The 2018 NFI plot analysis
Yield tables and carbon stocks at measurement

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Report information sheet

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Executive summary

Objective

To calculate national carbon stock and carbon stock change estimates (via yield tables) for pre-1990 and post-1989 planted forests using data from the annual national forest inventories in 2016, 2017 and 2018, and previous periodic national forest inventories between 2007 and 2015.

Key results

Out of 140 plots measured in 2018 in the inventory of planted forests, 112 were found suitable for generating yield tables. The remaining plots were either too young, recently harvested, unsuitable for modelling or were not part of the net-stocked plantation area.

Total net-stocked crop-related carbon stock estimates in 2018 plots averaged 70.7 tC ha^{-1} (CI ±5 tC ha^{-1}) for pre-1990 planted forest and 163.4 tC ha^{-1} (CI ±21 tC ha^{-1}) for post-1989 planted forest. Non-crop carbon in net-stocked areas averaged 2.9 tC ha^{-1} (CI ±0.8 tC ha^{-1}) for pre-1990 planted forest and 6.1 tC ha^{-1} (CI ±1.6 tC ha^{-1}) in post-1989 planted forest.

Among the 39 plots measured and analysed in 2018 pre-1990 planted forest, 12 plots measured for the first time had lower yields compared to plots with previous measurements. This highlights that it is critical to ensure that all plots (grid-points) present in the mapped area of pre-1990 planted forests and post-1989 planted forests are measured or at least randomly sampled to avoid a potential bias.

Yield tables based on plots measured in 2018 plus all other plots measured since 2008 were created using interpolation for multiple measurements. Mean yield tables were derived from these individual plot tables using plot area weighted averages. A further adjustment using an imputation method to account for forecasting/backcasting errors was also used. This method applies a greater weighting at yield table ages close to the plot measurement age.

The yield table method of estimating carbon stocks by applying the table to the age distribution of a forest was tested against the direct approach of estimating stocks directly from the inventory. This test indicated that the yield table method tends to over-estimate average stocks. This occurs because more productive stands tend to be harvested at younger ages than less productive stands. When the yield table is applied to these older less productive stands, many of which are not radiata pine, it tends to over-estimate their stocks, affecting the overall average across all stands.

Implications

The 2018 inventory data showed that additional plots in pre-1990 planted forests show different carbon sequestration rates than previously sampled plots but this was not the case in post-1989 planted forests. Ongoing analyses of annual inventory data will allow such differences to be identified and existing yield estimates to be adjusted accordingly over time. The new approach which accounts for prediction error in the yield table estimation is an example of the continuous improvement in the reporting of carbon stocks and stock changes in New Zealand’s planted forests. However, the way the yield table is used to estimate stocks, particularly for older forests needs further evaluation. There is still a tendency for the yield tables to over-estimate carbon stocks in older stands and stands stocked with non-radiata species due to differences in harvesting age between more and less productive stands and species. Therefore an approach deriving species specific yield tables and/or age-class dependent yield tables might be required combined with precise and accurate estimates of the net stocked area of these species and their age class distributions.

Further work

The analysis of annual inventory data should continue each year to identify any possible trends (e.g. new plots sequestering carbon at different rates to the current dataset). This will allow the updating of yield predictions based on the age-class changes that might be observed (e.g. through early harvesting). Further options to estimate carbon stocks and carbon stocks changes from the inventory data such as creating species-specific yield tables should be explored.

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Introduction

The Land Use and Carbon Analysis System (LUCAS) is a cross-government programme administered by the Ministry for the Environment (MfE) which supports New Zealand's international reporting requirements under the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. LUCAS combines information from field-based inventories and wall-to-wall satellite-based mapping.

An important part of LUCAS is the planted forest inventory comprising post-1989 planted forests and pre-1990 planted forests. This inventory consists of a network of permanent plots laid out on a 4 x 4 km grid covering the area of planted forest across New Zealand. The inventory is designed to provide an unbiased sample of permanent plots in post-1989 planted forests and pre-1990 planted forests. Based on this inventory New Zealand estimates its carbon stocks and stock change (via yield tables) on a per hectare basis for the net-stocked area in post-1989 planted forests and pre-1990 planted forests. The planted forest inventory plots were measured on a 5-year re-measurement cycle commencing in 2007. Using these data New Zealand has published annual reports of carbon stock changes in its planted forests since 2008 (Wakelin et al. 2016, Anon. 2017).

In 2016 New Zealand moved to a continuous forest inventory on a 5-year re-measurement cycle, with one fifth of ground plots measured each year. Moving to a continuous forest inventory provides annual information on changes in forest management practices such as harvest age and timing and intensity of thinning, and also provides annual information on natural disturbance and growth that can be used to improve carbon stock change projections. When compared with a periodic forest inventory, a continuous inventory also has the advantage of smoothing annual workloads and budgets.

Objective

To calculate national carbon stock and carbon stock change estimates (via yield tables) for post-1989 and pre-1990 planted forests for the four carbon pools Above-ground live (AGL), Below-ground live (BGL), Dead Wood Litter (DWL), Fine Litter (FL) and their total, using data from the annual national forest inventories undertaken in 2016, 2017, 2018 and previous periodic national forest inventories conducted between 2007 and 2015.

Materials and methods

Current 2018 plot dataset

At the beginning of the 2016-2020 period, planted forest inventory grid-points in post-1989 planted forests and pre-1990 planted forests were semi-randomly[1] assigned to annual panels with 1/5th of plots to be measured each year. During the 2018 field season 140 permanent sample plots from the 2018 panel were measured by field teams using methods described by Herries et al. (2013).

A further 20 grid points in the 2018 panel of the sampling frame, defined by the mapping of planted forests were not measured by the Interpine field teams (Chikono (2018); Table 1a).
Four of these grid locations were located in either grassland (2 plots), in a garden (1 plot) or in a duck-pond (1 plot), but are still part of the mapped planted forest area. These grid locations were assigned carbon stock estimates of zero and included in the calculation of carbon stocks for unstocked areas of post-1989 and pre-1990 planted forest. Ten of the remaining unmeasured plots were deferred for measurement at a later date due to access restrictions and one was replaced with another plot (see Table 1a). The deferred plots will be measured during the remaining two annual measurement cycles. One plot was abandoned for Health and Safety reasons and another plot was abandoned due to denied access. One plot was deemed to be in natural forests and transferred to the natural forest inventory list. And one plot was a “replacement plot” but surplus and therefore not measured.

Based on the national planted forest inventory design, the 2018 plot sample represents 1/5th of all plots in post-1989 and pre-1990 planted forests. Of the 140 plots, 111 were re-measured plots, established during earlier measurement cycles, and 29 were newly installed plots on additional grid-points, now included either due to the intensification of sampling (pre-1990 forest was previously sampled on an 8km x 8km grid but is now sampled on a 4km x 4km grid similar to post-1989 forest) or because of additional post-1989 forest area found while improving forest mapping.

Of the 140 plots measured in 2018, 112 were found suitable for generating a national yield table. The remaining 28 plots were deemed not to be suitable (Tables 1b & 2). Of these, 7 were in unstocked areas, 14 were recently harvested, 2 were classified as a wilding stand, 4 had a young crop present but measurements did not allow yield table generation, and 1 plot was windthrown. Three plot measurements were also found to produce suspicious FCP model runs and were excluded from the yield estimation. One plot was also replaced with another plot due to access problems.

Of the 112 plots used to generate yield tables, 39 were in pre-1990 planted forest and 73 in post-1989 forest. One plot in post-1989 planted forest and one plot in pre-1990 planted forests had multiple crop-types. Of these 112 plots, 12 pre-1990 planted forest plots and 11 post-1989 planted forest plot were measured for the first time in 2018.

[1] While randomly chosen points were assigned to each panel (year) the spatial distribution was taken into account to achieve a more or less even number of sample plots for each region.

Table 1: Inventory plots in the 2018 measurement period that were not included in the yield calculation for pre1990 and post1989 planted forests. Reasons are given for each plot and treatment suggestions given.

Part A	Plot-ID	Status	Land use classification	Reason	Treatment
Plots not visited by Interpine in 2018	AT122A5	Measurement delayed	Post-1989	Storm damage	Include in next years' measurement programme
	AU146E5	Measurement delayed	Post-1989	Not accessible at visit (access denied)	Include in next years' measurement programme
	BG129E1	Measurement delayed	Post-1989	Not accessible at visit (access denied)	Include in next years' measurement programme
	BL103	Measurement delayed	Post-1989	Not accessible at visit (access denied)	Include in next years' measurement programme
	CK78	Replaced with CR81E1	Post-1989	Not accessible at visit (access denied)	Replaced with CR81E1 and CK78 measure included into future measurement programme
	CO97A5	Measurement delayed	Pre-1990	Not accessible at visit (access denied)	Included in next years' measurement programme
	CP81A5	Abandoned	Post-1989	Cliff not safe	Abandoned
	CT97	Measurement delayed	Post-1989	Not accessible at visit (access denied)	Included in next years' measurement programme
	DK56E5	Measurement delayed	Post-1989	Failed to gain access	Included in next years' measurement programme
	BQ110	Natural forest	Pre-1990 natural forest	Shifted to natural forest	Will be measured as natural pre-1990 forest
	BT119	Measurement delayed	Post-1989	Previously measured as natural forest	Included in next years' measurement programme
	CX53	Measurement delayed	Pre-1990 planted forest	Previously measured as natural forest	Included in next years' measurement programme
	CJ97A5	Measurement delayed	Post-1989	Landowner wanted to be on side	Included in next years' measurement programme
	CW95A5	Replacement plot – not required	Pre-1990 planted forest	Was replacement plot for CO97A5 but not required in 2018	Reverted to 2020
	DO60E1	Measurement delayed	Post-1989	Site access not possible (track conditions)	Included in next years' measurement programme
	BM103A5	Need to be confirmed next year	Pre-1990 planted forest	Grassland within mapped planted forest area	Included in the calculation of c-stocks in unstocked areas
	CI33	Need to be confirmed next year	Pre-1990 planted forest	Garden within mapped planted forest area	Included in the calculation of c-stocks in unstocked areas
	CS50	Need to be confirmed next year	Pre-1990 planted forest	Grassland within mapped planted forest area	Included in the calculation of c-stocks in unstocked areas
	CZ55	Abandoned	Post-1989	Access denied	abandoned
	Z163E1	Need to be confirmed next year	Post-1989	Duck Pond within mapped planted forest area	Included in the calculation of c-stocks in unstocked areas

Table 1 cont.

Table 1 (B)	Plot-ID	Status	Land use classification	Reason	Treatment
Measured 2018 Plots not used for crop yield calculation	AJ165	Wilding plot	Pre-1990	No planted crop	Calculate C stocks for wilding area
	AM137E1	Wilding plot	Post-1989	No planted crop	Calculate C stocks for wilding area
	AZ136	Unstocked	Pre-1990	Unstocked	Calculate C stocks for non-stocked area
	AV141E5	Unstocked	Pre-1990	Unstocked (natives only)	Calculate C stocks for non-stocked area
	CQ59	Unstocked	Post-1989	On paddock	Outside of forest –not modelled but used for carbon stocks for stocked area
	CK99A5	Native	Pre-1990	unstocked	Calculate C stocks for non-stocked area
	CL98A5	Native	Pre-1990	unstocked	Calculate C stocks for non-stocked area
	BX102E5	Native	Post-1989	unstocked	Calculate C stocks for non-stocked area
	DU52A5	Native	Post-1989	unstocked	Calculate C stocks for non-stocked area
	BZ102	2012 measure excluded	Post-1989	Earlier measurement too young	Not modelled at age 2.1years
	DP58E5	2007 measure excluded	Post-1989	2007 measure did not enable FCP runs	Not modelled
	DQ60A5	2018 measure excluded	Post-1989	2018 measure did not enable FCP runs	Not modelled
	CG33E1	Measurement delayed	Pre-1990	Not accessible at visit (access denied)	has been replaced with CA21

Table 2. Inventory plots in the 2018 measurement period of which the 2018 measurement was not included in the yield calculation for pre1990 and post1989 planted forests because of recent harvest or young age. Plots were accounted for when calculating overall stock estimates at measurement.

Plot-ID	Status	Land use classification
AR159E1	Harvested	Post-1989
CA30A5	Harvested	Post-1989
DB55	Harvested	Post-1989
DD73E1	Harvested	Post-1989
DF82	Too young	Post-1989
DP61E5	Harvested	Post-1989
DT51	Harvested	Pre-1990
BO118	Harvested	Pre-1990
BW19	Harvested	Pre-1990
BZ19	Harvested	Pre-1990
CA20	Harvested	Pre-1990
CY65	Harvested	Pre-1990
DB62	Harvested	Pre-1990
DS58	Harvested	Pre-1990
DF79E5	Too young	Pre-1990
DS64E5	Too young	Pre-1990
CP66E5	Too young	Pre-1990
CA21	Harvested	Pre-1990
CL95	Windthrow	Pre-1990

Estimating carbon stocks at measurement

Carbon stocks per hectare at measurement were calculated for pre-1990 planted forests and post-1989 planted forest for all 140 plots measured in 2018 with 131 plots contributing to the net-stocked carbon stocks, 7 plots solely to carbon in the unstocked area of planted forests (plus four plots not measured by Interpine) and 2 plots representing carbon stocks in wilding areas. As in previous analyses, carbon stocks were calculated using the ratio estimator approach (to area weight the estimate) (Paul et al. 2014). For plots that were too young (~<3-4years), windthrown or recently harvested a carbon value of zero was assigned.

Non-crop data from the latest measurement from all plots in the inventory was used to calculate carbon stocks for the non-crop pool in the understorey of net-stocked area as well as unstocked areas (full plots). The last measurement was used without any time-series adjustment based on the assumption that average non-crop carbon stocks do not change significantly over time. Non-crop carbon stocks are all woody vegetation with a DBH ≥ 2.5 cm and estimated according to Paul et al. (2016). We used non-crop tree data from the inventory classified as crop-type “0” for understorey carbon stock calculations in stocked plots. Plots without crop-trees were used as the plot set for carbon stock calculations for unstocked areas.

Analysis approach to generate yield tables

Yield-table estimation is usually based on single plot measurements. However for the purpose of accurately estimating long-term inter-rotational carbon sequestration rates the use of multiple measurements of permanent sample plots becomes important. Over time the use of such repeated measurements not only improves the field data for a plot by identifying and correcting previous measurement errors but can also aid in the improvement of yield estimation for a site over the length of a rotation and beyond.

Interpolating yield from multiple measurements

An interpolation method was used to generate plot specific yield tables from multiple measurements. Yield values based on the backcast values from the first measurements were used from year zero to the year of the first measurement. A straight interpolation was used between the first and the second measurement and any subsequent measurements. From the last measurement onwards the forecasts based on the last measurement were used to predict the stand yield until age 40 for post-1989 planted forest plots or 60 years for pre-1990 planted forest plots. An example is given in Figure 1.

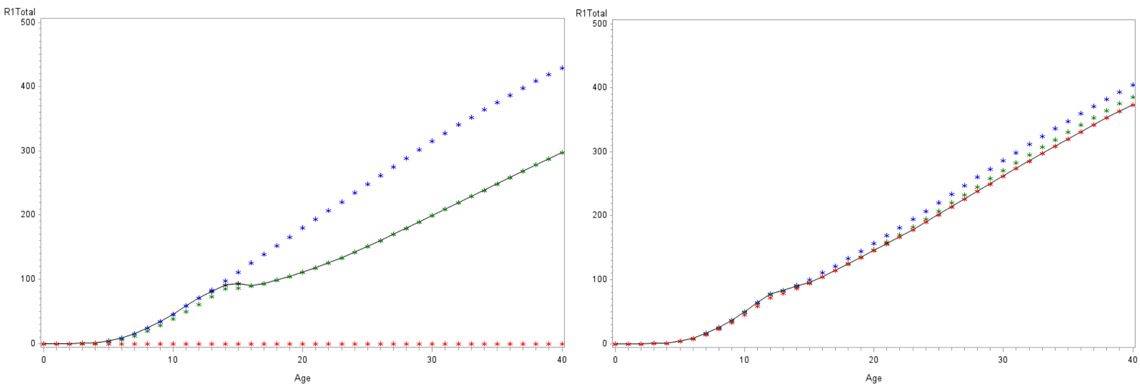

Figure 1: Yield table (dots) for two example post-1989 planted forest plots, constructed based on the interpolation method from three yield curves based on measurements in 2008 (blue), 2011 (green) and

2018 (red). Y-axis: total C t ha^{-1}. Left graph shows plots with two measurements and a thinning between the measurements. Right graph shows a yield curve based on three measurements.

Area weighted average yield table for plots measured in 2018

Once plot specific yield tables were generated using the above method, a ratio estimator approach was used to combine all plot specific yield tables into an area weighted average yield table in the same way as in previous analyses, e.g. Paul et al. (2016), Paul et al. (2017), Paul et al. (2018).

Imputation of yield

Yield tables for pre-1990 and post-1989 planted forest have been produced in the past using an average of all the plot-level yield tables weighted by plot area. However, this approach may not be optimal because the quality of the information contained within each plot-level table can vary with age and time since measurement. This is because the value of carbon in a plot-level yield table is exact (apart from model prediction error) only for ages coinciding with measurement ages. For all other ages, there is a degree of forecasting or backcasting error. We considered it desirable to take account of this when producing final average yield tables (Paul et al. 2017). At ages close to measurement age the tables should be given a higher weighting, and at ages more distant from the measurement age they should be given a lower weighting. The approach we used is described in this section.

Firstly, it was necessary to estimate typical forecasting and backcasting errors. Forecasting error can be estimated by comparing the predicted yield at the age of the second measurement from a yield table produced from the first measurement. Similarly, backcasting errors can be estimated by comparing predicted yield at the age of the first measurement from a yield table produced from the second measurement. In both cases, the error can be calculated as the absolute difference between the predicted and actual yield. For plots measured three times, forecasting errors can be obtained for time 1 to 2, time 1 to 3, and for backcasting from time 3 to 1, and 3 to 2. Across all plots, 527 estimates of forecasting error and an equal number of estimates of backcasting error were obtained in this way across all plots, with the time forecast or backcast ranging from 1 to 11 years and averaging 4.9 years. As expected, errors increase with time forecast or backcast, and by definition they are zero when forecasting or backcasting time is zero. Zero-intercept linear regression models were fitted for predicting forecast/backcast error, calculated as the square of the difference between the actual and the predicted yield, as a function of time forecast or backcast. These models estimate forecast/backcast error expressed as a variance and are of the form:

(1) $$\sigma_{fb}^2 = a \times (Forecast\ or\ backcast\ time)$$

where *a* is the regression coefficient.

When combining estimates of an unknown population mean with different errors, the correct procedure is to weight them by the inverse of their variances. For any plot-level yield table, the variance for a particular age is the sum of the sampling variance (σ^2_s) and the forecasting/backcasting error variance (σ^2_{fb}). The sampling variance between plots for a given age represents the natural variation between plots and accounts for variation in site productivity and management practices.

To estimate sampling variance, we firstly calculated the total variance (σ^2_{total}) between yields at each age across all plot-level yield tables. We then used Eqn (1) to estimate the forecasting/backcasting variance for each age in every plot-level yield table, and summed these across all plots to provide an estimate of the average forecasting/backcasting variance at each age. Sampling variance was then calculated by subtracting this from the total variance.

A weighting was then derived for each age in each plot-level yield table taking account of both forecast/backcast error and plot area as follows:

(2) $$Weight = Plotarea \times \sigma_s^2 / \left(\sigma_s^2 + \sigma_{fb}^2\right)$$

The average yield for each age was then calculated as a weighted average across all the plot-level yield tables using weights calculated by Equation (2).

Results and discussion

The 2018 inventory dataset

The average age of measured pre-1990 planted forests plots was 11.5 years. The age-class distribution of the 2018 inventory dataset is shown in Figure 2[2]. The pre-1990 planted forest age class distribution for the 2018 inventory is skewed towards very young stands (<5 years) as a result of recent harvesting. The number of stands 20 years and older is very small, also the result of recent harvesting of age classes 20 years and over. Eleven plots were recently harvested (between 2015 and 2018, age less than 3 years) with an average harvesting age of approximately 32 years[3].

The average age of measured post-1989 planted forests is 19 years. The post-1989 planted forest age distribution is skewed towards ages close to rotation end (20-25 years) reflecting the high planting rate in the early to mid-90's. Eight plots with trees younger than 5 years were found in post-1989 planted forest, six of them now in the second rotation. These six plots were recently harvested with an average harvesting age of 22 years[4].

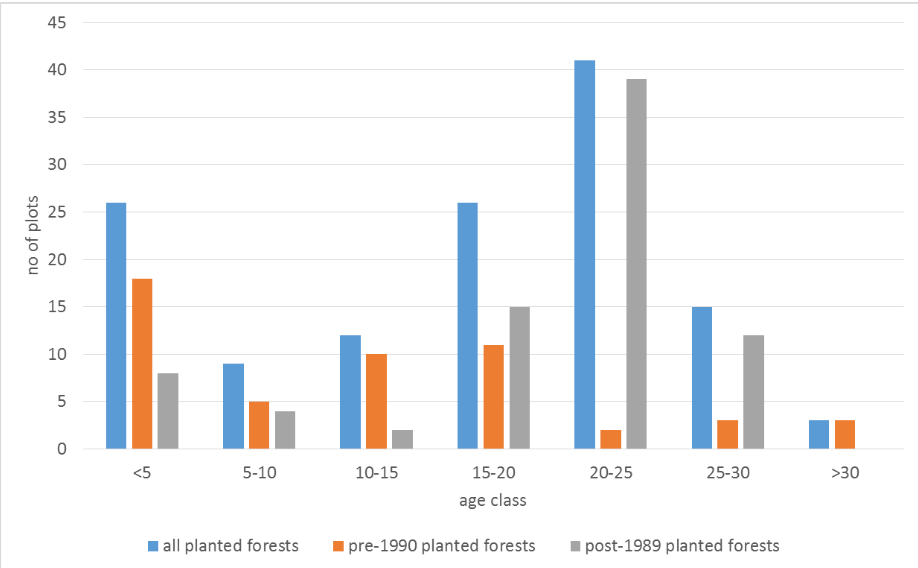

Figure 2: Age class distribution of plots measured and analysed in 2018 for all planted forests, pre-1990 planted forest and post-1989 planted forest.

The average 300 Index and Site Index for pre-1990 forest plots measured in 2018 were 22.5 m^3 ha^{-1} yr^{-1} and 28.8 m respectively, similar to the estimates for the 2017, 2016 panels and the 2015 full periodic inventory (Table 3). Average stocking in 2018 was 496 stems ha^{-1} while in 2017 and 2016 it was higher at 645 stems ha^{-1} and 616 stems ha^{-1} respectively (576 stems ha^{-1} in 2015).

The average 300 Index and Site Index for post-1989 forest plots measured in 2018 were 27.2 m^3 ha^{-1} yr^{-1} and 29.5 m respectively, compared to slightly lower estimates for 2017 and 2016 (Table 3). The last full inventory in post-1989 forests in 2012 reported a similar 300 Index (26 m^3 ha^{-1} yr^{-1}) and Site Index (29 m). Average stocking for the 2018 plots in post-1989 planted forests was with 587 stems ha^{-1}, somewhat higher compared with 512 stems ha^{-1} in 2017 and 475 stems ha^{-1} in 2016, although similar to the 600 stems $ha^{-1}$for the full inventory in 2012.

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[2] Plots with unknown age (e.g. unstocked plots) were excluded from the graph.
[3] Calculated as the age at the last measurement plus 1.5 years ((2018-2015)/2).
[4] Calculated as the age at the last measurement plus 3 years ((2018-2012)/2).

Table 3: Indices values for pre-1990 and post-1989 planted forests for the last periodic inventory (full sample) and the annual inventories in 2016, 2017, 2018 each based on a random sample of 1/5th of all plots located in planted forests.

		LAST PERIODIC INVENTORY	2016	2017	2018
PRE-1990 PLANTED FORESTS	300 Index (m^3 ha^{-1} yr^{-1})	24	24.9	24.8	22.5
	Site Index (m)	30	30.0	28.6	28.8
POST-1989 PLANTED FOREST	300 Index (m^3 ha^{-1} yr^{-1})	26	24.2	25.9	27.2
	Site Index (m)	29	27.7	28.8	29.5

Carbon stocks at measurement for plots measured in 2018

Crop-tree carbon stocks in net stocked areas were estimated to total 70.7 tC ha^{-1} (95% CI ±5.0 tC ha^{-1}) in pre-1990 planted forest and 163.4 tC ha $^{-1}$ (95% CI ±21.0 tC ha^{-1}) in post-1989 planted forest. The breakdown into the four carbon pools Above-ground live (AGL), Below-ground live (BGL), Dead Wood Litter (DWL) and Fine Litter (FL) is given in Table 4.

Table 4: Crop carbon stocks in net-stocked area of pre-1990 planted forests and post-1989 planted forests at measurement in plots measured in 2018.

2018	Total Crop (tC ha^{-1})	AGL Crop (tC ha^{-1})	BGL Crop (tC ha^{-1})	DWL Crop (tC ha^{-1})	FL Crop (tC ha^{-1})
Pre-1990 planted forests	70.7 (CI±5.0)	51.0 (CI±5.3)	11.0 (CI±1.0)	3.5 (CI±1.3)	5.2 (CI±0.4)
Post-1989 planted forests	163.4 (CI±21.0)	123.5 (CI±16.2)	26.1 (CI±3.5)	5.7 (CI±1.4)	8.1 (CI±2.8)

Non-crop carbon stocks in net stocked areas were estimated to total 2.9 tC ha^{-1} (95% CI ±0.8 tC ha^{-1}) in pre-1990 planted forest and 6.1 tC ha^{-1} (95% CI ±1.6 tC ha^{-1}) in post-1989 planted forest. The breakdown into the different pools is given in Table 5.

Table 5: Average non-crop carbon stocks in net-stocked area of pre-1990 planted forests and post-1989 planted forests at last measurement in all stocked plots.

	Total Non-crop (tC ha^{-1})	AGL Non-crop (tC ha^{-1})	BGL Non-crop (tC ha^{-1})	DWL Non-crop (tC ha^{-1})
Pre-1990 planted forests	2.9 (CI±0.8)	2.2 (CI±0.6)	0.5 (CI±0.1)	0.2 (CI±0.1)
Post-1989 planted forests	6.1 (CI±1.6)	4.5 (CI±1.2)	1.1 (CI±0.3)	0.5 (CI±0.2)

Non-crop carbon stocks in unstocked areas in pre-1990 planted forest were 28.2 tC ha^{-1} (n=7). In post-1989 planted forest, unstocked areas carried 47.6 tC ha^{-1} (n=17) of carbon in woody biomass (Table 6).

Table 6: Average non-crop carbon stocks in unstocked areas of pre-1990 planted forests and post-1989 planted forests at the last measurement of all plots.

	Total Non-crop (tC ha^{-1})	AGL Non-crop (tC ha^{-1})	BGL Non-crop (tC ha^{-1})	DWL Non-crop (tC ha^{-1})
Pre-1990 planted forests	28.2 (CI±41.3)	22.1 (CI±33.1)	5.5 (CI±8.1)	0.6 (CI±0.9)
Post-1989 planted forests	47.6 (CI±34.2)	36.5 (CI±26.3)	9.1 (CI±6.5)	1.9 (CI±2.0)

The non-crop carbon estimates in net-stocked areas, and the carbon estimate for unstocked areas in planted forests include those plots that were not visited by the inventory teams recently and need to be confirmed in another measurement year (Z163E1, CS50,CI33 and BM103A5; Table 1).

Comparison between yield tables derived from the 2018 and 2017 plot sets

Analysis of the 2018 measurement of permanent sample plots in the national planted forest inventory showed differences in carbon sequestration between previously measured plots and plots measured for the first time in 2018 for pre-1990 but not for post-1989 planted forest.

The pre-1990 planted forests area weighted yield table based on plots measured for the first time in 2018 had lower carbon stocks at older ages compared to the table based on 2018 plots with previous measurements (Figure 3). While the 2018 pre-1990 planted forest yield table based on plots with multiple measurements matched the 2017 adjusted final yield table, the 2018 yield table based on plots measured for the first time differed in its average mean annual increment by - 0.9 tC ha^{-1}.

The area weighted yield tables for post-1989 planted forest based on plots measured for the first time in 2018 and those with multiple measurements showed no large discrepancy with both strata having nearly identical yield curves (Figure 3). Comparing the 2017 and 2018 yield tables for post-1989 planted forest, the 2017 yield table is lower having a reduction of the mean annual increment of -0.75 tC ha^{-1} (Figure 3).

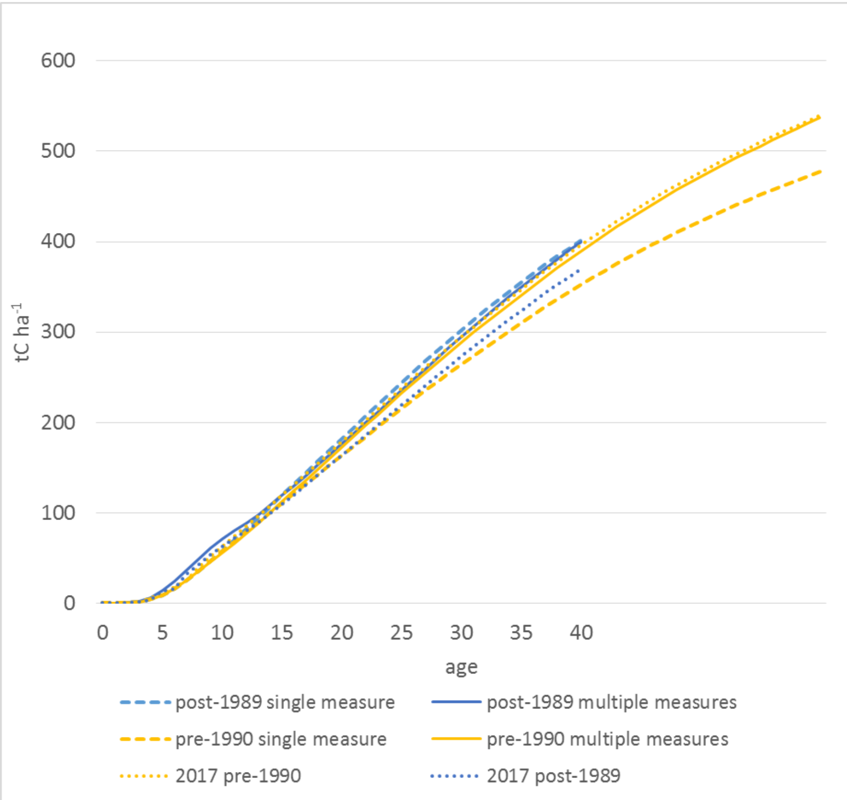

Figure 3: Difference between net-stocked, area weighted carbon yield tables (crop-trees only; total C t ha^{-1}) generated for pre-1990 and post-1989 planted forests using different subsets (single measured plots, plots with multiple measurements).

The 2018 analysis indicates that pre-1990 planted forest plots measured in 2018 are sequestering slightly less than those measured in the previous year compared to slower growing stands that were measured the first time in 2018. This is in contrast to the 2017 and 2016 analyses where pre-1990 planted forest sequestered more than the post-1989 planted forests (Figure 4).

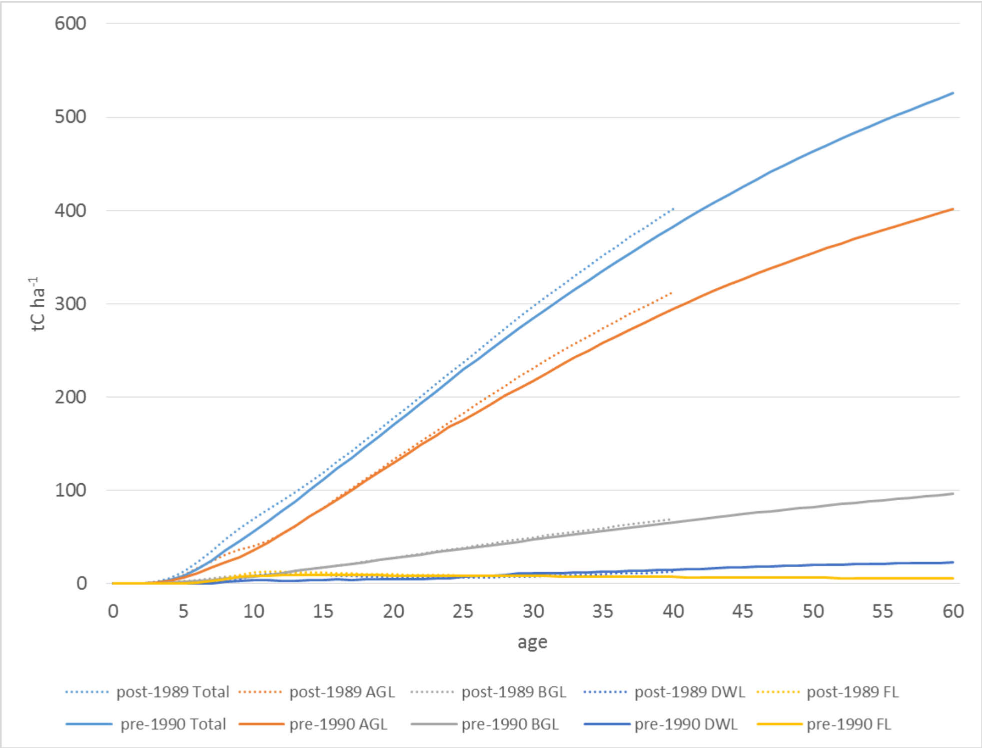

Figure 4: Difference between the area-weighted pre-1990 planted forest and post-1989 planted forest carbon yield tables created from all plots measured in 2018.

Adjustments for forecasting and backcasting error

The regression coefficients for Eqn (1) for estimating forecasting and backcasting error are given in Table 5. These show that forecasting errors are generally greater than backcasting errors, e.g., there is generally a greater error in estimating yield 5 years after a measurement than 5 years prior to a measurement.

Table 5. Regression coefficients for Equation (1).

	FORECASTING	BACKCASTING
Total	132.6	60.4
AGL	97.1	28.1
BGL	4.41	1.34
DWL	18.12	1.92
FL	1.96	1.31

The Eqn (1) models were used to estimate forecasting/backcasting variance for each age in every plot-level yield table, and summed across all plots to provide an estimate of the average forecasting/backcasting variance at each age. Sampling variance was then calculated by subtracting this from the total variance. The results are shown in Figures 5 and 6 with total, sampling and casting variation expressed as standard deviations.

The results show that except at very young ages, the error from forecasting or backcasting is much less than the level of sampling variation between plots. This means that plots requiring a considerable level of forecasting or backcasting can provide useful information on yield and are therefore given a significant weighting by Eqn (2). For example, to estimate the mean yield at age 10 years, a plot measured at age 10 years will be assigned a weighting of 1, while the projected yield from a plot measured at age 30 will be assigned a weighting of 0.76 in post-1989 forest and 0.73 in pre-1990 forest.

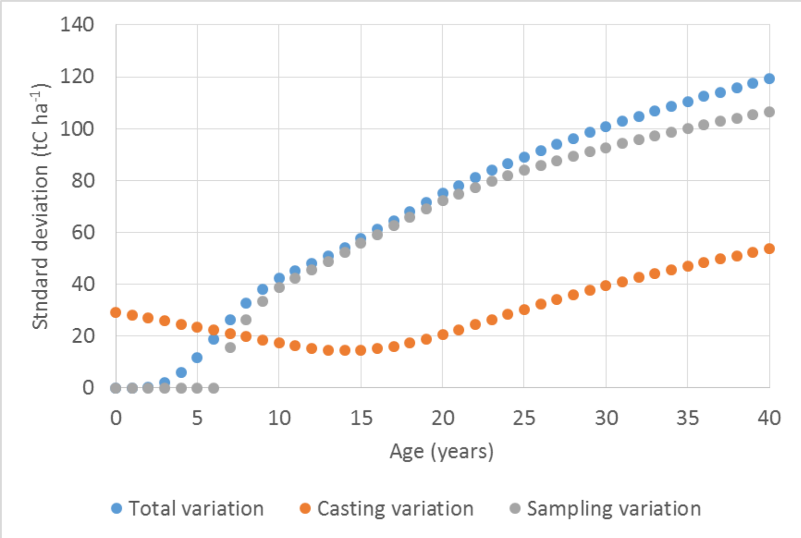

Figure 5: Sources of variation in total carbon yield table estimates between plots by age in post-1989 forest expressed as standard deviations. Shown are the total variation, sampling variation, and forecasting/backcasting variation.

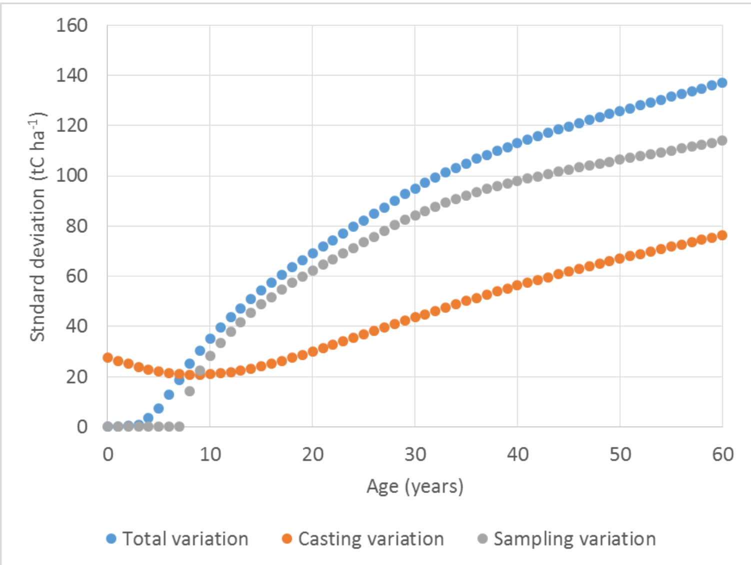

Figure 6: Sources of variation in total carbon yield table estimates between plots by age in pre-1990 forest expressed as standard deviations. Shown are the total variation, sampling variation, and forecasting/backcasting variation.

2018 Yield tables based on all inventory plots

Volume yield tables

Adjusted volume yield tables for pre-1990 planted forest and post-1989 planted forest, based on all measurements in the current and past inventory cycles (2007 – 2018) are shown in Tables 6
Volume tables were generated using the plot area weighted method without adjustments for backcast and forecast errors, which are assumed to be minimal based on the carbon backcasting/forecasting error analysis.

Carbon yield tables

Adjusted yield tables for pre-1990 planted forest and post-1989 planted forest, based on all measurements in the current and past inventory cycles (2007 – 2018), and using the forecasting/backcasting weighting method described above are shown in Tables 7 and 8. These adjusted yield tables take into account the estimated forecasting and backcasting error and should therefore give more precise estimates of stocks than simple area-weighted tables.

The adjusted yield tables for pre-1990 planted forests and post-1989 planted forests are compared in Figure 7 and show that yields at any given age are very similar. The comparison also shows the result observed in the 2018-only data of stocks being greater at a given age for post-1989 planted forest compared with pre-1990 planted forest did not hold for the yield tables based on all measurements.

The age-class distribution difference between post-1989 and pre-1990 planted forests is the main driver bringing the yield tables for both forest-classes closer together when using all plots with the imputation method. The pre-1990 forest age class distribution is overall more skewed towards younger ages than the post-1989 planted forests which is skewed toward older age-classes (e.g. for 2018 see Fig. 2). The differences in age-class distribution has a number of effects that “equalises” the yield between post-1989 and pre-1990 planted forests.

Firstly the older stock over 20 years in post-1989 planted forests is the less productive part of the post-1989 planted forest. The high number of post-1989 planted forests over 20 years have only a 300 Index of 25 m^3 ha^{-1} yr^{-1}, compared with 27 m^3 ha^{-1} yr^{-1} in the age class 10-20 years. Post-1989 planted forests 25 years and older only reaching a 300Index of 21.7 m^3 ha^{-1} yr^{-1}. Post- 1989 planted forests older than 28 years have only a 300 Index of 13 m^3 ha^{-1} yr^{-1} and this affects the overall yield curve for post-1989 planted forest at the older end. While according to the age these stands should not be accounted as post-1989 planted forests (planted before 1990) they are mapped as such and need to be included.
In comparison the few pre-1990 planted forests older than 20 years have a 300Index of 23 m^3 ha^{-1} yr^{-1} and forests over 25 years have a slightly higher 300Index (22.7 m^3 ha^{-1} yr^{-1}) than post-1989 planted forests. The high number of pre-1990 planted forests aging between 10 and 20 years averaging a 300 Index of 25 m^3 ha^{-1} yr^{-1} while the few post-1989 planted forests averaging a 300 Index of 27 m^3 ha^{-1} yr^{-1}, so post-1989 planted forests are still slightly more productive when comparing the same age-range but do not carry that much weight than the large cohort of older post-1989 forests.
Secondly the age-class distribution will also trigger the influence of the known better genetic improvement in New Zealand’s plantation forests and more recent planted plantations will carry better genetic stock than rotations before and older stands. The younger pre-1990 planted forests might therefore show better growth than the older post-1989 plantation forests, this is already evident as the 300Index in younger pre-1990 planted forests is the same (25 m^3 ha^{-1} yr^{-1} at age 10-20 years compared to ten years older post-1989 planted forests) irrespective of the still assumed farm-fertility effect.
Silvicultural effects could also play a role as silviculture differences can affect sequestration rates. Stocking as a mayor indicator of silvicultural differences does not vary much between strata, as in pre-1990 planted forests the overall stocking is 600 with stands less than 10 years old (at measurement) having a stocking of 857 stems ha^{-1}. The overall average stocking in Post-1989 planted forests is 534 stems ha^{-1} with stands younger than 10 years have on average 915 stems/ha. Similar average stockings are present in both post-1989 and pre-1990 planted forests.

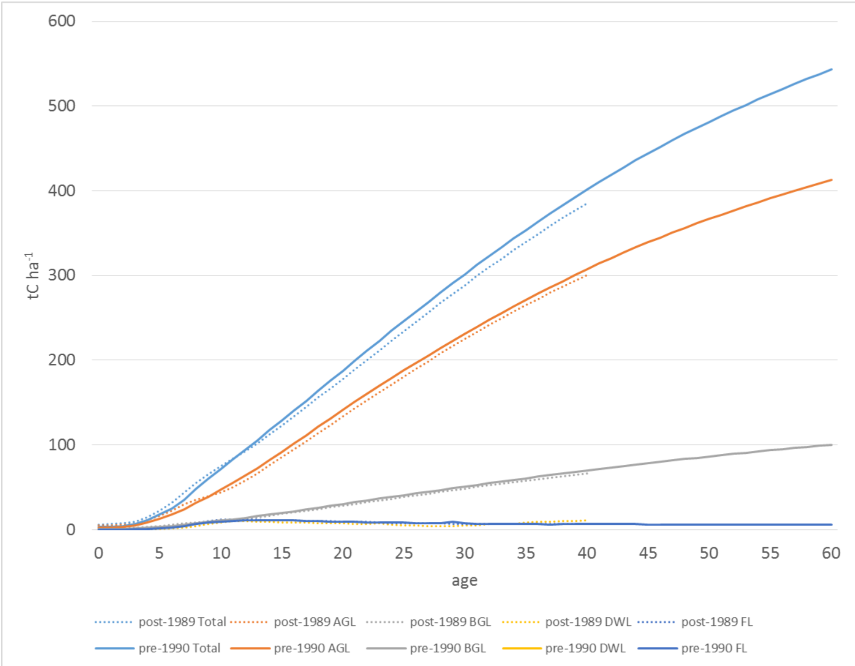

Figure 7: Difference between the adjusted pre-1990 planted forest and post-1989 planted forest yield table. Total carbon and the four pools, AGB, BGB, DW and FL are shown. A non-crop constant carbon amount was added (assumed to be constant over age; table 3)

Table 6: Adjusted pre-1990 and post-1989 planted forest volume yield tables (calendar years; crop-tree only in m^3 ha^{-1}). Means and 95% confidence intervals are given.

Age	pre-1990 planted forests Volume (m^3)		post-1989 planted forests Volume (m^3)	
	mean	**±95%CI**	**mean**	**±95%CI**
0	0.1	0.0	0.1	0.0
1	0.3	0.0	0.4	0.0
2	1.1	0.1	1.4	0.2
3	3.9	0.5	5.0	0.6
4	10.9	1.3	13.5	1.4
5	23.6	2.6	28.2	2.6
6	42.4	4.3	49.4	4.2
7	67.0	6.4	75.0	5.8
8	94.2	8.4	101.3	7.1
9	121.8	10.1	125.1	8.4
10	151.6	12.0	144.4	9.2
11	185.1	13.8	164.9	9.7
12	219.0	15.7	192.4	10.7
13	253.1	17.6	225.7	12.0
14	291.0	19.4	262.4	13.3
15	328.6	20.8	300.3	14.7
16	366.8	22.1	339.6	16.0
17	407.5	23.6	380.2	17.3
18	448.1	25.0	421.0	18.6
19	488.0	26.3	461.3	19.8
20	527.3	27.6	501.3	21.0
21	566.4	28.8	541.6	22.1
22	604.9	30.0	581.7	23.1
23	643.0	31.2	621.8	24.1
24	681.2	32.3	661.0	25.0
25	718.4	33.5	699.7	25.8
26	754.8	34.7	738.7	26.6
27	790.6	35.9	777.2	27.4
28	826.0	37.1	815.0	28.2
29	860.4	38.2	852.1	28.9
30	894.5	39.3	888.5	29.6
31	928.4	40.2	924.3	30.3
32	961.5	41.1	959.3	31.0
33	994.0	41.9	993.5	31.6
34	1026.0	42.7	1027.0	32.2
35	1057.2	43.4	1059.7	32.8
36	1087.8	44.1	1091.8	33.4
37	1117.7	44.9	1123.2	34.0
38	1147.0	45.5	1154.0	34.5
39	1175.8	46.2	1184.2	35.1
40	1204.1	46.9	1214.2	35.6
41	1231.7	47.5	--	--
42	1258.5	48.2	--	--
43	1284.6	48.8	--	--
44	1310.0	49.5	--	--
45	1334.8	50.1	--	--
46	1358.8	50.7	--	--
47	1382.3	51.3	--	--
48	1405.1	51.9	--	--
49	1427.4	52.6	--	--
50	1449.2	53.2	--	--
51	1470.4	53.8	--	--
52	1491.2	54.4	--	--
53	1511.5	55.0	--	--
54	1531.4	55.6	--	--
55	1550.9	56.2	--	--
56	1570.1	56.8	--	--
57	1588.9	57.5	--	--
58	1607.3	58.1	--	--
59	1625.5	58.7	--	--
60	1643.5	29.5	--	--

Table 7: Adjusted pre-1990 planted forest yield table (calendar years; crop-tree carbon plus net-stocked non-crop carbon in C t ha^{-1}). Means and 95% confidence intervals are given for total carbon and carbon in the four pools: AGB, BGB, DW and FL.

Age	Total		AGB		BGB		DWL		FL	
	mean	±95%CI	mean	±95%CI	Mean	±95%CI	mean	±95%CI	mean	±95%CI
0	2.94	0.79	2.23	0.59	0.51	0.1	0.2	0.1	0	0
1	3.19	0.79	2.4	0.59	0.58	0.1	0.2	0.1	0.01	0
2	3.87	0.79	2.92	0.6	0.71	0.1	0.2	0.1	0.03	0
3	6.26	0.85	4.66	0.63	1.26	0.13	0.2	0.1	0.14	0.01
4	11.03	1.12	8.12	0.82	2.22	0.19	0.22	0.1	0.47	0.05
5	17.68	1.61	13.15	1.18	3.21	0.27	0.25	0.1	1.07	0.12
6	24.79	2.19	18.25	1.57	4.3	0.33	0.31	0.13	1.92	0.22
7	34.77	2.89	24.38	1.98	5.81	0.43	0.65	0.27	3.93	0.48
8	47.77	3.68	31.8	2.43	7.44	0.54	2.05	0.63	6.48	0.77
9	59.94	4.36	38.92	2.89	8.89	0.63	3.95	0.92	8.18	0.86
10	71.42	4.94	46.59	3.37	10.46	0.73	5.15	0.99	9.22	0.86
11	82.72	5.48	54.77	3.86	12.12	0.82	5.79	1.08	10.05	0.86
12	93.98	5.97	63.21	4.34	13.83	0.92	6.33	1.17	10.61	0.85
13	105.24	6.45	71.72	4.79	15.56	1.02	7.33	1.15	10.63	0.8
14	116.82	6.93	80.98	5.16	17.46	1.1	7.66	1.44	10.72	0.82
15	128.54	7.37	90.8	5.5	19.48	1.18	7.51	1.79	10.75	0.84
16	140.3	7.78	99.21	5.88	21.22	1.27	9.53	2.1	10.33	0.77
17	152.19	8.18	109.14	6.23	23.29	1.34	9.73	1.84	10.02	0.7
18	164.12	8.56	121.38	6.56	25.88	1.42	6.94	1.12	9.92	0.64
19	175.95	8.95	132.37	6.88	28.21	1.5	5.73	0.99	9.64	0.59
20	187.65	9.32	140.91	7.16	30.06	1.58	7.36	1.26	9.33	0.5
21	199.34	9.67	149.66	7.45	31.99	1.66	8.68	1.48	9	0.47
22	211.07	10.03	160.62	7.72	34.41	1.73	7.67	1.45	8.37	0.52
23	222.77	10.38	171.53	7.99	36.84	1.8	6.36	1.13	8.04	0.51
24	234.44	10.74	180.85	8.26	38.95	1.88	6.39	0.83	8.26	0.46
25	245.97	11.09	189.97	8.53	41.03	1.94	6.93	0.94	8.05	0.41
26	257.34	11.45	198.98	8.8	43.11	2.01	7.5	1.15	7.75	0.36
27	268.56	11.84	207.77	9.09	45.16	2.09	8.32	1.31	7.31	0.32
28	279.68	12.21	214.64	9.38	46.8	2.18	10.38	1.68	7.85	0.33
29	290.7	12.56	221.37	9.66	48.44	2.26	11.9	1.99	8.99	0.45
30	301.59	12.87	232.57	9.88	51.06	2.32	10.46	1.69	7.5	0.45
31	312.35	13.17	243.88	10.07	53.72	2.38	8.44	1.26	6.3	0.35
32	322.91	13.47	254.03	10.26	56.14	2.44	6.1	0.95	6.64	0.33
33	333.31	13.74	263.6	10.43	58.45	2.5	4.66	0.79	6.6	0.32
34	343.59	13.98	272.16	10.58	60.56	2.55	4.24	0.8	6.62	0.33
35	353.67	14.22	280.63	10.71	62.66	2.59	3.78	0.83	6.59	0.34
36	363.56	14.44	288.31	10.85	64.61	2.64	4.13	0.91	6.5	0.35
37	373.28	14.66	295.6	10.98	66.49	2.69	4.9	0.86	6.3	0.33
38	382.84	14.87	301.62	11.1	68.09	2.74	6.72	0.94	6.41	0.31
39	392.25	15.06	307.58	11.21	69.68	2.78	8.32	1.18	6.67	0.32
40	401.5	15.24	314.86	11.33	71.59	2.82	8.4	1.24	6.65	0.32
41	410.54	15.43	322.04	11.45	73.47	2.87	8.42	1.29	6.61	0.31
42	419.32	15.61	329.07	11.57	75.33	2.92	8.37	1.33	6.55	0.3
43	427.85	15.77	333.9	11.68	76.7	2.96	10.78	1.45	6.47	0.31
44	436.13	15.93	338.72	11.79	78.08	3	12.97	1.54	6.36	0.32
45	444.18	16.1	348.31	11.9	80.57	3.04	9.77	1.25	5.53	0.35
46	452	16.26	352.9	12.01	81.91	3.08	11.72	1.31	5.47	0.35
47	459.61	16.4	353.92	12.11	82.43	3.12	17.06	1.69	6.19	0.31
48	467.02	16.56	359.09	12.22	83.92	3.16	17.8	1.71	6.2	0.3
49	474.23	16.71	364.27	12.33	85.42	3.2	18.39	1.73	6.15	0.29
50	481.25	16.86	369.36	12.44	86.9	3.24	18.9	1.75	6.08	0.28
51	488.1	17	374.34	12.54	88.37	3.27	19.37	1.77	6.02	0.28
52	494.79	17.14	379.23	12.65	89.82	3.31	19.8	1.79	5.94	0.28
53	501.32	17.28	384	12.76	91.24	3.35	20.2	1.8	5.87	0.28
54	507.71	17.43	388.68	12.86	92.65	3.39	20.58	1.81	5.8	0.28
55	513.96	17.58	393.27	12.97	94.04	3.43	20.92	1.82	5.73	0.27
56	520.09	17.71	397.77	13.09	95.41	3.47	21.25	1.82	5.66	0.26
57	526.1	17.85	402.18	13.19	96.77	3.51	21.55	1.82	5.59	0.26
58	531.99	18	406.52	13.3	98.11	3.55	21.83	1.82	5.53	0.26
59	537.79	18.15	410.79	13.42	99.44	3.59	22.09	1.82	5.46	0.26
60	543.54	9.13	415.04	13.54	100.75	3.63	22.34	1.82	5.4	0.26

Table 8: Post-1989 planted forest yield table (calendar years; crop-tree carbon plus net-stocked non-crop carbon in C t ha^{-1}). Means and 95% confidence intervals are given for total carbon and carbon in the four pools: AGB, BGB, DW and FL.

Age	Total		AGB		BGB		DWL		FL	
	mean	±95%CI	mean	±95%CI	Mean	±95%CI	mean	±95%CI	mean	±95%CI
0	6.15	1.57	4.53	1.18	1.12	0.29	0.5	0.2	0	0
1	6.44	1.57	4.75	1.18	1.19	0.29	0.5	0.2	0.01	0
2	7.38	1.58	5.44	1.18	1.4	0.3	0.5	0.2	0.04	0
3	8.82	1.6	6.35	1.2	1.84	0.31	0.5	0.2	0.12	0.02
4	14.63	1.79	10.7	1.35	2.98	0.34	0.52	0.2	0.43	0.07
5	22.01	2.18	16.12	1.61	4.17	0.39	0.55	0.2	1.17	0.15
6	31.54	2.6	21.85	1.86	5.42	0.44	1.47	0.3	2.79	0.3
7	44.17	3.14	29.5	2.14	7.03	0.5	2.45	0.53	5.18	0.53
8	54.97	3.6	35.44	2.39	8.24	0.55	3.65	0.72	7.65	0.72
9	65.22	3.97	39.82	2.54	9.08	0.57	6.33	0.96	9.97	0.85
10	74.48	4.26	44.26	2.63	9.99	0.59	8.72	1.16	11.52	0.9
11	83.23	4.49	50.31	2.81	11.25	0.63	9.69	1.19	11.98	0.86
12	92.27	4.72	57.89	3.08	12.82	0.69	9.7	1.14	11.86	0.79
13	101.95	4.96	66.47	3.36	14.58	0.74	9.36	1.08	11.54	0.71
14	112.18	5.22	75.5	3.65	16.41	0.8	9.03	1.03	11.23	0.65
15	122.74	5.51	84.86	3.94	18.31	0.87	8.66	0.98	10.91	0.6
16	133.57	5.79	94.45	4.23	20.26	0.92	8.27	0.93	10.59	0.55
17	144.62	6.07	104.2	4.51	22.25	0.99	7.88	0.86	10.28	0.5
18	155.74	6.37	113.92	4.78	24.25	1.05	7.6	0.82	9.98	0.46
19	166.87	6.66	123.51	5.02	26.23	1.11	7.44	0.8	9.69	0.43
20	177.98	6.94	133.09	5.27	28.22	1.17	7.27	0.77	9.39	0.39
21	189.09	7.21	142.91	5.5	30.29	1.23	6.79	0.71	9.1	0.36
22	200.25	7.47	152.31	5.71	32.3	1.27	6.85	0.73	8.79	0.34
23	211.53	7.72	160.96	5.91	34.17	1.32	7.8	1.27	8.6	0.37
24	222.78	7.96	172.46	6.09	36.65	1.37	6.01	1.12	7.64	0.41
25	234	8.18	183.08	6.27	38.96	1.42	4.57	0.54	7.38	0.37
26	245.19	8.39	191.56	6.44	40.84	1.46	4.87	0.55	7.92	0.31
27	256.28	8.6	201.59	6.59	43.06	1.5	4.17	0.56	7.46	0.28
28	267.25	8.8	210.94	6.75	45.14	1.54	3.99	0.56	7.18	0.28
29	278.09	9	220.01	6.9	47.19	1.59	4.22	0.55	6.66	0.29
30	288.78	9.2	228.47	7.05	49.12	1.64	4.7	0.55	6.49	0.31
31	299.31	9.38	236.26	7.18	50.92	1.68	5.16	0.56	6.96	0.3
32	309.64	9.56	243.58	7.32	52.63	1.72	6.7	0.47	6.72	0.24
33	319.75	9.73	251.95	7.45	54.59	1.74	6.7	0.42	6.51	0.23
34	329.68	9.89	259.75	7.56	56.43	1.77	6.74	0.59	6.75	0.25
35	339.41	10.06	266.1	7.68	57.97	1.81	8.42	0.75	6.92	0.24
36	348.96	10.22	273.35	7.79	59.72	1.85	8.98	0.79	6.9	0.24
37	358.33	10.38	280.54	7.91	61.48	1.89	9.47	0.83	6.84	0.23
38	367.53	10.53	287.61	8.02	63.21	1.92	9.93	0.86	6.78	0.22
39	376.58	10.67	294.54	8.13	64.93	1.95	10.4	0.89	6.7	0.22
40	385.56	5.54	301.42	8.24	66.65	1.99	10.86	0.93	6.63	0.22

Using yield tables for estimating carbon stocks and stock change

Data collected from the national forest inventory can be used to estimate carbon stocks and stock changes using two approaches:

- The direct approach in which the carbon stock at a particular date is estimated by the average stock across all plots at that date
- The yield table approach in which a yield table derived from the inventory is applied to the age distribution of stands in the forest and summed to provide an average stock across the forest

To estimate stock change using the direct approach, it is necessary to apply the method at two separate dates, and calculate stock change as their difference. Therefore, using this approach, stock change can only readily be calculated between dates close to actual measurements. The yield table approach is far

more flexible as it can be used to calculate stock change between any pair of dates simply by applying the yield table to the appropriate age distribution at each date and calculating the difference. This allows the annual estimates required for GHG inventory reporting to be calculated.
However, while the direct approach provides unbiased estimates of stocks as long as the plots in the inventory are a representative sample of the forest, the yield table method may not always provide unbiased estimates.

In this section of the report, we compare these two approaches for estimating stocks in pre-1990 and post-1989 planted forest. To do this, we applied the direct approach by calculating average stocks across all plots at all measurement dates. The yield table approach was applied by estimating the stock for each plot measurement from the appropriate yield table using the measurement age. In this comparison we used simple averages and did not weight by plot area. Nor did we consider the effect of unstocked or very young plots. In practice these effects should be taken into account with both approaches, but for purposes of comparing the methods, they can be ignored. We used the yield tables given in Tables 7 and 8 for applying the yield table approach. A similar analysis was reported previously for the 2017 analysis. The results for 2018 are shown in Figure 8 and 9.

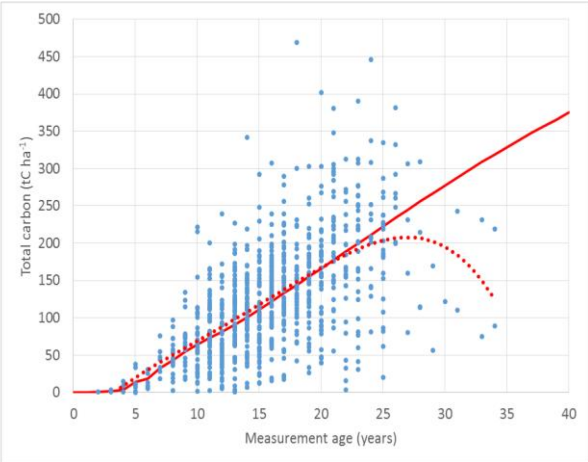

Figure 8. Total carbon stocks for individual plots compared with the national yield table for post-1989 planted forest. The blue dots show carbon stocks for individual plots measured since 2010 at time of measurement including multiple measurements. The solid red line shows total carbon by age predicted by the national yield table. The red dashed line is a 4th order polynomial regression curve fitted to the plot data.

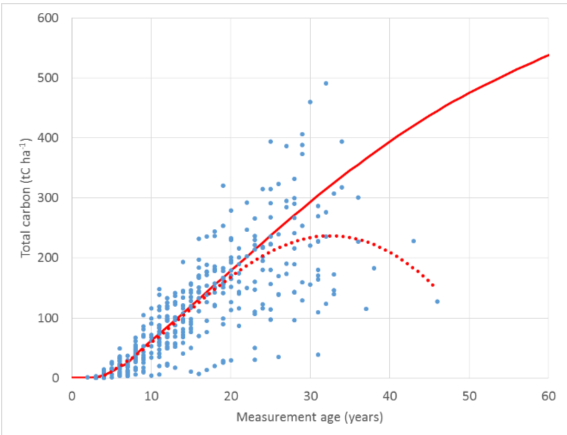

Figure 9. Total carbon stocks for individual plots compared with the national yield table for pre-1990 planted forest. The blue dots show carbon stocks for individual plots measured since 2010 at time of measurement including multiple measurements. The solid red line shows total carbon by age predicted by the national yield table. The red dashed line is a 4th order polynomial regression curve fitted to the plot data.

For post-1989 forest, the estimate of total carbon stocks using the yield table approach was 135.32 (2017: 128.5) tC ha^{-1} compared with the direct estimate of 125.95 (2017: 119.5) tC ha^{-1}. For pre-1990 forest, the yield table estimate was 121.4 (2017: 119.8) tC ha^{-1} compared with the direct estimate of 107.04 (2017: 106.9) tC ha^{-1}. For both forest types, the yield table method over-estimated stocks when compared with the direct method, by 7.4% in post-1989 forest and 13.5% in pre-1990 forest.

There could be a number of reasons for this effect. One of the main reasons for the difference between the yield table and direct methods is that stands are not selected for harvesting in a random fashion. In practice stands harvested at younger ages tend to have above average productivity as they reach their productivity goal earlier. Conversely, stands on less productive sites may be left to grow longer to achieve an economic mean tree size. As the more productive stands are harvested, less productive stands are left to grow to older ages. When the yield table is applied to these older stands, it tends to over-estimate their stocks.

A second reason is the species-mix used to derive the overall yield table. Figure 10 shows the yield table compared with measurements for three species groups for pre-1990 planted forests. The non-radiata species (Douglas-fir and other species) show much lower direct carbon estimates than the yield table. As these alternative species tend to be managed with longer rotations than radiata pine, this partly explains why the yield curve over-predicts at older ages. This result suggests that incorporating species-specific yield tables into the LUCAS system could remove the much of the over-prediction produced by the generalised common yield table for older-aged stands.

When the post-1989 planted forest yield table is compared to radiata pine plots, the difference between yield table and direct measures is minimal (Figure 11). These species with longer rotation lengths such as Douglas-fir are a large reason for the discrepancy between direct stock estimates and the generated yield table. However, Eucalypts, having a strong early growth and represented at younger ages do not contribute to the discrepancy. Also, the divergence beyond age 25 years for radiata pine plots is driven by three older plots established before January 1990 (and not measured in 2018). The presence of these much older-aged stands in the post-1989 planted forest strata due to mapping errors or other reasons contributes to the yield difference.

A further reason for the over-prediction at older ages may be that younger stands are generally more productive than older stands due to improvements in forest management, genetic improvement, or other reasons. As the yield table is based on all plots, this would result in an over-estimate of yield in older stands. The behaviour can be seen by plotting the yield table estimate of total carbon against the measured stock at each measurement age (Figures 8 and 9). This shows that the yield table closely follows measured stocks until about age 20 years, but beyond this age it begins increasingly to over-predict actual stocks. This trend is visible for both pre-1990 and post-1989 forest. With the harvest of older unproductive stands in the near future the age-issue may decrease as the NZ Forest industry improves the efficiency of plantation forestry in post-1989 planted forests and post-1990 planted forests but will not fully disappear due to ongoing improvements in genetics and changes in silviculture.

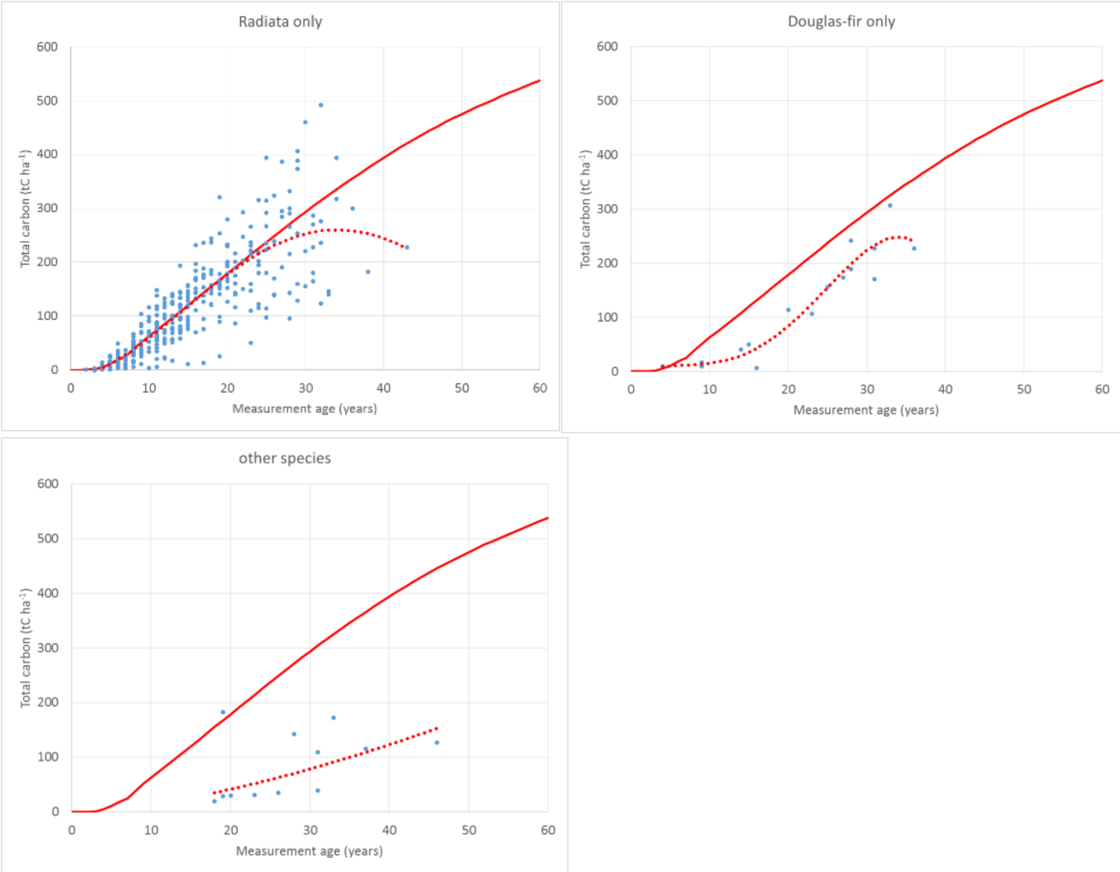

Figure 10. Total carbon stocks for individual plots compared with the national yield table for pre-1990 planted forest, broken down in three species groups: Top-left: Radiata pine; Top-right: Douglas-fir; Lower-left: other species. Within each plot, the blue dots show carbon stocks for individual plots measured since 2010 at time of measurement including multiple measurements, the red dashed line is a 4th order polynomial regression curve fitted to the plot data, and the solid red line shows total carbon by age as predicted by the national yield table.

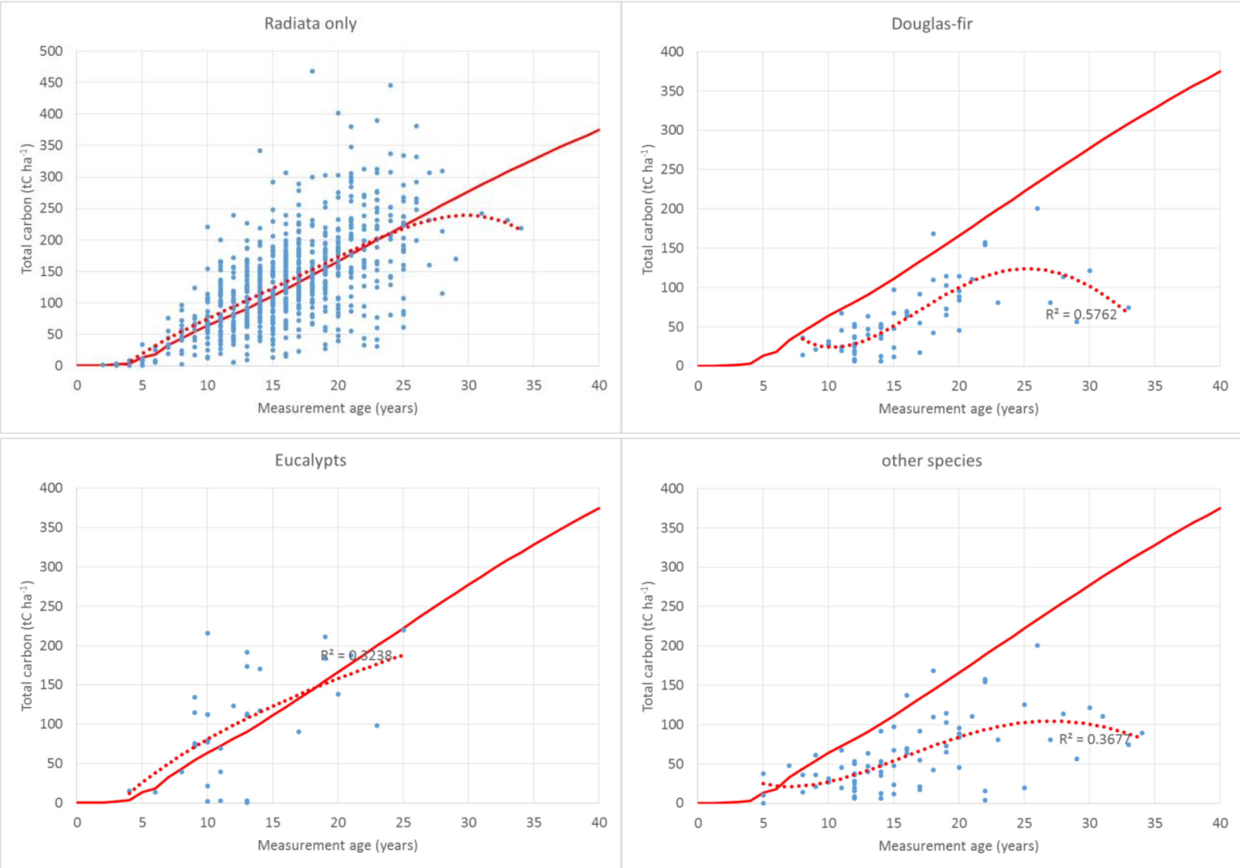

Figure 11. Total carbon stocks for individual plots compared with the national yield table for post-1989 planted forest, broken down in four species groups. Top-left: Radiata pine, Top-right: Douglas-fir, Lower-left: Eucalypts; Lower-right: other species. Within each plot, the blue dots show carbon stocks for individual plots measured since 2010 at time of measurement including multiple measurements, the red dashed line is a 4th order polynomial regression curve fitted to the plot data, and the solid red line shows total carbon by age as predicted by the national yield table.

These results clearly raise questions in how yield tables should be used for predicting carbon stocks at the national level. The results suggest that the yield table approach as currently implemented will tend to over-estimate stocks. This over-estimate has probably not been serious in post-1989 planted forest up until now, but will become an increasing issue as the majority of post-1989 planted forests has reached now harvesting age and increasingly more productive stands are harvested earlier than less productive stands. For pre-1990 forest, the issue is probably already significant.

One possible solution would be to separate non-radiata forest from radiata forest, and use separate yield tables for each as shown in figures 10 and 11. This would reflect the fact that higher yielding radiata stands tend to felled at about age 27 years or younger, whereas other lower yielding plantation species e.g. Douglas-fir are usually felled at about 40 years of age. To be able to develop and use such non-radiata yield tables would however require a larger sample of plots as part of the national forest inventory design (e.g. plots on the 4km grid) and species-specific area mapping e.g. the area of douglas-fir plantation forests needs to be spatially known. A complementary sampling approach for specific substrata like an increase in sampling density informed by species mapping under the general NFI design could be developed to derive species specific yield tables that meet reporting criteria (unbiased and precise).

Another solution would be to use a general yield table obtained by fitting a curve through the carbon in each plot of the inventory at a particular date (similar to the dashed lines shown in Figures 8 and 9). However, although this approach should remove the bias in estimating carbon stocks for each age class, it would result in under-estimates of average stocks removed at harvest and harvest residues.

There are also implications for the use of an accounting approach based on the long term average carbon stocks in forests, as New Zealand intends to apply in estimating its Nationally Determined Contribution. If the yield table over-predicts at older ages, the long term average stock calculated from it will be too high, allowing an excess of units to be credited.

Recommendations and conclusions

The analysis of the 2018 data of the planted forest inventory provided estimates of carbon stocks and carbon stock changes in pre-1990 planted forest and post-1989 planted forest. Pre-1990 planted forest plots measured for the first time in 2018 had lower carbon stocks compared with those measured previously. Plots measured for the first time in post-1989 planted forest did not differ from plots measured previously, but as was shown in 2017 the yield from the 2017 plot set for post-1989 planted forests did not align with the full dataset nor the 2018 plot set. The same situation seems to be present for the 2018 pre-1990 planted forests plot set. Both of those deviations might be a possible random variation between the annual measurements, but a separate more detail analysis between the new identified plots for pre-1990 and post-1989 planted forests and the already periodic measured plots could identify differences leading to those deviations. The ongoing addition of new plots to complete the representative sample of pre-1990 planted forests and post-1989 planted forests will assist in removing any possible bias that might previously existed. It also emphasises the importance of ensuring that all plots (grid-points) that are present in the mapped areas of pre-1990 and post-1989 planted forest are measured or at least randomly sampled to avoid a potential bias.

Yield tables were derived for pre-1990 planted forest and post-1989 planted forest using all measurements in the current and past inventory cycles (2007 – 2018). These tables are our current best estimates of average yields for these forests without allowance for the effects of harvest age differing between types of forest. As in the 2016 and 2017 analysis (Paul et al. 2017, 2018), an imputation method which adjusts for forecasting/backcasting errors when deriving the mean yield tables was used. While the adjustments for the backcasting and forecasting errors are not huge the method ensures that the important modelling error sources to generate the yield tables are accounted for. With the completion of the 5 year cycle of annual re-measurements in 2020, all plots in the inventory will have been measured within the previous 5 years and an average time since measurement of 2.5 years meaning that forecasting and backcasting errors have a minimal effect and that the full set of plots can be used confidently for carbon yields. This method has been adopted now that New Zealand has moved to a continuous forest inventory from the previously used periodic 5-year re-measurement cycle.

The yield table method of estimating carbon stocks by applying the table to the age distribution of a forest was compared with the approach of estimating stocks directly from the inventory. This comparison indicated that the yield table method tends to over-estimate average stocks. This occurs for a number of reasons, In particular, more productive stands tend to be harvested at younger ages compared with less productive stands including those containing species other than radiata pine stands such as Douglas-fir. Exploring the use of species and or age-class specific yield tables based on an adaptive inventory design adding possible non-permanent substrata plots across the National Inventory is a possible further option to improve the yield table approach. Identifying yield defining trends and their amplitude over time (age-classes) could also result in the better representation of yield estimations across reporting periods e.g. based on the time of increased uptake of new improved genetic stock (e.g. MPI nursery sale statistics; see Beets et al. (2011)) but need to be further evaluated for its feasibility.

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