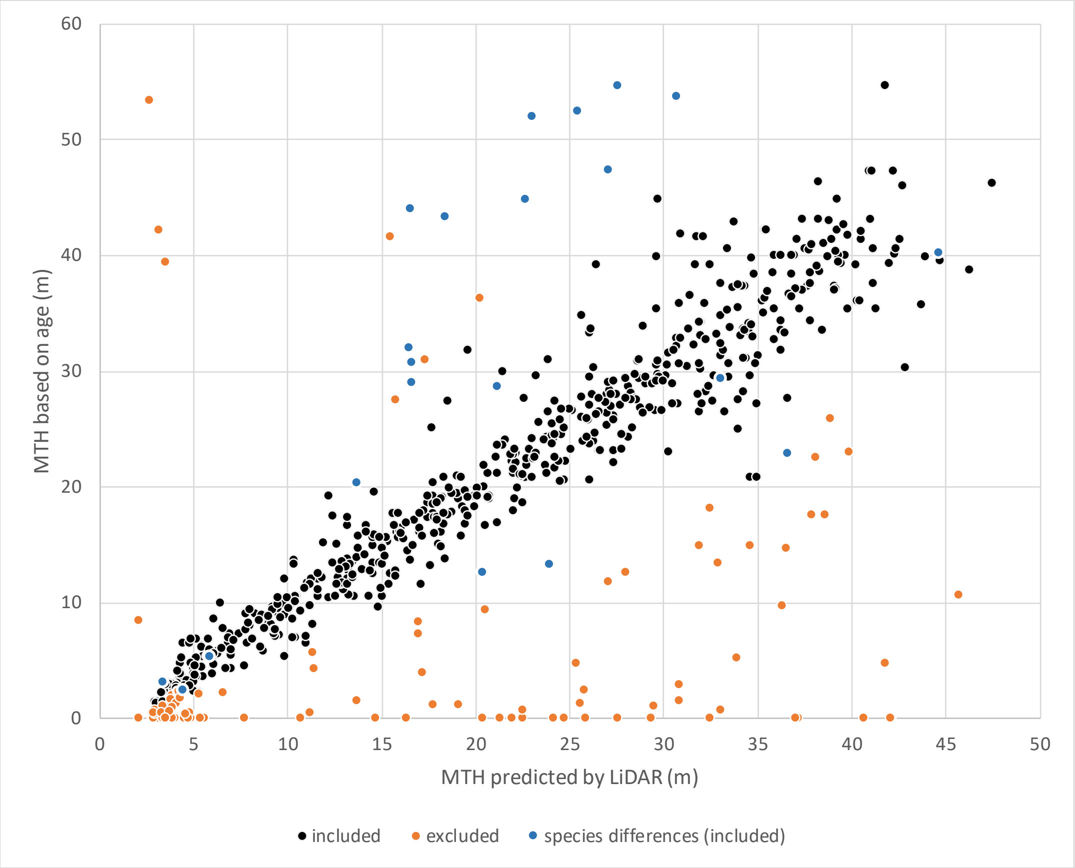

**Figure 2:** Lidar-only plots (Phase 2) and their estimated height based on age (y-axis) versus the LiDAR height (P59ht; x-axis). Obvious outliers (not included) had wrong ages assigned.

The following approach was used. For each Phase 1 plot, total carbon at age 20 years was obtained from the FCP yield table predicted from the 2015 measurement for that plot. A regression model was then fitted to the Phase 1 plots using the SAS version 9.3 GLM procedure. Age-20 carbon was used as the dependent variable, and LiDAR metrics along with stand age as the independent variables. Various models were tested using correlation analysis to identify the most promising LiDAR metrics. Quadratic and interaction terms of all significant variables were also tested for inclusion in the model.

This regression model was then used to predict age-20 carbon for the Phase 2 plots, and the double sampling procedure described in Beets et al. (2012) was used to estimate mean age-20 carbon for pre-1990 forest. The ratio of the double sampling regression estimator to the estimate obtained from the ground plots only, was used to adjust the yield table. The adjustment was used for all ages in the yield table and was also applied to all carbon pools in the table.

The double sampling regression estimator used for this inventory design is given in Beets et al. (2012), and is as follows:

(3) $\bar{y}_{reg} = \bar{y} + \sum_j b_j(\bar{x}_{mj} - \bar{x}_j)$,

where, $\bar{y}$ is the mean age-20 carbon in the Phase 1 plots, $b_j$ is the regression slope coefficient for the jth LiDAR metric used in the regression model, $\bar{x}_j$ is the mean of the jth LiDAR metric in the Phase 1 plots, and $\bar{x}_{mj}$ is an unweighted mean of the transect means (calculated using all sampled Phase 1 and 2 plots in each transect) for the jth LiDAR metric. The method of calculating the standard error for this estimator is given in Beets et al. (2012).

# Results

## Description of pre-1990 planted forests based on the 2015 inventory data

In 2015 an additional 25 plots were included in the pre-1990 planted forest dataset due to improved mapping while six plots were excluded which had been part of the previous dataset. Of the 25 new plots 9 plots were postponed and not completed in 2015 (Table 3) and three sites were abandoned. Reasons for the changes are given in Table 3. This left in total 202 sites, including three abandoned sites as non-stocked plots (one in pasture and two on roads) for analysis of carbon stocks. Of these available 202 sites, eight sites were situated in riparian (three), native (three) or wilding areas (two) and two sites on roads and in pasture respectively. We were unable to run two plots successfully (AM165, AW119) due to the lack of suitable ground measurements and two plots (CX50, CW49) are now deemed as unstocked.
This left 187 plots that allowed a net-stocked growth analysis. Five of these plots had multiple crop-types in separate areas.

Net stocked plot area, used for calculating carbon stocks totalled 10.27 ha compared to a total plot area in pre-1990 planted forests of 11.43 ha, resulting in a ratio of 0.89 for pre-1990 planted forest. This ratio was the same for the pseudo-plots analysed through LiDAR (0.89).

New Zealand's pre-1990 planted forests are dominated by *P. radiata* (92% of net stocked area). The second most common planted species is *Ps. menziesii* (4.6% of net stocked area). Other pines (>1% of net stocked area) and all other species (2.3 % of net stocked area) are rarely found in pre-1990 planted forests.

**Table 3:** Plots added or removed since first measurement in 2010, mostly due to improved mapping. Symbols mean: O – postponed, due in 2016; (√) – did not contribute to net-stocked area; √̲ - previously classified as post-1989 forest plot; √ - plot affected net-stocked area carbon stocks and sequestration.

| Plot ID | Added in 2015 | Removed in 2015 | Reason |
|---|---|---|---|
| AD165 | O | | Postponed |
| AF156 | (√) | | Abandoned, falls on road, assumed zero |
| AF166 | O | | LiDAR only in 2010, postponed in 2015 |
| AP164 | | √ | Forest status undetermined |
| AU122 | √ | | Was not mapped as pre-1990 forest in 2010 |
| AZ136 | (√) | | Riparian; Forest status previously undetermined |
| BL122 | | √ | Forest status undetermined |
| BM121 | (√) | | Riparian; Forest status previously undetermined |
| CD77 | | √ | Post-1989 forest |
| CG30 | (√) | | Pasture; Was not mapped as pre-1990 forest in 2010 |
| CL95 | O | | Postponed |
| CS43 | O | | Postponed |
| CS50 | (√) | | Abandoned, pasture assumed zero both in 2010 and 2015 |
| CT71 | O | | Postponed |
| CU44 | √ | | Was not mapped as pre-1990 forest in 2010 |
| CU98 | √ | | Was not mapped as pre-1990 forest in 2010 |
| CV48 | (√) | | Native; Was not mapped as pre-1990 forest in 2010 |
| CW49 | (√) | | Deemed as noncrop; was mapped as post-1989 forest in 2011 |
| CW61 | O | | Postponed |
| CX53 | O | | LiDAR only in 2010, postponed in 2015 |
| DC55 | | √ | Forest status undetermined |
| DE57 | | √ | Post-1989 forest |
| DE64 | (√) | | No planted tree data. Natives plot |
| DM68 | √̲ | | Was mapped as post-1989 forest in 2010 |
| DM70 | √ | | Was Lidar only plot in 2010 |
| DN66 | √ | | Was not mapped as pre-1990 forest in 2010 |
| P163 | (√) | | Abandoned Was not mapped as pre-1990 forest in 2010, full non-stocked area in 2015 |
| S172 | √ | | Was not mapped as pre-1990 forest in 2010 |
| U162 | √̲ | | Was mapped and measured as post-1989 planted forest before |
| U167 | O | | LiDAR only in 2010, postponed |
| Z153 | O | | Was not mapped as pre-1990 forest in 2010, postponed in 2015 |

Nearly all plots representing pre-1990 planted forests have been measured twice. Of the 25 plots added in 2015, nine were not measured (postponed; awaiting measurement), three were abandoned as they contained no planted trees and five plots were measured but did not contain any planted trees. Eight new plots were included in the analysis for carbon on a net stocked area basis; two using previous measurements as they had been measured as post-1989 forests previously, and the remaining six with a back-casting approach from the single 2015 measurement.

At time of ground measurement just under 20% of the present stands in pre-1990 planted forests were established before 1990, with the majority of stands now in their second or third rotation and 15 years or younger (54%) indicating that for most of the pre-1990 forests, the major silvicultural treatments in the current rotation are not completed yet. Over 12% of pre-1990 planted forest has been replanted since 2012 and is less than 3 years old (Figure 3).

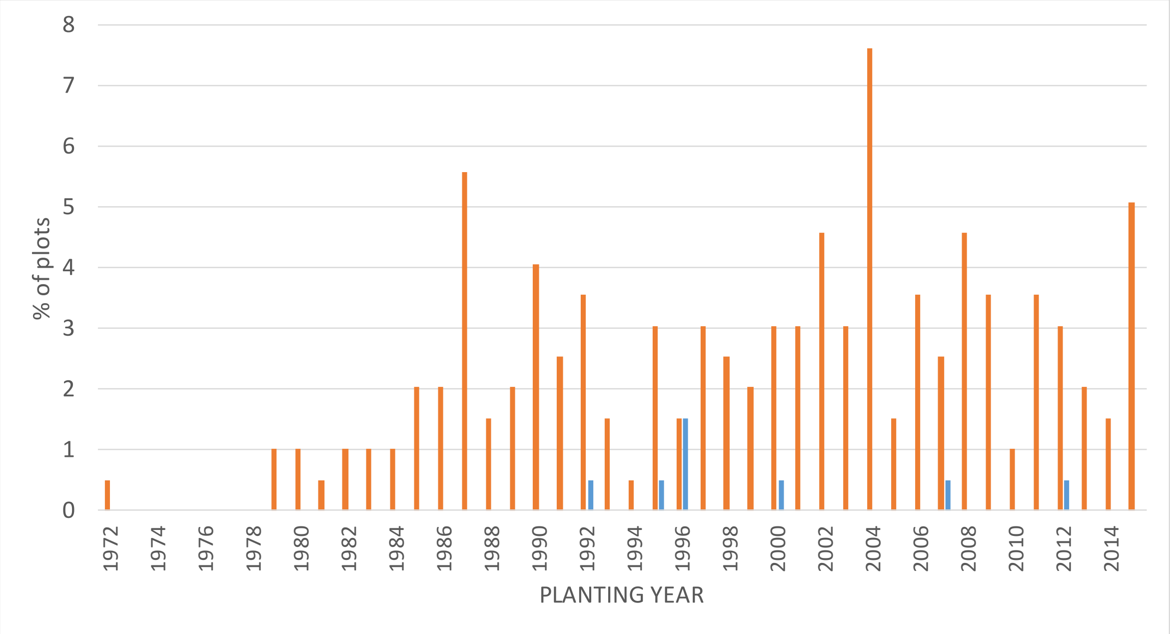

**Fig. 3:** Age class distribution (x-axis: establishment year) shown for ground plots as of 2015 (n= 197 croptypes). Orange: measured twice; blue: measured only in 2015 (4% of plots). In 6% of plots no age could be determined (e.g. native, unstocked).

Average stocking in pre-1990 planted forests as of 2015 is 576 stems per hectare (SE ±25 stems per hectare) and the forests carry a mean stem volume of 336 $m^3$ per hectare (SE ±23 $m^3$ per hectare).

Based on the 2015 plot measurements the average productivity index (300Index & 500Index used respectively for *P. radiata* and *Ps. menziesii*) for pre-1990 planted forests was 24 $m^3$ per hectare (net stocked) per year and average Site Index (SI) was close to 30m.

Understorey and other non-planted shrubs and trees in gaps and unstocked areas are a minor component in the carbon stocks of pre-1990 planted forests. Non-planted shrubs or trees (dead or alive) with a DBH equal or greater than 2.5cm were present in 149 plots. The associated estimated carbon in the above ground live biomass is 4.49 t C/ha across the pre-1990 planted forests. However non-crop carbon stocks per hectare differ between net-stocked and unstocked areas in pre-1990 planted forests. Under crop trees, non-crop carbon was 2.67 t C/ha (±0.8). Non-crop carbon in unstocked areas was, as expected, higher with 18.49 t C/ha (±0.14). The live aboveground biomass carbon in the net stocked area is estimated to be 2.14 t C/ha (±1.06), live belowground is estimated to be 0.52 t C/ha (±0.36) and estimated non-planted dead wood carbon is 0.15 t C/ha (±0.36). Estimates of non-crop carbon across unstocked and stocked area in 2015 was 4.49 t C/ha compared to the lower total carbon stocks at 3.56 t C/ha estimated in 2010. This is an increase in carbon stocks between the two measurements and may be the result of changes in crop structures that promote better non-crop growth on average, or the result of changes in the methodology of measuring understory vegetation with major simplifications over time (Payton et al. 2008), Herries *et al.* 2012)[3]. Previous work (Paul *et al.* 2009) indicated that the small understory carbon pools do not change significantly across all pre-1990 planted forests, but the now available repeated plot measurements would allow a more in-depth analysis of understorey dynamics.

## Carbon stocks and sequestration based on remeasured inventory ground plots

Remeasured plots can provide good estimates of carbon sequestration for a given period, particularly if measurements are taken at the start and end of the period of interest. Assuming the 187 plots measured twice are an unbiased sample, their repeated measurements provide direct estimates of carbon sequestration for New Zealand pre-1990 planted forest.

The estimated carbon stocks and sequestration rates for the period 1st Jan 2010 to 31st Dec 2014 based on the latest measurement are given in Table 4. Total sequestration rate over the five year period is estimated to be -8.32 t C/ha ± 11.1 t C/ha. This amount of carbon stock loss over the five years is based on the loss in aboveground live biomass (AGB) through harvesting between 2010 and 2015 and associated losses in below ground live biomass (BGB). Carbon sequestration in the DW pool and Litter, through an influx from harvesting residue, counteracts the losses in AGB and BGB but only slightly.

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[3] This might be well worth exploring, especially if the national forest inventory will be used for other international reporting commitments such as Montreal Process reporting.

**Table 4:** Total carbon stocks and sequestration (t/ha) between 2010 and 2014 for each pool in pre-1990 planted forests based on measurements taken in 2010 and 2015 (n=187).

| Component | Carbon stocks 1st Jan 2010 | | Carbon stocks 31st Dec 2014 | | Carbon sequestration 2010-2014 | |
|---|---|---|---|---|---|---|
| | Estimate C t/ha | 95% CI | Estimate C t/ha | 95% CI | Estimate ΔC t/ha | 95% CI |
| Total | 139.04 | ±11.3 | 130.72 | ±11.4 | -8.32 | ±11.1 |
| AGB | 80.49 | ±11.2 | 69.17 | ±11.0 | -11.31 | ±13.1 |
| BGB | 17.21 | ±2.4 | 14.82 | ±2.4 | -2.39 | ±2.8 |
| DW | 23.29 | ±3.4 | 26.55 | ±3.6 | 3.25 | ±4.7 |
| Litter | 18.06 | ±1.8 | 20.18 | ±1.9 | 2.13 | ±2.4 |

## Comparison between the 2015 inventory and the previous 2010 inventory based on the 2008-2012 period

The analysis of the complete 2015 ground plot dataset revealed that previous estimates based on the 2010 measure were very similar to the newly calculated carbon stocks in pre-1990 planted forests (Table 5). The first initial carbon stock estimate for 2008 based on calculations without a net-stocked area adjustment showed lower carbon stocks per hectare as expected. All further carbon stock calculations, based on net-stocked area, were very similar. Calculated carbon stocks based on the 2010 measure, one carried out in 2014 (Paul et al. 2014) and the "corrected" 2010 measurement in this current report, differs slightly (carbon stock change dropped by 5.5 t C per hectare). The reason for this decline is mostly the use of an average carbon stock in just harvested or young stands in Paul et al. (2014), while in the current analysis these plots were populated with 2nd rotation data based on the current runs (2015 data)[4]. Small corrections to the 2010 plot-data that were picked up during the second inventory assessment in 2015 (e.g. correction of missed trees) also had a small influence on the carbon stocks and their predictions over time.

The difference in estimated carbon stocks (2008 & 2012) between the 2010 and the 2015 inventories is a decline in carbon stocks and a much smaller but still positive rate of change between 2008 and 2012 (Table 5). The cause for this reduction of carbon stocks in pre-1990 planted forests has been the harvesting of stands between 2010 and 2012 and thinning during that time as well. The previous input decay (previous harvest residues) in the dead wood pool is now balanced by additional residue accumulation from

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[4] Based on 2015 data we were able to run a yield table with the current regime. Based on this we were able to estimate carbon stocks at 2008 and 2012 including 2nd rotation carbon residuals (harvesting residue) for these plots that were either too young in 2008 or just harvested before 2010.

harvest and thinning. The live carbon pools do not show significant change through growth, as this is again balanced by live carbon removal due to harvest and thinning.

**Table 5:** Comparison of carbon stocks and change for the four pools calculated previously (Paul et al. 2011) and with the updated plot dataset with measurements in 2010 and 2015. All estimated are back-casted to 1 Jan 2008 and 31 December 2012. Only crop-tree carbon is shown.

| | **Full area approach** | **Net-stocked area approach** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Study** | **Paul 2011 IY 2010** | **Paul et al. 2014 IY 2010** | | | **This report IY 2010 revisited** | | | **This report IY 2015** | | |
| **Pool** | **2008 only C t/ha** | **2008 C t/ha** | **2012 C t/ha** | **ΔC t/ha** | **2008 C t/ha** | **2012 C t/ha** | **ΔC t/ha** | **2008 C t/ha** | **2012 C t/ha** | **ΔC t/ha** |
| AGB | 60.65 ±10.1 | 87.71 ±12.1 | 97.70 ±14.0 | 9.99 ±11.4 | 80.75 ±11.0 | 98.28 ±11.8 | 17.52 ±10.7 | 82.46 ±11.1 | 84.1 ±11.4 | 1.64 ±12.3 |
| BGB | 12.69 ±2.1 | 18.81 ±2.6 | 20.70 ±2.9 | 2.11 ±2.4 | 17.38 ±2.4 | 20.9 ±2.5 | 3.51 ±2.3 | 17.76 ±2.4 | 17.91 ±2.4 | 0.15 ±2.7 |
| DW | 26.41 ±3.4 | 19.53 ±2.6 | 20.25 ±2.8 | 0.73 ±3.1 | 23.83 ±3.4 | 17.21 ±2.6 | -6.62 ±3.1 | 22.69 ±3.1 | 22.67 ±3.2 | -0.02 ±3.9 |
| L | 20.72 ±1.9 | 17.32 ±1.6 | 17.55 ±1.8 | 0.23 ±1.7 | 17.97 ±1.7 | 14.87 ±1.4 | -3.10 ±1.5 | 17.66 ±1.6 | 17.77 ±1.6 | 0.11 ±1.9 |
| **Total** | **120.41 ±8.3** | **141.9 ±13.4** | **154.9 ±15.7** | **13.06 ±10.5** | **139.94 ±11.4** | **151.25 ±12.4** | **11.32 ±11.7** | **140.57 ±11.6** | **142.45 ±11.6** | **1.89 ±11.4** |

IY: Inventory Year

When compared on a plot by plot basis the effect of harvested and thinned plots on carbon stock change becomes more evident. While the majority of plots without a major disturbance show a very close and strong relationship of carbon stock changes based on the 2010 and 2015 data (Figure 4; r2= 94.8). As expected plots with major disturbances show wider differences with negative or reduced positive carbon stock changes when the 2015 data were used. Disturbed plots (identified through the 2015 measure) had a 10.64t C/ha lower carbon stock change compared to estimates based on 2010 data as a result of unaccounted silvicultural activity (not known in 2010) .

Previously the average deadwood carbon stock was applied on plots that had been harvested or were too young. This time estimates were based on current stand data (from 2015 measure). Stocks in the 31 plots affected shifted from 6.5 t (total) to 9.85 t (total).

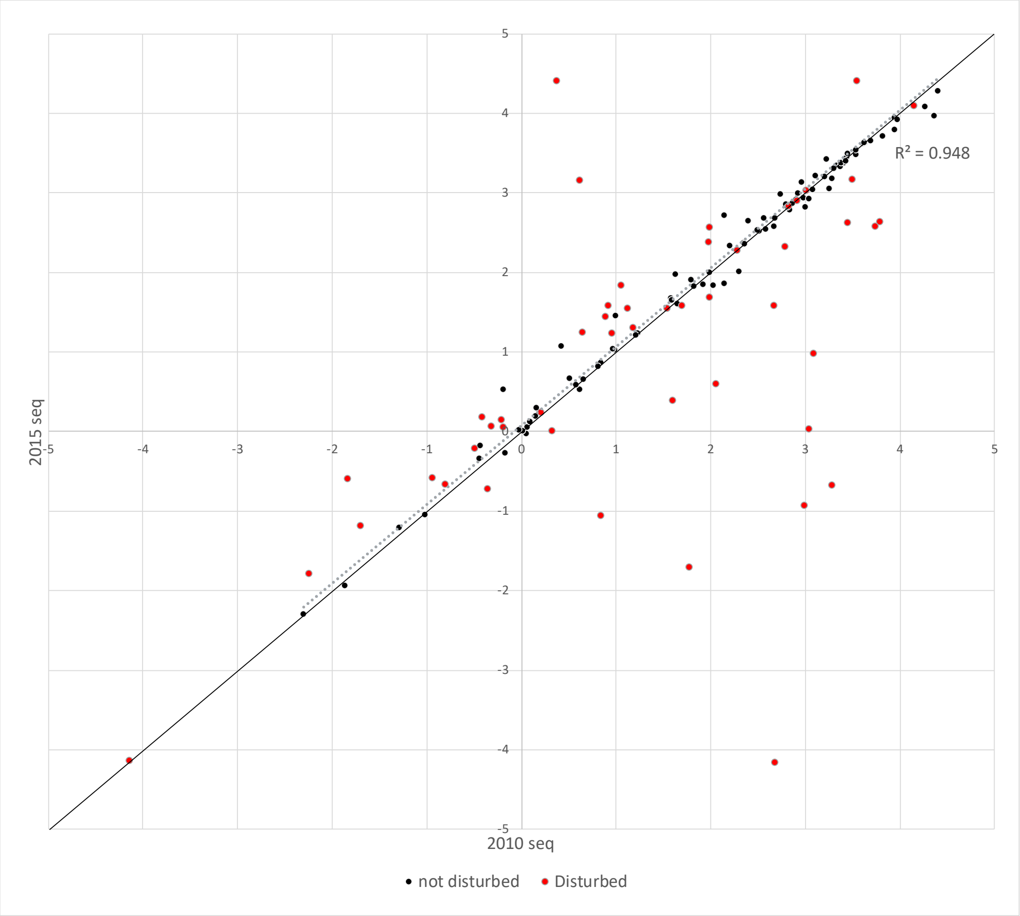

**Figure 4:** Relationship between carbon stock change estimates from 2010 and 2015 measurements for the period 2008-12. Undisturbed plots show a strong nearly 1:1 relationship while disturbed plots do not show such a relationship (n = 164).

## Creating pre-1990 planted forest yield table

Yield tables for a rotation age of 60 years were generated based on 1st rotation runs as dead wood from a previous rotation is modelled separately in LUCAS. The plots used in this analysis were the same as those used to estimate carbon sequestration, with the exception that plots that had been recently harvested or planted were excluded as it was considered that these plots provided no useful data for developing yield tables.

As the age class distribution in pre-1990 indicates many plots are younger than 15 years with often a Mean Top Height (MTH) of 14 meters or less. For these plots we applied “average standard” future silvicultural treatments based on the current situation of the plot. To determine the average silviculture in pre-1990 planted forests we analysed the thinning and pruning events in the plot dataset. Based on this the average silvicultural treatments applied were:

- For unpruned stands a thinning down to 478 stems per hectare at age 10 years
- For pruned stands a thinning down to 348 stems per hectare at age 11 years and pruning to a pruned height of 6 m at the third lift at age 9 years.

If MTH, age or stocking already significantly exceeded the thresholds no future silviculture was assumed.

The yield table provided (Table 6 and Fig. 5) represents a first rotation stand as dead wood from a previous rotation is modelled separately in LUCAS. Again, carbon estimates were obtained for the net stocked area of each plot, with plots omitted from the analysis if they had been recently harvested or planted. This left 156 plots in the inventory considered suitable for producing a yield table for stocked pre-1990 forest.

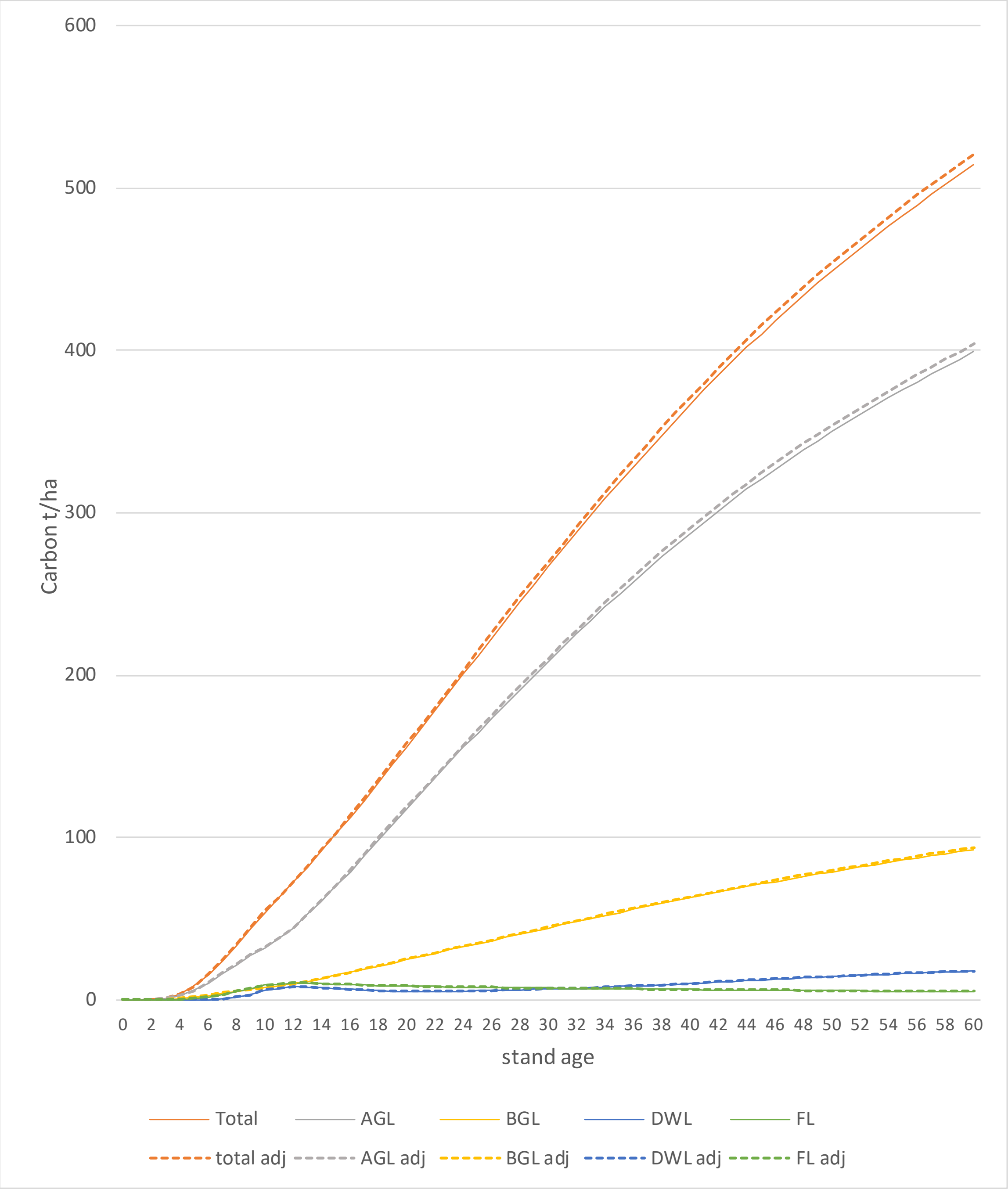

**Figure 5.** Visual representation of the pre-1990 carbon yield table ground plot only and LiDAR adjusted. Total carbon and the four pools, AGB, BGB, DW and FL are shown. Non-crop carbon is not shown

**Table 6.** Ground plot based and LiDAR adjusted 1st rotation carbon yield tables for pre-1990 planted forest (crop-trees only) assuming a rotation age of 60 years. Values are in tonnes Carbon per hectare.

| Carbon yield table based on ground plots | | | | | | | LiDAR adjusted yield table | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Age | Crop | | | | | Non-crop | Crop | | | | | Non-crop |
| | Total | AGL | BGL | DWL | FL | Total | Total | AGL | BGL | DWL | FL | Total |
| 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.82 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.82 |
| 1.5 | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 | 2.82 | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 | 2.82 |
| 2.5 | 0.7 | 0.5 | 0.2 | 0.0 | 0.0 | 2.82 | 0.7 | 0.5 | 0.2 | 0.0 | 0.0 | 2.82 |
| 3.5 | 2.3 | 1.6 | 0.6 | 0.0 | 0.1 | 2.82 | 2.4 | 1.7 | 0.6 | 0.0 | 0.1 | 2.82 |
| 4.5 | 6.0 | 4.1 | 1.3 | 0.0 | 0.5 | 2.82 | 6.1 | 4.2 | 1.3 | 0.0 | 0.5 | 2.82 |
| 5.5 | 11.8 | 8.1 | 2.3 | 0.1 | 1.3 | 2.82 | 12.0 | 8.2 | 2.3 | 0.1 | 1.3 | 2.82 |
| 6.5 | 19.7 | 13.3 | 3.5 | 0.4 | 2.5 | 2.82 | 19.9 | 13.4 | 3.5 | 0.4 | 2.6 | 2.82 |
| 7.5 | 29.0 | 18.9 | 4.7 | 1.2 | 4.3 | 2.82 | 29.4 | 19.1 | 4.8 | 1.2 | 4.3 | 2.82 |
| 8.5 | 39.0 | 24.5 | 5.9 | 2.5 | 6.2 | 2.82 | 39.5 | 24.7 | 5.9 | 2.5 | 6.2 | 2.82 |
| 9.5 | 48.9 | 29.5 | 6.9 | 4.5 | 8.1 | 2.82 | 49.5 | 29.8 | 7.0 | 4.6 | 8.2 | 2.82 |
| 10.5 | 58.4 | 34.7 | 8.0 | 6.3 | 9.4 | 2.82 | 59.1 | 35.1 | 8.1 | 6.4 | 9.6 | 2.82 |
| 11.5 | 67.7 | 40.9 | 9.2 | 7.4 | 10.1 | 2.82 | 68.5 | 41.4 | 9.3 | 7.5 | 10.2 | 2.82 |
| 12.5 | 76.9 | 48.1 | 10.7 | 7.9 | 10.3 | 2.82 | 77.9 | 48.7 | 10.8 | 8.0 | 10.4 | 2.82 |
| 13.5 | 86.5 | 56.5 | 12.4 | 7.5 | 10.1 | 2.82 | 87.5 | 57.2 | 12.5 | 7.6 | 10.2 | 2.82 |
| 14.5 | 96.4 | 65.3 | 14.1 | 7.1 | 9.8 | 2.82 | 97.6 | 66.1 | 14.3 | 7.2 | 10.0 | 2.82 |
| 15.5 | 106.8 | 74.4 | 16.0 | 6.8 | 9.6 | 2.82 | 108.0 | 75.3 | 16.1 | 6.9 | 9.7 | 2.82 |
| 16.5 | 117.4 | 83.7 | 17.8 | 6.4 | 9.3 | 2.82 | 118.8 | 84.7 | 18.1 | 6.5 | 9.5 | 2.82 |
| 17.5 | 128.2 | 93.4 | 19.8 | 5.9 | 9.1 | 2.82 | 129.7 | 94.5 | 20.0 | 6.0 | 9.2 | 2.82 |
| 18.5 | 139.2 | 103.1 | 21.8 | 5.6 | 8.8 | 2.82 | 140.9 | 104.3 | 22.0 | 5.7 | 8.9 | 2.82 |
| 19.5 | 150.3 | 112.7 | 23.7 | 5.3 | 8.6 | 2.82 | 152.1 | 114.0 | 24.0 | 5.4 | 8.7 | 2.82 |
| 20.5 | 161.4 | 122.2 | 25.7 | 5.1 | 8.3 | 2.82 | 163.3 | 123.7 | 26.0 | 5.2 | 8.4 | 2.82 |
| 21.5 | 172.6 | 131.6 | 27.7 | 5.1 | 8.2 | 2.82 | 174.6 | 133.2 | 28.0 | 5.1 | 8.3 | 2.82 |
| 22.5 | 183.8 | 141.0 | 29.7 | 5.1 | 8.0 | 2.82 | 186.0 | 142.7 | 30.0 | 5.2 | 8.1 | 2.82 |
| 23.5 | 195.1 | 150.5 | 31.7 | 5.1 | 7.8 | 2.82 | 197.4 | 152.3 | 32.0 | 5.1 | 7.9 | 2.82 |
| 24.5 | 206.3 | 159.6 | 33.6 | 5.4 | 7.7 | 2.82 | 208.8 | 161.5 | 34.0 | 5.4 | 7.8 | 2.82 |
| 25.5 | 217.6 | 168.7 | 35.6 | 5.6 | 7.6 | 2.82 | 220.1 | 170.7 | 36.0 | 5.7 | 7.7 | 2.82 |
| 26.5 | 228.7 | 177.8 | 37.6 | 5.7 | 7.5 | 2.82 | 231.4 | 179.9 | 38.0 | 5.8 | 7.6 | 2.82 |
| 27.5 | 239.7 | 186.7 | 39.5 | 6.0 | 7.5 | 2.82 | 242.5 | 188.9 | 40.0 | 6.1 | 7.5 | 2.82 |
| 28.5 | 250.6 | 195.4 | 41.4 | 6.4 | 7.4 | 2.82 | 253.6 | 197.7 | 41.9 | 6.5 | 7.5 | 2.82 |
| 29.5 | 261.4 | 204.0 | 43.4 | 6.7 | 7.3 | 2.82 | 264.5 | 206.4 | 43.9 | 6.8 | 7.4 | 2.82 |
| 30.5 | 272.1 | 212.7 | 45.3 | 6.9 | 7.2 | 2.82 | 275.3 | 215.2 | 45.9 | 6.9 | 7.3 | 2.82 |
| 31.5 | 282.7 | 221.3 | 47.3 | 7.1 | 7.1 | 2.82 | 286.1 | 223.9 | 47.8 | 7.1 | 7.2 | 2.82 |
| 32.5 | 293.2 | 229.7 | 49.2 | 7.3 | 7.0 | 2.82 | 296.7 | 232.4 | 49.8 | 7.4 | 7.1 | 2.82 |
| 33.5 | 303.5 | 237.9 | 51.1 | 7.6 | 6.9 | 2.82 | 307.1 | 240.7 | 51.7 | 7.7 | 7.0 | 2.82 |
| 34.5 | 313.7 | 245.9 | 53.0 | 7.9 | 6.8 | 2.82 | 317.4 | 248.9 | 53.6 | 8.0 | 6.9 | 2.82 |
| 35.5 | 323.7 | 253.8 | 54.8 | 8.3 | 6.8 | 2.82 | 327.5 | 256.8 | 55.5 | 8.4 | 6.8 | 2.82 |
| 36.5 | 333.5 | 261.5 | 56.6 | 8.7 | 6.7 | 2.82 | 337.4 | 264.6 | 57.3 | 8.8 | 6.8 | 2.82 |
| 37.5 | 343.1 | 269.0 | 58.4 | 9.1 | 6.6 | 2.82 | 347.2 | 272.2 | 59.1 | 9.2 | 6.7 | 2.82 |
| 38.5 | 352.6 | 276.4 | 60.2 | 9.5 | 6.5 | 2.82 | 356.8 | 279.7 | 60.9 | 9.6 | 6.6 | 2.82 |
| 39.5 | 361.9 | 283.6 | 62.0 | 9.9 | 6.4 | 2.82 | 366.2 | 287.0 | 62.7 | 10.0 | 6.5 | 2.82 |
| 40.5 | 371.2 | 290.7 | 63.7 | 10.3 | 6.4 | 2.82 | 375.6 | 294.2 | 64.5 | 10.5 | 6.4 | 2.82 |
| 41.5 | 380.2 | 297.7 | 65.5 | 10.8 | 6.3 | 2.82 | 384.7 | 301.2 | 66.2 | 10.9 | 6.4 | 2.82 |
| 42.5 | 389.1 | 304.5 | 67.2 | 11.2 | 6.2 | 2.82 | 393.7 | 308.1 | 67.9 | 11.3 | 6.3 | 2.82 |
| 43.5 | 397.7 | 311.0 | 68.8 | 11.7 | 6.2 | 2.82 | 402.4 | 314.7 | 69.6 | 11.8 | 6.2 | 2.82 |
| 44.5 | 406.1 | 317.4 | 70.4 | 12.1 | 6.1 | 2.82 | 410.9 | 321.2 | 71.3 | 12.2 | 6.2 | 2.82 |
| 45.5 | 414.3 | 323.7 | 72.0 | 12.5 | 6.0 | 2.82 | 419.2 | 327.5 | 72.9 | 12.7 | 6.1 | 2.82 |
| 46.5 | 422.2 | 329.7 | 73.6 | 13.0 | 5.9 | 2.82 | 427.3 | 333.6 | 74.5 | 13.1 | 6.0 | 2.82 |
| 47.5 | 430.0 | 335.6 | 75.2 | 13.4 | 5.9 | 2.82 | 435.1 | 339.6 | 76.1 | 13.5 | 5.9 | 2.82 |
| 48.5 | 437.6 | 341.4 | 76.7 | 13.8 | 5.8 | 2.82 | 442.8 | 345.4 | 77.6 | 14.0 | 5.8 | 2.82 |
| 49.5 | 445.1 | 347.0 | 78.2 | 14.2 | 5.7 | 2.82 | 450.3 | 351.1 | 79.1 | 14.4 | 5.8 | 2.82 |

**Cont.**

| Age | Total | AGL | BGL | DWL | FL | Non-crop | Total | AGL | BGL | DWL | FL | Non-crop |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 50.5 | 452.3 | 352.4 | 79.7 | 14.6 | 5.6 | 2.82 | 457.7 | 356.6 | 80.6 | 14.8 | 5.7 | 2.82 |
| 51.5 | 459.4 | 357.8 | 81.1 | 15.0 | 5.6 | 2.82 | 464.9 | 362.0 | 82.1 | 15.1 | 5.6 | 2.82 |
| 52.5 | 466.4 | 363.0 | 82.6 | 15.3 | 5.5 | 2.82 | 471.9 | 367.3 | 83.5 | 15.5 | 5.5 | 2.82 |
| 53.5 | 473.2 | 368.1 | 84.0 | 15.7 | 5.4 | 2.82 | 478.8 | 372.5 | 85.0 | 15.9 | 5.5 | 2.82 |
| 54.5 | 479.9 | 373.2 | 85.4 | 16.0 | 5.3 | 2.82 | 485.6 | 377.6 | 86.4 | 16.2 | 5.4 | 2.82 |
| 55.5 | 486.4 | 378.1 | 86.8 | 16.3 | 5.3 | 2.82 | 492.2 | 382.6 | 87.8 | 16.5 | 5.3 | 2.82 |
| 56.5 | 492.9 | 382.9 | 88.1 | 16.6 | 5.2 | 2.82 | 498.7 | 387.4 | 89.2 | 16.8 | 5.3 | 2.82 |
| 57.5 | 499.2 | 387.6 | 89.5 | 16.9 | 5.1 | 2.82 | 505.1 | 392.2 | 90.5 | 17.1 | 5.2 | 2.82 |
| 58.5 | 505.4 | 392.3 | 90.8 | 17.2 | 5.1 | 2.82 | 511.4 | 397.0 | 91.9 | 17.4 | 5.1 | 2.82 |
| 59.5 | 511.5 | 396.9 | 92.1 | 17.5 | 5.0 | 2.82 | 517.6 | 401.6 | 93.2 | 17.7 | 5.1 | 2.82 |

## The non-crop component

Native and exotic non-crop tree and tree-fern species are measured in planted forests as part of the national forest inventory as an important structural component in planted forests that influences biodiversity and forest health. However carbon stocks and their change are small compared to the over-storey (crop-trees). Two non-crop components in planted forests are currently distinguished based on where they occur in the forest; either under crop trees inside the net-stocked area, or outside the stocked production area e.g. unplanted gullies.

The analysis across all plots (149 plots) with non-crop tree and tree-fern species showed that on average pre-1990 planted forests carry 2.82 t C/ha in the net-stocked area (n = 138 plots). Non-crop carbon outside of the net-stocked area was seven times larger at 30.03 t C/ha (n = 21 plots). Specific non-crop areas such as wilding pines (n = 2) and riparian sites (n = 3) carried in total an average of 146.90 t C/ha, (Table 7).

For the net-stocked yield table (Table 5) the average amount of 2.82 t C/ha non-crop carbon was added, assuming at this stage no differences across stand age.

**Table 7**. Non-crop carbon for modelled vegetation types in pre-1990 planted forests

| *Category* | *Carbon* | *AGB* | *BGB* | *DW* |
|---|---|---|---|---|
| *Non-crop understory (net stocked area)* | 2.82 t C/ha (± 0.85) | 2.14 t C/ha (± 0.64) | 0.52 t C/ha (± 0.16) | 0.15 t C/ha (± 0.09) |
| *Unstocked area (incl. native forest plots; n=21)* | 30.03 t C/ha (± 26.81) | 21.7 t C/ha (± 19.73) | 5.36 t C/ha (± 4.88) | 2.97 t C/ha (± 3.01) |
| *Wilding and riparian (n=5)* | 146.90 t C/ha (± 257.39) | 117.17 t C/ha (± 206.80) | 25.73 t C/ha (± 43.38) | 3.99 t C/ha (± 7.33) |

## LiDAR based yield table adjustment

A regression equation was fitted using the Phase 1 ground plots in the inventory for predicting age-20 total carbon from stand age and LiDAR metrics. The variables used in the model were stand-age, P50ht, and percentage 1st returns above 0.5. A quadratic term for age, and the interaction between P50ht and Age were also included in the final model. The final model explained 58% of the variation in age-20 total carbon and its coefficients are given in Table 8.

**Table 8.** Coefficients of regression model for predicting Age-20 total carbon from stand age and LiDAR metrics. This model was derived from 143 Phase 1 plots in the pre-1990 forest inventory.

| ***Parameter*** | ***Estimate*** | ***Standard error*** | ***t value*** | ***P value*** |
|---|---|---|---|---|
| *Intercept* | 168.8 | 18.17 | 9.29 | <0.0001 |
| *Age* | -25.12 | 3.42 | -7.34 | <0.0001 |
| *P50* | 15.10 | 2.46 | 6.13 | <0.0001 |
| *% 1$^{st}$ returns* | 1.017 | 0.179 | 5.69 | <0.0001 |
| *Age x Age* | 0.524 | 0.112 | 4.67 | <0.0001 |
| *Age x P50* | -0.288 | 0.103 | -2.79 | 0.0060 |

The model was then used to estimate age-20 total carbon in the inventory. The estimate using ground plots only, and the estimate using the LiDAR regression estimator, are compared in Table 9. The probable limits of error (PLEs, 95% confidence intervals expressed as a percentage of the mean) indicate that a moderate improvement in precision was achieved using the additional LiDAR data. The PLE of ±5.9% for age-20 total carbon should be a good approximation to the PLE for total carbon for any age in the LiDAR adjusted yield table presented in this report.

The ratio of the regression estimate to the ground plot estimate is also shown in Table 7 and is 1.01186. Therefore, the appropriate adjustment for the yield table is 1.186%. This adjustment was applied to carbon for all ages and all pools in the yield table presented in this report.

Note that the dependent variable used in this analysis and estimated in Table 9 is not identical to the age-20 value of total carbon in the yield table presented in this report. Firstly, the value was obtained from the yield table obtained from the 2015 ground measurement only, as this was considered to relate more closely to the LIDAR data than the yield table based on both measurements. Secondly, to relate better to the LiDAR metrics which were always obtained from whole 0.06 ha circular plots, the per-hectare yields from the yield table were adjusted for net stocked area by multiplying by (net stocked area)/0.06. Note that in contrast, the adjusted yield table presented in this report gives per-hectare carbon within the net stocked forest area.

**Table 9.** Estimates of age-20 total carbon obtained using ground plots only, and using a LIDAR double sampling regression estimator. Also shown are measures of the precision of these estimates.

| ***Method*** | ***Estimate age-20 total carbon (tC/ha)*** | ***Standard error (tC/ha)*** | ***PLE (%)*** |
|---|---|---|---|
| *Ground plot estimate* | 146.49 | 4.8 | 6.5 |
| *Regression estimate* | 148.23 | 4.4 | 5.9 |

# Discussion

The use of the new Forest Carbon Predictor model (FCP Version 4.12), where the estimate of stem volume is conditioned to be equal to the inventory at time of measurement, provides an integrated, consistent inventory and projection calculation system. The model has been improved from previous versions by adding *Ps. menziesii* specific routines that improve the estimates of growth and carbon for the second most common species in pre-1990 planted forests.

The under-storey and the vegetation in gaps in the planted tree canopy are highly variable in species and plant form. There is a moderately high level of uncertainty in the estimate of the non-planted carbon stocks in ground plots due to the difficulty of measurement and the different relative amounts of biomass in open versus shaded conditions. As non-crop vegetation measurements changed between 2010 and 2015 inventories, specifically the classification into understory and non-crop in unstocked areas carbon stocks and sequestration rates cannot be readily compared for these classes but only for the total mapped area. The overall importance of the non-crop pool in planted forest net stocked areas is minor with non-crop trees comprising less than 2% (1.9%) of the total carbon stocks in the pre-1990 planted forests at 2015. All non-crop carbon including all pre-1990 planted forest gross area amounted to 3.15 % of the crop-carbon, which is only a small contribution to the overall carbon pool in planted forests. Therefore, errors in estimates of the planted component far outweigh the uncertainty of the non-planted vegetation.

LiDAR adjusted yield tables as shown in this report are a unique approach utilising ground measurements from permanent sample plots, stand information from forest owners in LiDAR only plots and LiDAR data. The double sampling approach for estimating carbon stocks or volume from LiDAR is now well known and used in New Zealand and internationally. Predicting actual sequestration over the existence of a forest “stand” is however new and the approach is promising for potentially predicting other forestry related indices such as site index. The available LiDAR dataset and ground analysis should also allow further modelling of carbon sequestration based on the multi-temporal LiDAR dataset and ground plot measurement. This was not part of this project but would be worthwhile to test the usability of LiDAR directly for carbon sequestration.

The carbon stock analysis revealed a decline in carbon stocks in pre-1990 planted forests between 2010 and 2015. Cause for this negative carbon stock change has been the relatively high harvesting activity during these years in the plot-represented forest stands.

The annual measurement of 20% of all planted forest plots each year will provide an ongoing indication of whether this trend will continue or reverse as the proportion of mature stands changes.

# Recommendations and Conclusions

This report provides the first complete analysis of the ground based inventory data collected during two inventory periods in pre-1990 planted forests in New Zealand. The total amount of carbon sequestered in New Zealand’s pre-1990 planted forests was successfully estimated from a double sampling approach using a ratio estimator and an adjusted yield table created by using additional LiDAR data in a new and efficient way. The methods described are part of the LUCAS system and provide the official estimates for New Zealand’s reporting to the UNFCCC, bringing New Zealand’s national forest inventory up to a standard comparable to countries with large and well inventoried forest resources (Tomppo et al, 2010). The inventory of forest carbon sequestration provides empirical data required for operating the FCP model that is specific to New Zealand and is therefore a Tier 3 method (IPCC, 2003; IPCC 2006). The inventory is credited with assisting in reducing the uncertainty of New Zealand’s estimate of net greenhouse gas emissions.

The carbon sequestration rate is close to previous rates estimated with fewer plots and/or modelled stocks for 2008, the back-casted date of the 2010 inventory (Paul *et al.,* 2011, Paul *et al.,* 2014). Previous forecasts for 2012 values showed higher stocks than the now back-casted values from 2015, due to previously unaccounted changes occurring between 2010 and 2012. As back-casting is far less uncertain (events are well documented for the past history) the current estimates are more reliable than previous estimates of carbon stocks and their changes based on previous forecast approaches.

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