

Article

The Inventory of Carbon Stocks in New Zealand's Post-1989 Natural Forest for Reporting under the Kyoto Protocol

Peter N. Beets ^{1,*}, Mark O. Kimberley ¹, Thomas S. H. Paul ¹, Graeme R. Oliver ¹,
Stephen H. Pearce ¹ and Joanna M. Buswell ²

¹ New Zealand Forest Research Institute Ltd., 49 Sala Street, Rotorua 3010, New Zealand;
E-Mails: mark.kimberley@scionresearch.com (M.O.K.);
thomas.paul@scionresearch.com (T.S.H.P.); graeme.oliver@scionresearch.com (G.R.O.);
stephen.pearce@scionresearch.com (S.H.P.)

² Ministry for the Environment, 23 Kate Sheppard Place, Thorndon, Wellington 6011, New Zealand;
E-Mail: joanna.buswell@mfe.govt.nz

* Author to whom correspondence should be addressed; E-Mail: peter.beets@scionresearch.com;
Tel.: +64-7-343-5899; Fax: +64-7-348-0952.

Received: 14 January 2014; in revised form: 1 September 2014 / Accepted: 5 September 2014 /
Published: 19 September 2014

Abstract: To meet international greenhouse gas reporting obligations, New Zealand must report on carbon stocks in forests established after 1989 (post-1989 forest). Although predominately comprised of planted forest, post-1989 forest also contains a component of natural vegetation amounting to less than 10% by area. New Zealand undertook a national inventory of this natural stratum of post-1989 forest to provide estimates of carbon stocks and stock change in woody species over the first commitment period (2008–2012) of the Kyoto Protocol. Plots were installed on a 4-km grid, and the basal diameters and heights of trees and shrubs were measured for the first time from November 2012, to March 2013. Carbon stocks in 2012 were calculated using allometric functions developed from biomass samples from each site. Basal disc samples provided data on diameter increment and shrub and tree age annually from 1990 to 2012. These were used to predict carbon stocks per ha for individual plots in 2008 and to provide annual predictions by pool back to 1990. Carbon stocks summed across live and dead biomass pools (excluding soil) averaged 3.04, 16.70 and 28.73 t C/ha in 1990, 2008 and 2012, respectively. The disposition by pool was 2.25, 12.54 and 21.84 t C/ha in aboveground biomass, 0.56, 3.13 and 5.46 t C/ha in belowground biomass (using a root/shoot ratio of 0.25), 0.03, 0.17 and 0.23 t C/ha in deadwood, and 0.18, 0.86 and 1.21 t C/ha in litter in 1990, 2008 and 2012, respectively.

In 1990, the woody biomass stock estimate per plot ranged from zero to 40 t C/ha and averaged 3.04 t C/ha across all plots. The methodology used to predict annual carbon stocks required an assumption concerning stem annual mortality. Sensitivity analysis suggested that varying this assumption had only a minor impact on predicted carbon stocks and changes. Plant age varied markedly within and between the natural forest plots, and therefore, the mean age of woody vegetation at each site was obtained by setting a threshold woody biomass carbon stock that needed to be achieved, and vegetation age was calculated as years since the threshold was achieved. This threshold approach facilitated the development of a yield table for predicting carbon (t/ha) as a function of vegetation mean age.

Keywords: aboveground tree biomass; manuka; kanuka; shrubland; stem analysis; basal diameter; height; allometric equations

1. Introduction

Globally, there is potential to greatly influence atmospheric CO₂ concentrations through the effects of land use change and forest management activities on the terrestrial biomass carbon pool [1]. Reforestation of agricultural and pastoral lands has the potential to sequester considerable carbon [2,3], as these low biomass systems revert to forest with high biomass. Secondary forest development in the tropical regions, where deforestation activities have been historically high, has the potential to contribute substantially to the global carbon cycle [4]. Likewise, it has been estimated that reforestation of the approximately 1.45 Mha of marginal hill country grassland in New Zealand has the potential to sequester 2.9 Mt·C·year⁻¹, assuming a carbon accumulation rate of 2.1 t C·ha⁻¹·year⁻¹ [5]. This is the mean rate for manuka (*Leptospermum scoparium* J.R. Forst. & G. Forst.) and kanuka (*Kunzea ericoides* (A. Rich) Joy Thomps.) live biomass. These are the most commonly occurring indigenous species colonising farmland in New Zealand that is released from grazing pressure. However, a diverse range of species may be present in seral vegetation types [6], including isolated large trees.

Woody vegetation that invades pasture is normally cleared periodically by chemical or mechanical means and through the use of fire. However, since forestry entered the New Zealand Emissions Trading Scheme (ETS) in 2008, an increasing area of grassland has been purposefully destocked of grazing animals to facilitate reforestation and then registered under the scheme. To meet international greenhouse gas reporting obligations, New Zealand must report carbon stock and stock change in all forest established after 1989 (post-1989 forest), which includes natural vegetation that colonizes farmland after the land management practice has changed from grazing to forest (post-1989 natural forest). The species composition, age structure and carbon accumulation rate in post-1989 natural forest are largely unknown [7].

The Land Use Carbon Analysis System (LUCAS) was developed by the New Zealand Ministry for the Environment to report and account for greenhouse gas emissions associated with land use and land use change in New Zealand. In the LUCAS approach, the total area of post-1989 forest in New Zealand is estimated using wall-to-wall mapping based on remote sensing techniques and includes both planted and natural forest [8]. It has not been possible to separate the natural and planted forest geospatially, and

therefore, a point sampling approach is used to apportion the total area into natural and planted post-1989 forest. This approach is aligned with IPCC guidelines for reporting [9]. The area data are used in combination with yield tables and an area by age class table to provide national estimates of carbon stocks and changes in New Zealand's entire post-1989 forest estate. The yield and age class tables are based on field inventories. A national forest inventory system was put in place to inventory post-1989 planted forest [10] in 2008 and 2012. However, it was not feasible to inventory post-1989 natural forest until 2012. Under the terms of the Kyoto Protocol, the carbon stock change between January 2008, and December 2012, of land reforested since 1990 is required for national reporting purposes. An approach was required to estimate carbon stocks in post-1989 natural forest in 2008, to meet the reporting requirements, based on measurements taken in 2012.

This carbon assessment methodology required careful consideration. Assessment methods involving vegetation height and cover have been developed to allow rapid and cost-effective determinations of carbon stocks of shrublands [11,12]; however, few repeated measurements of plots have currently been made, and it is uncertain whether such methods will be adequate for estimating carbon stock changes over time intervals of five years with an acceptable level of precision [7]. For plots with only a single measurement, the mean rate of carbon accumulation can be determined by dividing the carbon stock by shrubland age [5]. Carbon stocks and changes over defined periods can be estimated using stem analysis methods from measurements of annual growth rings and bud scale scars, as first described by Whittaker [13,14].

The applicability of stem analysis methods to inventory carbon stocks and changes in post-1989 natural forest in New Zealand was tested in a pilot study undertaken within two diverse regions [15], where land use changed from grazing management to forest restoration. The pilot study included 18 plots, growing over an elevation range from sea level to 1250 m a.s.l. Analysis of these data showed that a modification of the Whittaker [14] approach provided accurate indirect estimates of carbon stocks per plot in live and dead biomass pools in 2008 from plot measurements and biomass samples and basal disc samples acquired in 2012. Further, the pilot study showed that an allometric model fitted to all of the biomass data combined across both years (2008 and 2012) and sites gave similar estimates for each shrub to those obtained when separate allometric models were fitted by year.

This paper describes the carbon inventory of post-1989 natural forest, including sampling procedures and calculations for directly estimating carbon stocks per hectare in live and dead carbon pools in December 2012, and basal disc assessment methods and calculations for indirectly estimating annual changes in carbon stocks per hectare back to 1990. Variability in carbon stocks and shrubland age within and between plots is documented, as a basis for developing an age-based carbon yield table for post-1989 natural forest to be used by New Zealand in its system for greenhouse gas reporting. Pools estimated or modelled included:

- (1) Aboveground biomass (AGB) for stems with a basal diameter ≥ 1 cm (measured 10 cm above the ground);
- (2) Belowground biomass in live roots (BGB);
- (3) Deadwood (includes carbon in standing dead trees ≥ 10 cm in diameter and coarse woody debris ≥ 10 cm in diameter on the forest floor);
- (4) Litter (includes dead leaves, reproductive parts and woody debris < 10 cm in diameter), fermenting (F) and humus (H) material on the forest floor.

Carbon stocks in mineral soil were not included, because these were assessed using a different system, which is not described here.

2. Methods

2.1. Plot Network Design

To select sample plots for the inventory of post-1989 forest, a 4-km grid with a random starting point was overlaid on the mapped area of post-1989 forest. Plots in planted stands within post-1989 forest (more than 90% of the area) were measured at the start and end of the Kyoto Protocol first commitment period, and a yield table was developed from these data [10]. From November 2012, to March 2013, plots were established at locations where post-1989 natural forest occurred (less than 10% of the area), where access was permitted, which resulted in the sampling of a total of 20 of 28 possible locations (Figure 1). Access was denied to 8 locations. There is uncertainty associated with mapping using remote sensing, and not all 4-km grid points fell in post-1989 forest [16]. The uncertainty associated with this, the inability to sample plots for which access was denied, and the point sampling approach used to estimate the proportion of the post-1989 forest area occupied by planted and natural forest types, are accounted for in New Zealand's system for greenhouse gas reporting [8] and are therefore not considered further here. This paper is focused on developing a yield table for vegetation that is known to be post-1989 natural forest.

2.2. Plot Measurement Protocols: Nondestructive Measurements

The 20 sites sampled were measured using a nested plot design, involving three assessment plot types: (I) stems < 10 cm diameter at 1.35 m breast height (dbh) were measured in four 1.5-m horizontal radius circular subplots; (II) stems ≥ 10 cm dbh were measured in a 20×20 m square plot laid out on the slope; (III) stems ≥ 60 cm dbh were measured in a 20-m horizontal radius plot. Plots were installed at each site as follows. Firstly, a 20-m horizontal radius plot was laid out. Secondly, a 20×20 -m plot was laid out on the slope, centred on the 20-m radius plot. Thirdly, to locate the four 1.5-m horizontal radius subplots, the 20×20 -m plot was divided into quarters and one subplot installed at the centre of each 10×10 -m quarter. The horizontal areas of 20×20 m plots were determined as described in Section 2.4. Measurement protocols depended on the assessment plot type.

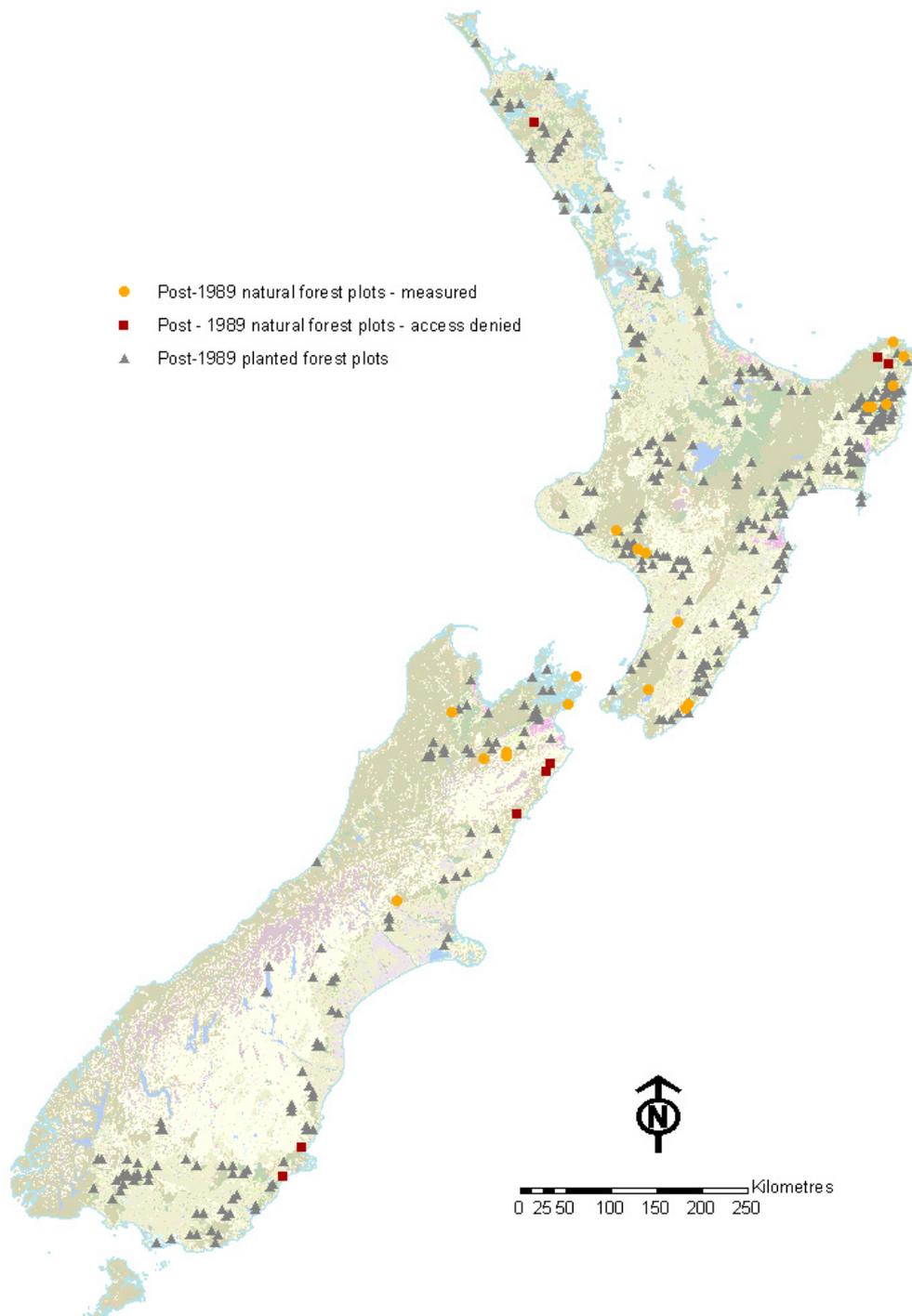
2.2.1. Stems < 10 cm dbh in the 1.5-m Radius Subplot

The basal diameter (at 10 cm above ground level) of plants < 10 cm dbh with a basal diameter ≥ 1 cm and height ≥ 30 cm, and the height of the tallest leader associated with each base were measured, excluding plants with at least one fork ≥ 10 cm dbh. Plants that forked below a 10-cm height were deemed to be different plants, because it is often difficult to determine whether such stems are from different plants or from the same plant, but forked at ground level. Callipers were used to measure the basal diameter of stems < 2.5 cm. If the stem was elliptical in the cross-section, two orthogonal diameters (the maximum width and the diameter at right angles to this) were measured. Orthogonal diameters (D_{01} and D_{02}) were converted to a quadratic mean diameter (D) using the formula:

$$D = \sqrt{D_{O1} \times D_{O2}} \quad (1)$$

A diameter tape was normally used to measure the diameter of stems ≥ 2.5 cm, including plants with elliptical stems. Height from tip to base was measured along the stem using a tape. Stems that were dead at the time of measurement were considered to be litter, because diameters were less than 10 cm, and assigned a decay class. Litter on the forest floor was not directly measured.

Figure 1. Location of sample sites in post-1989 forest in New Zealand. The majority occurs in planted forest. Natural forest plots were established at 20 of the 28 potential locations where natural forest intersected the 4-km grid used to sample post-1989 forest.



2.2.2. Stems ≥ 10 cm and < 60 cm dbh in the 20×20 -m Plot

Breast height diameter (at 1.35 m above ground level) of plants with stems ≥ 10 cm and < 60 cm dbh were measured, including plants with at least one fork (≥ 10 cm dbh) originating from between a 10-cm and a 1.35-m height above ground level. In addition, total height (of the tallest stem if forked) and basal diameter were measured for a sample of plants in the plot. If plants forked above a 10-cm height, multiple dbh_i measurements were converted to an equivalent single plant dbh with same cumulative cross-sectional area using the formula:

$$dbh = \sqrt{\sum_i dbh_i^2} \quad (2)$$

Heights from tip to base were measured using either a tape or a hypsometer. If a tree was leaning, height was corrected for lean, either by measuring along the stem or by correcting vertical height (as measured by a hypsometer) to length by applying the stem lean angle, which was recorded in the field. Standing dead stems ≥ 10 cm diameter at base (including < 10 cm diameter material associated with these stems) were assumed to be coarse woody debris (CWD) and assigned a decay class. The litter-sized material (material < 10 cm diameter) was allocated to the deadwood pool, because no functions existed to estimate the fraction that was < 10 cm. The length and large and small end diameters of fallen logs and the height and small end diameter of stumps ≥ 10 cm in diameter and ≥ 0.30 m in length were measured and recorded by species and classified as CWD [11].

2.2.3. Stems ≥ 60 cm dbh in the 20-m Horizontal Radius Plot

Breast height diameter (at 1.35 m above ground level) of trees with stems ≥ 60 cm dbh was measured if within a 20-m horizontal distance from the plot centre. In addition, total height and basal diameter were measured for a sample of trees in the plot.

The length and large and small end diameters of fallen logs and height and small end diameter of stumps ≥ 60 cm in diameter and ≥ 0.30 m in length were measured and recorded by species and classified as CWD [11].

2.3. Destructive Sampling for Aboveground Biomass and Increment Analysis

2.3.1. Aboveground Biomass

A sample of shrubs and small trees outside the 20×20 -m plot boundary were harvested to determine aboveground biomass. It is generally recognised that local biomass sampling is advisable when estimating biomass in secondary forest using allometric equations [17]. At each site, four shrubs and small trees < 10 cm dbh that were representative in terms of size and species composition of the vegetation being assessed in the 1.5-m radius subplots were harvested by cutting each stem at ground level. The total and sample (if subsampling was necessary) fresh weights of individual shrubs were measured in the field, subdivided if necessary into crown and stem components. Samples were labelled by shrub number and plant component. Samples were kept cool while in the field and later frozen until they were transported to the laboratory for further processing. The diameter at base and total height of these shrubs were measured. A basal disc sample was taken from each harvested shrub. The disc was

always taken from the subsample to be discarded in the field, except if plants were too small to subsample. In the latter case, the basal disc was taken from the woody base of the total shrub sample, and following growth ring analysis, the dry weight of these basal discs was added to determine shrub total dry weight.

Tree ferns grow by increasing in height, but not in diameter (although some fibrous matter is laid down in the lower part of the stem), so annual growth rings are absent. Biomass was estimated using existing allometric equations for tree ferns [18].

Large trees ≥ 10 cm in the 20×20 -m plot and trees with a dbh ≥ 60 cm in the 20-m radius plot were not harvested, because of their large size and because they were not expected to contribute substantially to the national total sequestration estimate of the transitional vegetation component of post-1989 forest.

2.3.2. Basal Disc Sampling for Increment Analysis and Age Determination

A total of 8 shrubs outside each plot (4 biomass samples, as described above, and 4 supplementary basal disc samples) were sampled to estimate diameter increment and age of plot trees and shrubs back to 1990 from measurements in 2012. The supplementary samples were taken from arboreal shrubs of dbh greater than 10 cm, but less than 15 cm outside the plot boundary that were representative of the size and species composition of vegetation in the 20×20 -m plot, to extend the age and diameter increment data over a greater size range than exhibited by biomass shrubs. The sample size used was based on the results of the pilot study [15], which showed that acceptable estimates of basal area and height increments were possible using 7 basal discs on average, the range in the pilot study being 4–13 basal disc samples per plot.

2.3.3. Sample Processing

Biomass samples, including basal disc samples, were weighed fresh on arrival at the laboratory and the biomass samples then oven-dried at 65°C to constant weight. Moisture content corrections were applied on an individual shrub and component basis.

Prior to growth ring analysis, the surface of each basal disc sample was sanded smooth or planed with an electric planer to reveal the growth rings and enable shrub age to be determined from annual ring counts. Stem diameter over and under bark was measured, to give bark thickness. Growth ring increments (these exclude bark) were measured as the difference between cumulative diameters, (from the mean of 2 orthogonal diameter measurements per annual growth ring, using callipers). Diameter increments on discs extended back to the youngest growth ring observed, or back to 1990, whichever came sooner.

The fresh weights obtained in the laboratory were cross-checked with field weights, to identify and correct any measurement or procedural errors.

2.4. Intermediate Calculations

The area of 4 circular 1.5-m horizontal radius subplots combined was 0.002827 ha. The 20×20 -m plots were laid out following the terrain, and the horizontal distance of the 4 sides was measured. Plot horizontal area (potentially 0.04 ha) was calculated from horizontal distance measurements obtained using a hypsometer. The horizontal lengths of opposite sides of a plot were averaged and plot horizontal area calculated assuming plots were rectangular or square in shape. The summed horizontal areas of the

20 × 20-m plots obtained using a hypsometer were within 0.2% of the horizontal areas calculated from slope-corrected distances measurements (check method) obtained using a tape. The area for the 20-m horizontal radius plot was 0.1257 ha.

Each basal diameter measurement was considered to be of a unique plant. Where basal diameter was not recorded in the field, it was estimated using the following linear relationship between *dbh* and basal diameter *D* for trees and shrubs with a *dbh* ≥ 10 cm:

$$D = 1.29 + 1.10 \times dbh, n = 178, R^2 = 0.86 \quad (3)$$

For this process, the *dbh* of multi-stemmed plants was converted into a single *dbh* of equivalent cross-sectional area.

Where height was not measured in the field, it was estimated using height/basal diameter functions based on data collected in the plot network. The height model form allowed for specific adjustments of plot and species effects for species with at least 10 individuals represented in the dataset. Species with less than 10 individuals were grouped together into a single group, although the plot-level adjustments were still applied.

2.5. Calculation of Carbon Stocks per Plot in 2012

Plot inventory data in 2012 were converted to oven dry weight per hectare using allometric equations developed from the biomass data collected adjacent to each plot. To estimate carbon stocks per plant, allometric models of the following general form were derived from the biomass data:

$$DryWeight = a_{species} (BA \times Height)^b \quad (4)$$

where *DryWeight*, *BA* and *Height* are oven dry weight (kg per plant), basal area (cm²) and height (m), for each plant in the database. Species effects on allometry were highly significant ($F_{21,58} = 45.10$, $p < 0.0001$), so separate coefficients $a_{species}$ were fitted for each species (Table 1). For species in the inventory not included in the biomass data, an average species effect was used. The coefficient, *b*, allows for a slightly non-linear relationship between dry weight and $BA \times Height$. The model was fitted using the SAS Version 9.2 procedure GLIMMIX by fitting *DryWeight* using a log link function to $\log(BA \times Height)$ and assuming a gamma distribution function [19]. All other analyses were also performed using SAS procedures.

The allometric model was applied to each plant to estimate its dry weight, and these were summed (live separately from dead) by assessment plot type (20 × 20-m, 1.5 m-radius, 20-m radius plots) and the subtotals divided by the appropriate assessment plot type area to express stocks in t/ha. The total biomass stock for the plot was obtained by summing the stock estimates for each assessment plot type. Carbon was assumed to comprise 50% of the dry matter [11].

When applying the allometric equation to dead stems, heights predicted using the height/diameter regressions developed for live plants were used (not the actual height of dead plants), as this provided estimates of the total dry weight of dead plants, including any material broken off. Dead plants with diameters < 10 cm at base were allocated to the litter pool, while large diameter material (including standing and fallen CWD) were allocated to the deadwood pool. A decay class-dependent mass loss was applied to all dead material using wood density adjustment factors for pre-1990 natural forest in New Zealand [11].

A small amount of fallen deadwood was found in a few of the 20 × 20-m plots. The volume of each piece was assessed by measuring its length and its large and small end diameter. The species (if known) and decay class were assigned to each piece, to allow calculation of its dry mass. The stock change in the deadwood pool over time was assessed using previously published decay functions [20]. On the basis of piece size, decay class and species, each piece was assessed to be either pre-1990 (dead prior to 1990) or post-1989 deadwood. Carbon estimates of pre-1990 material are provided separately. In New Zealand’s Land Use Carbon Analysis System, it is assumed for reporting purposes, in accordance with reporting guidelines, that pre-1990 forest carbon pools (apart from soil carbon) are instantly emitted to the atmosphere following deforestation [8]. However, pre-1990 deadwood was found at some reforested sites. To avoid double counting the emission in New Zealand’s Greenhouse Gas Inventory, for which our estimates were developed, the pre-1990 deadwood residues were excluded from carbon yield tables used to estimate carbon stocks and stock changes for post-1989 natural forest.

Table 1. Coefficients ($a_{species}$, b) of the allometric model for estimating dry weight (kg) of each tree or shrub from the summed basal area of stems (m^2) measured 10 cm above ground level and height (m) using the equation: $DryWeight = a_{species} (BA \times Height)^b$. Model coefficients were obtained using the SAS GLIMMIX procedure, while the R^2 value is reported for the log-log model.

Common Name	Estimate $a_{species}$	SE
rangiora	141	39
marble leaf	166	64
<i>Coprosma areolata</i>	137	48
<i>Coprosma propinqua</i>	478	171
<i>Coprosma rhamnoides</i>	229	30
Spanish heather	132	28
tree fuchsia	99	35
<i>Gaultheria antipoda</i>	170	61
hangehange	88	31
broadleaf	178	47
<i>Hebe traversii</i>	259	95
kanuka	174	26
prickly mingimingi	313	112
manuka	220	30
mingimingi	228	45
kawakawa	70	25
mahoe	147	43
tauhinu	207	39
Douglas-fir	150	53
gorse	165	29
kamahi	114	41
Average species effect	184	
Estimated b	0.837	0.029
R^2	0.92	

2.6. Calculations of Carbon Stocks per Plot Annually Back to 1990

The “backcast” estimate of dry weight in 2008 was obtained for these stems using the 2012 measurement as a basis. The backcast method required estimating 2008 values for the basal diameter overbark of each stem and the height of each plant. The 2012 dry weight allometric model was then applied to these backcast estimates of basal area and height to predict dry weight in 2008.

Backcast estimates of basal diameter overbark of each stem in 2008 were obtained using the following approach. Underbark diameter increments from annual growth ring analysis were converted to overbark diameter increments each year, by assuming that the overbark cross-sectional area/underbark cross-sectional area ratio measured in 2012 applied to previous years. A regression model relating 2008 to 2012 diameter increment overbark (D_{inc}) was fitted as a function of basal diameter in 2012 (D_{2012}). The following model form, which allows for specific adjustments of each plot and species, was used:

$$D_{inc} = a_{plot} + b_{species} + c_{plot} \times D_{2012} \quad (5)$$

Terms for both plot and species were statistically highly significant ($p < 0.01$), and the model fit was satisfactory ($n = 159$, $R^2 = 0.89$). This model was then applied to the individual stems in the inventory plots to predict the diameter increment of each stem and, hence, the backcast basal diameter in 2008. The same method was used to backcast stem diameter each year back to 1990. For example, the 1990 diameter was estimated using a regression model relating the 1990–2012 diameter increment to the diameter in 2012.

Backcast estimates of height were obtained as follows. Firstly, a regression of the following form relating the age of each stem in 2012 (Age_{2012}) to its basal diameter in 2012 was fitted to the disc data:

$$Age_{2012} = a_{plot} + b_{species} + c_{plot} \times D_{2012} \quad (6)$$

Terms for both plot and species were statistically highly significant ($p < 0.01$), and the model fit was satisfactory ($n = 159$, $R^2 = 0.84$). This model was then applied to the individual stems in the inventory plots to predict the age of each stem in 2012. A generic height/age function, which has been derived from planted shrub data [21], was used to predict height n years previously (e.g., $n = 5$ for 2008) for each stem from its height and age in 2012 ($Height_{2012}$, Age_{2012}) as follows:

$$Height_{2012-n} = a(1 - \exp[-0.0643(Age_{2012-n})])^{1.221} \quad (7)$$

where: $a = Height_{2012} / (1 - \exp[-0.0643(Age_{2012})])^{1.221}$.

In summary, the calculation steps to estimate the dry weight of each plant in a plot back to 1990 were as follows. Equation (5) was used to backcast stem basal diameters each year from the basal diameter in 2012. Equation (6) was applied to predict the age in 2012, and Equation (7) was applied to predict the plant height by year from 1990 to 2011. The dry weight allometric model (Equation (4)) was then applied to these backcast estimates of basal area and height to predict the dry weight of each plant each year back to 1990.

A different approach was required for tree ferns (these comprised a small proportion of the carbon stock), because no biomass data or basal disc samples were acquired for post-1989 natural forest. Carbon stocks were therefore estimated using the general tree fern allometric function for natural forest [18]. Stock changes (sequestration estimates) were obtained by applying this allometric function to heights

reduced by 20 cm per year, which was the mean height growth rate of tree ferns in re-measured pre-1990 natural forest plots, from the 2012 measurement, and by assuming that diameter did not change over time (most tree ferns increase in height, but not in diameter).

The backcasting procedure described above provides estimates of dry weight for each live plant in 2012, and therefore, by summing these estimates with appropriate weightings for plot assessment type area, it was possible to estimate per hectare carbon in AGB annually for each site. However, the backcast estimate of AGB obtained using this method represents plants that were live in 2012 and will therefore underestimate AGB in earlier years by an amount that depends on the mortality rate. Adjustments were therefore applied to the backcast AGB estimates prior to 2012 to account for mortality using the following approach.

Firstly, the dry weights of all dead stems (*i.e.*, predictions made without applying decay class multipliers) were obtained for each plot. It was assumed that this value represented the dry weight of plants suffering mortality over the previous 5 years, because it was found that stems in re-measured plots of the pilot study that were dead at the first measurement made 5 years previously had generally fallen over by the second measurement [15]. Based on this assumption, annual mortality was calculated by dividing by 5.

The 2011 backcast estimate of AGB was adjusted for mortality by adding this annual mortality to the backcast estimate. Similarly, twice annual mortality was added to the 2010 backcast estimate, 3-times mortality to the 2009 estimate, and so on, back to 2007, which was adjusted by adding 5-times the annual mortality. The amount of dry mass entering dead pools per year was then expressed as a proportion M of the AGB by dividing annual mortality by the average adjusted AGB over the 2007–2011 period.

This mortality proportion M was used to derive adjusted estimates, AGB'_i , for each plot starting with 2012 (when no adjustment was required) and working backward in time by year. If the backcast estimates of AGB in years i and $i + 1$ are AGB_i and AGB_{i+1} , respectively, and if $R = AGB_{i+1}/AGB_i$, then the mortality adjusted estimate AGB'_i is calculated using:

$$AGB'_i = AGB'_{i+1} / R \times (1/(1 - M)) \quad (8)$$

The main assumption underlying this method is that the time taken for dead standing stems to fall over owing to decay is 5 years. An indication of the sensitivity of estimates to this assumption was obtained by varying this period between 3 and 7 years.

To predict the litter and deadwood pools in years prior to 2012, their ratios to the AGB pool in 2012 were used. It was assumed that these ratios remained constant through time. Lack of data makes it impossible to test this assumption.

Belowground biomass was not directly measured, but was estimated by applying a root:shoot ratio of 0.25 to the aboveground biomass estimate, to be consistent with carbon stock calculations used previously for New Zealand's natural forests [11]. Note that a more conservative ratio of 0.2 was reported for twenty five-year-old regenerating manuka/kanuka in the central North Island [22].

2.7. Plot Age Determination

A threshold method was used to assign a mean age to each natural forest plot, defining age zero to be when the AGB carbon first exceeded 2 t/ha. Each plot was assigned an age of zero years in December of the calendar year when its AGB carbon stock estimate was closest to 2 t C/ha. Five plots exceeded this threshold in 1990 and were therefore assumed to be 22-year-old natural forest in 2012. Prior to 1990, all plots were mapped as grassland subcategories, and some contained woody biomass. The distribution of plot ages based on the threshold method provided an indication of the timing of conversion from grassland to post-1989 forest.

2.8. National Average Carbon Stocks by Year and Stock Change Estimates

Mean carbon stock estimates over the period from 1990 to 2012 were obtained by averaging stocks across all plots by year. These annual estimates were used to calculate stock changes from 2008–2012. Means and 95% confidence intervals (standard error times t -value with 19 degrees of freedom) were calculated for stocks in 1990, 2008, 2012 and for sequestration over the period from 2008–2012. A yield table for predicting carbon stocks of woody species from plot age was then developed from the annual estimates for each plot using the plot ages defined using this threshold method. Cubic or quadratic polynomial regression models were fitted for predicting each pool using as independent variables Age , Age^2 and Age^3 (when necessary), with separate slope and intercept parameters for each plot. The yield table was generated by predicting annual carbon stocks from these regression models averaged across all plots.

3. Results

3.1. Plot Description

Site elevation and estimated mean, minimum and maximum age of stems in each plot (area weighted according to assessment plot type) in 2012 are given in Table 2. In total, 1489 live stems and 100 dead stems were measured. The majority (88% of live stems and 90% of dead stems) occurred in 1.5-m radius subplots, and only three stems (all live) exceeded 60 cm dbh. The mean, minimum and maximum number of stems measured per plot (summed across plot assessment type) were 74, 18 and 225, respectively. Shrub age varied (maximum–minimum age) by more than 10 years in all but one plot. This was not surprising, because secondary successions can commence from isolated colonizers, or from uniformly-aged cohorts of shrubs following fire or other disturbances, or some combination of these. In a few cases, the maximum age was high, due to solitary trees that would have survived the conversion to farmland. Eight plots had a weighted mean plant age greater than 23 years, although maximum plant age exceeded 23 years in all but five plots, which indicates that some woody biomass was present at most sites in 1990.

Table 2. Plot vegetation type, site elevation (“Elev.”), mean, minimum and maximum age of stems, mean age of stems weighted by aboveground biomass (AGB) carbon (“Wtd. Mean”) and years (“Thresh. Age”) since AGB carbon exceeded a threshold of 2 t/ha.

Plot	Vegetation Type	Elev. (m)	Age (year)				
			Mean	Min	Max	Wtd. Mean	Thresh. Age
1	gorse	663	12.9	7.6	21.8	15.7	11
2	manuka/kanuka	373	24.2	4.1	65.5	33.4	22
3	kanuka/wilding conifers	880	12.3	1.0	30.9	10.4	8
4	kanuka	623	60.7	17.6	182.0	68.8	22
5	manuka/kanuka	1240	34.6	8.3	56.4	43.7	22
6	manuka/wilding conifers	390	10.9	4.0	115.2	25.4	9
7	tauhinu/ <i>Coprosma</i> sp.	105	9.4	1.0	26.0	13.2	10
8	manuka	260	10.6	7.7	14.0	11.9	8
9	mixed broadleaf /tree ferns	250	28.3	8.1	47.6	34.3	15
10	manuka/kanuka	100	14.5	9.0	27.4	19.0	14
11	gorse/manuka/kanuka	200	17.1	6.2	38.3	22.9	16
12	mixed broadleaf	180	11.6	2.5	15.3	12.9	9
13	manuka	190	10.8	2.5	19.2	12.1	4
14	manuka/kanuka	365	14.5	5.6	25.6	17.8	11
15	mixed broadleaf/manuka	719	18.4	1.0	26.1	15.6	15
16	mixed broadleaf	725	15.4	8.7	30.9	22.1	16
17	kanuka	300	25.0	12.0	52.6	31.7	22
18	manuka/mixed broadleaf/tree ferns	50	8.6	4.1	17.0	10.3	9
19	manuka/kanuka	227	14.1	2.2	77.7	29.6	22
20	manuka/kanuka	160	14.9	2.0	43.9	28.1	17
	mean of measured plots		18.4	5.8	46.7	23.9	14.1

3.2. Aboveground Carbon Stocks by Species and Assessment Plot Type

The 20 most common species ranked by aboveground carbon were manuka (*Leptospermum scoparium* J.R. Forst. & G. Forst.), kanuka (*Kunzea ericoides* (A. Rich.) Joy Thomps.), gorse (*Ulex europaeus* L.), mahoe (*Melicytus ramiflorus* J.R. Forst. & G. Forst.), tauhinu (*Ozothamnus leptophyllus* (G. Forst.) Breitw. & J.M. Ward), radiata pine (*Pinus radiata* D. Don), mingimingi (*Leucopogon fasciculatus* (G. Forst.) A. Rich.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), *Coprosma propinqua* A. Cunn., broadleaf (*Griselinia littoralis* Raoul), marble leaf (*Carpodetus serratus* J.R. Forst. & G. Forst.), lancewood (*Pseudopanax crassifolius* (A. Cunn.) C. Koch), Spanish heather (*Erica lusitanica* Rudolphi), *Coprosma rhamnoides* (Buchanan) A. Cunn., prickly mingimingi (*Leptecophylla juniperina* (J.R. Forst. & G. Forst.) C.M. Weiller), five finger (*Pseudopanax arboreus* (Murray) Philipson), *Hebe traversii* (Hook.f.) Cockayne & Allan, kamahi (*Weinmannia racemosa* J.R. Forst.), mountain beech (*Nothofagus solandri* (Hook.f.) Oerst.) and silver fern (*Cyathea dealbata* (G. Forst.)

Sw.) (Table 3). Kanuka, manuka and gorse comprised 71% of the carbon stock, with most other species being of lesser importance. The plot type where carbon was assessed indicates that 75% of the aboveground biomass carbon was in plants of less than 10 cm dbh (Tables 3 and 4).

3.3. Carbon Stocks in Live and Dead Pools by Assessment Plot Type

Carbon estimates per ha in 2012 by pool and plot assessment type are shown in Table 4. The stock of carbon in deadwood assessed to have been dead prior to 1990 averaged 1.29 t/ha in 2012 and was excluded from all remaining calculations (for reasons explained in Section 2.5).

The carbon stock in post-1989 forest averaged 28.73 t/ha in 2012, of which 95% was live biomass and 5% was dead organic matter (0.78% was deadwood, and 4.2% was litter). Most of the carbon stock (76%) was associated with stems < 10 cm dbh, with 22% associated with stems ≥ 10 –<60 cm dbh and less than 3% in stems ≥ 60 cm dbh.

Table 3. Aboveground biomass (AGB) carbon stocks in 2012 (t C/ha) for the 20 most important species by plot assessment type and sum across types.

Common Name	AGB Carbon	Plot Assessment Type		
		1.5-m Radius Subplots (dbh < 10 cm)	20 × 20-m Plot (dbh \geq 10 cm)	20-m Radius Plot (dbh \geq 60 cm)
manuka	7.04	6.61	0.43	0.00
kanuka	6.40	3.44	2.96	0.00
gorse	2.03	2.03	0.00	0.00
mahoe	1.07	0.86	0.21	0.00
tauhinu	0.92	0.92	0.00	0.00
radiata pine	0.79	0.00	0.24	0.55
mingimingi	0.56	0.54	0.02	0.00
Douglas-fir	0.40	0.20	0.20	0.00
<i>Coprosma propinqua</i>	0.31	0.31	0.00	0.00
broadleaf	0.28	0.28	0.00	0.00
marble leaf	0.21	0.12	0.10	0.00
lancewood	0.20	0.03	0.17	0.00
Spanish heather	0.19	0.19	0.00	0.00
<i>Coprosma rhamnoides</i>	0.17	0.17	0.00	0.00
prickly mingimingi	0.16	0.16	0.00	0.00
five finger	0.14	0.00	0.14	0.00
<i>Hebe traversii</i>	0.13	0.13	0.00	0.00
kamahi	0.11	0.11	0.00	0.00
mountain beech	0.11	0.00	0.00	0.11
silver fern	0.08	0.00	0.08	0.00
Others	0.55	0.32	0.23	0.00
Total	21.84	16.40	4.78	0.66

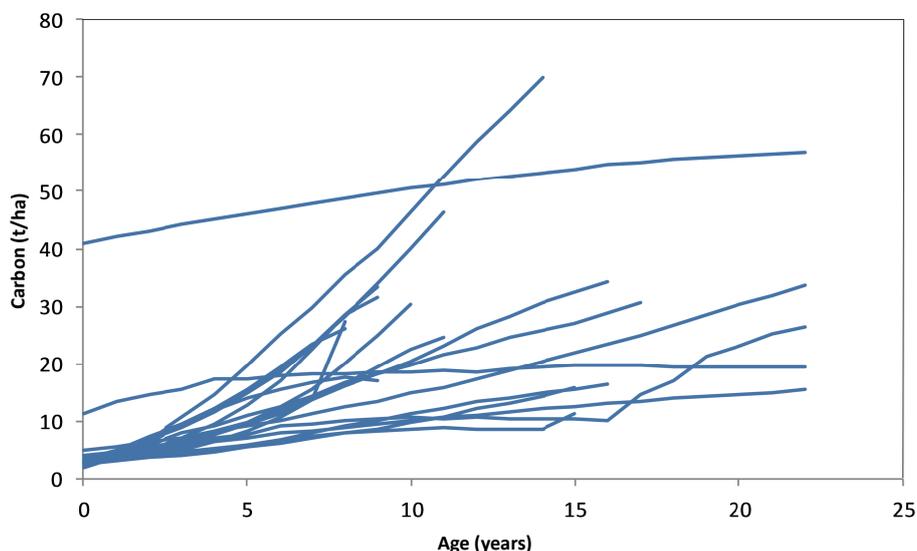
Table 4. Mean basal area 10-cm above ground level and mean carbon stocks by pool in 2012 (t C/ha), including pre-1990 deadwood by plot assessment type and sum across all types. Note that post-1989 deadwood includes litter attached to stems with a basal diameter ≥ 10 cm, whereas the litter pool includes litter attached to stems with a basal diameter < 10 cm.

Plot Assessment Type	Basal Area at 10-cm (m ² /ha)	Carbon (t/ha)					
		AGB	BGB	Dead wood	Litter	Total (Excl. pre-1990 Deadwood)	Pre-1990 Deadwood
1.5-m radius subplots (dbh < 10 cm)	24.70	16.40	4.10	0.00	1.21	21.71	0.00
20 × 20-m plot (dbh ≥ 10 cm)	5.97	4.78	1.20	0.23	0.00	6.21	1.29
20 m-radius plot (dbh ≥ 60 cm)	0.59	0.66	0.16	0.00	0.00	0.82	0.00
All	31.26	21.84	5.46	0.23	1.21	28.73	1.29
SE	3.84	2.68	0.67	0.11	0.29	3.41	0.83
95% CI	8.04	5.60	1.40	0.22	0.61	7.14	1.74

3.4. Carbon Stocks per Plot by Age

The carbon stock for each plot is shown in relation to age in Figure 2, where age is defined using the threshold method. This shows that carbon increased steadily once a plot had exceeded the threshold and that there was considerable variation between plots. Very noticeable is that one plot and, to a much lesser extent, another plot have a relatively large stock of carbon at age zero compared with other plots in the inventory. The plot with the highest carbon at age zero was in forest at an elevation of 623 m that was mapped as post-1989 forest and contained relatively large, but slow-growing kanuka and an isolated large beech tree, with stems ranging in age between 18 and 182 years old in 2012 (Table 2).

Figure 2. Carbon stock vs. age (threshold method) for each plot.



3.5. Carbon Stocks and Changes over CPI of the Kyoto Protocol

Estimated carbon stocks (t C/ha) by plot and across all plots as on 31 December 2012, 1 January 2008, and 1 January 1990, as well as the 2008–2012 carbon stock changes for live and dead pools (excluding mineral soil) are given in Table 5, together with the standard errors of means and 95% confidence intervals. There were large differences in the growth rate evident among plots. This is not surprising, because plots ranged in elevation from around sea level to approximately 1200 m. The most productive plot sequestered almost 30 t C/ha during the first commitment period of the Kyoto Protocol (CP1), while the least productive plot lost 0.05 t C/ha over CP1. This latter plot showed considerable evidence of mortality with 3.8 t/ha of carbon in the dead pool in 2012.

Table 5. Estimated carbon stocks (t C/ha) by plot and mean across all plots as of 31 December 2012, 1 January 2008, and 1 January 1990, along with the estimated 2008–2012 increase in carbon stocks. Standard errors of means and 95% confidence intervals (CI) are also given.

Plot	Carbon (t C/ha)			
	2012	2008	2008–2012	1990
1	46.46	18.60	27.86	0.00
2	26.31	14.61	11.70	3.13
3	27.44	4.94	22.50	0.00
4	56.98	55.15	1.83	39.88
5	15.43	13.35	2.07	3.58
6	33.36	9.36	24.00	0.00
7	30.44	9.87	20.57	0.00
8	26.25	9.61	16.64	0.00
9	15.81	9.72	6.09	0.23
10	69.91	39.92	29.99	0.00
11	34.23	23.11	11.11	0.02
12	31.70	11.94	19.76	0.00
13	7.06	1.69	5.38	0.00
14	24.63	11.88	12.75	0.00
15	11.35	8.49	2.86	0.10
16	16.46	12.30	4.16	0.67
17	33.76	25.01	8.75	4.21
18	16.91	12.01	4.90	0.00
19	19.56	19.61	−0.05	8.93
20	30.63	22.84	7.78	0.00
Mean	28.73	16.70	12.03	3.04
SE	3.41	2.77	2.07	2.00
95% CI	7.14	5.79	4.34	4.19

The stock change over all plots averaged 12.03 t C/ha over CP1, with a standard error of 2.07 t C/ha (95% CI = 12.03 ± 4.34). As noted above, estimates of AGB carbon were adjusted to reflect the effect of mortality using an assumption that dead standing stems remain standing on average for five years. Without this adjustment for mortality, the 2008–2012 stock change estimate would have been

13.7 t C/ha. A sensitivity analysis to the assumption that dead stems remain standing for five years was provided by recalculating stock change assuming dead standing times of three and seven years. These assumptions produced sequestration estimates of 10.5 and 12.6 t C/ha, respectively, indicating that estimates are not particularly sensitive to this assumption.

Carbon stock change over CP1 tended to be slower in older plots and faster in plots with a more recent change in land use (correlation between stock change and age, $r = 0.39$). Stock change was especially low in the five plots that were aged using the threshold method to be 22 years old in 2012. However, there was little trend between carbon sequestration and plot elevation (the correlation between stock change and elevation, $r = 0.07$).

3.6. National Average Carbon Stocks per Hectare by Year and Pool

Annual average carbon stocks in post-1989 natural forest between 1990 and 2012 and the disposition by pool, averaged by year across all 20 plots in the inventory, are shown in Figure 3. The woody biomass carbon stock at the beginning of 1990 averaged 2.82 t C/ha and provides an estimate of the average carbon stock in woody vegetation across the grassland subcategories used for mapping (grassland with woody biomass, high producing grassland, low producing grassland) at that time. The distribution of ages of plots in the inventory of post-1989 natural forest provided an indication of when land defined as post-1989 natural forest changed from grassland to forest (Table 6).

Table 6. Year of conversion of grassland to post-1989 natural forest, based on the threshold method for determining stand age. Shown is the cumulative number of plots converted to post-1989 forest at the end of each calendar year and their cumulative area as a percentage of their total area in 2012.

Year	Cumulative Number of Post-1989 Forest Plots	% Area Converted to Forest
1990	5	25
1991	5	25
1992	5	25
1993	5	25
1994	5	25
1995	6	30
1996	8	40
1997	10	50
1998	11	55
1999	11	55
2000	11	55
2001	13	65
2002	14	70
2003	17	85
2004	19	95
2005	19	95
2006	19	95
2007	20	100

A generalized yield table, shown graphically in Figure 4, indicates that the annual carbon sequestration rate is quite steady over at least the first 20 years, typically averaging about 2.2 tonnes of carbon per hectare per year. However, wide variation was evident between plots (sites) (Figure 2). Note that the average carbon stock per ha in post-1989 natural forest vs. calendar year follows a very different profile, showing an accelerating trend (Figure 3), compared with the age-based relationship, which shows a decelerating trend (Figure 4). This difference is to be expected, because Figure 4 reflects the net rate of carbon accumulation (growth, mortality and decay) with age, while Figure 3 in addition reflects the faster growth of younger vegetation on land converted progressively into post-1989 natural forest (Table 6) over the period since 1990.

Figure 3. Average carbon stock in post-1989 forest annually (as of December) between 1990 and 2012 and by pool: AGB, BGB, deadwood and litter.

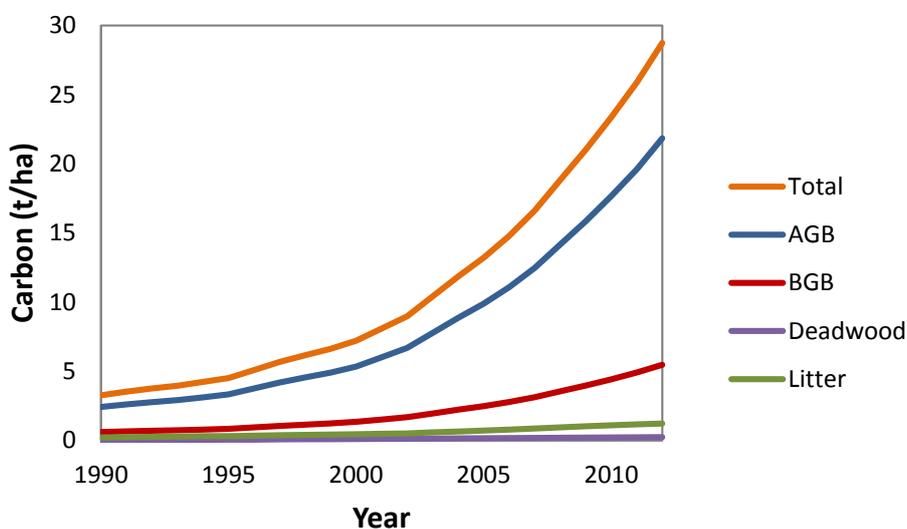
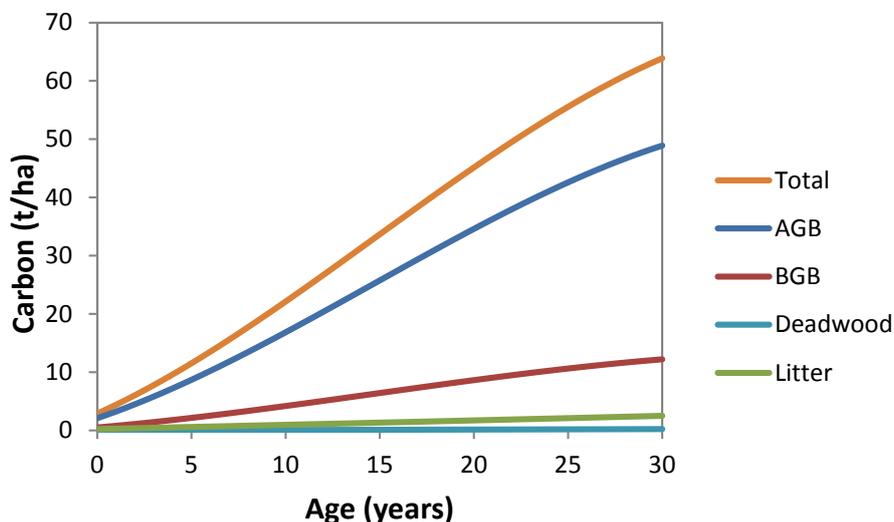


Figure 4. Estimated carbon stocks in relation to age for post-1989 natural forest (with one outlier plot excluded) across all pools and for individual pools: AGB, BGB, deadwood and litter.



4. Discussion

New Zealand's inventory of post-1989 natural forest was sampled on a 4-km grid using a nested plot design, which facilitated rapid measurement of the shrubland vegetation. By far, the majority of the above ground biomass was in plants < 10 cm dbh. The nested plot design will help ensure that plots can be remeasured efficiently in future as small arboreal shrubs grow into trees. The two dominant species encountered were arboreal shrubs (manuka and kanuka). Aboveground biomass was calculated using allometric equations applied to basal diameters and height. The allometric equations incorporated adjustments for species effects, which was necessary because of the number of shrub species found with different allometries. Manuka and kanuka were of similar form, and previous work has shown that they do not differ in allometry [5]. Allometric equations for primary forests in New Zealand are based on stem diameter at breast height and tree total height [18]. In the present study, on secondary forests, basal diameter was used as the independent variable, irrespective of plant size, because the backcasting methodology relied on the basal disc measurements of annual stem diameter increments and shrub age determinations. Basal diameter has been assessed in shrubland biomass studies previously [23], in preference to using stem diameter at breast height.

4.1. Basal Disc Diameter Increment and Aging

Carbon stock changes can be estimated from repeated measurements of inventory plots. However, New Zealand's inventory of post-1989 natural forest relied on predictions of basal area prior to 2012 using diameter increment functions developed using basal disc samples from shrubs growing outside inventory plots. Annual growth rings provided the markers needed to determine stem diameter each year following Whittaker [14]. Annual growth rings have to be visible around most of a disc circumference to distinguish false rings from true annual rings. Ring counts from basal disc samples also provided accurate estimates of shrub age. Many discs from *Coprosma* species and some discs of tauhinu proved difficult to age, because of very ill-defined colour/texture difference between earlywood (spring) and latewood (winter) cell growth. This difficulty was overcome by fine sanding and surface wetting of the discs. Discs needed to be stored frozen prior to processing in the laboratory to prevent sap stain fungi from obscuring annual rings and to prevent dehydration. To accurately backcast stem diameters, harvested shrubs need to be representative, in terms of species and size range, of plants growing inside the plots. This was achieved using a nested plot design, where four basal disc samples represented stems within the 20 × 20-m plot and four basal disc samples represented stems within the 1.5-m radius circular plots. For practical reasons, basal disc samples were not taken from stems > 60 cm dbh. In the inventory of post-1989 natural forest, the absence of increment data for large trees was not of concern, because large trees contributed negligibly to the aboveground biomass per hectare. If necessary, this issue could be resolved by taking increment core samples.

4.2. Predicting Stock Changes by Backcasting from 2012 Inventory Data

Because no inventory of post-1989 natural forest occurred in 2008, stock changes needed to be estimated from plot measurements in 2012/2013. The diameter increment data, when coupled with height predictions from a height/age function developed using planted shrub data from a national

study [21], allowed biomass stock estimates annually back to 1990. Knowing the age is the primary benefit of using planted indigenous shrubs for developing height/age curves. The use of height/age curves is standard practice in forest inventory [24]. After taking species and age into account, predictions of stock change in live plants, derived by backcasting basal area and height from the 2012 measurement, were generally very satisfactory, as demonstrated in the pilot study [15].

Gross dry matter production in 2012 was calculated from the aboveground live tree biomass and the litter mass in 2012. The increase in litter was added to the increase in live plant dry matter, to estimate total sequestration. Backcast stocks to 1990 were calculated in a similar way, by assuming that mortality was a constant proportion of aboveground biomass. The change in the litter pool over time was therefore not necessarily estimated accurately, because: (1) the mortality rate was assumed to be constant; and (2) a decay rate based on an assumed decay function (taking into consideration the decay class) was applied. However, litter comprised a small pool, and the effects of mortality and decay assumptions on carbon stocks and changes over time are expected to be small. We estimated the dry weight of deadwood and litter from plants that were dead in 2012. Because basal diameter increments of plants that died after 2008 are unknown, our stock change estimates do not include the possible growth of these plants over CP1. However, growth was likely to have been small, because plants that died over CP1 would likely have already been suppressed.

4.3. National Carbon Stocks

A national carbon yield table for post-1989 natural forest was developed giving carbon stocks by year, which can be used to calculate stock changes over defined periods. The backcasting methodology allowed estimates of woody biomass stocks annually back to 1990 for each plot. The stock is greater than zero in 1990, because woody vegetation was present at some of the grassland sites at that time. Carbon stocks can also be presented by age; however, only a mean age can be assigned to shrubland. By assumption, a woody AGB carbon stock of 2 t/ha was considered to be the threshold present at age zero, and shrubland mean age to 2012 was calculated from that threshold year onwards.

Having a method to assign a mean age to woody vegetation at each site allowed the carbon yield table to be presented as a function of age for use within New Zealand's carbon accounting system. An associated table giving the timing of conversion of grassland into post-1989 natural forest was also derived from the inventory data using the same assumption that land use change from grassland to forest (reforestation) occurred when AGB carbon first exceeded a threshold of 2 t/ha, so the two tables are compatible with each other.

The annual rate of carbon sequestration (in t/ha) for post-1989 natural forest is similar to the mean rate reported for manuka/kanuka stands in New Zealand [5], which possibly reflects the fact that manuka and kanuka were the dominant species encountered in New Zealand's national inventory plots. Annual sequestration rates per unit area in New Zealand are not unlike values for agroforestry systems in tropical areas [25].

Post-1989 forest includes both planted forest and natural forest. Natural forest is only a minor component, both in terms of area and carbon stocks, relative to planted forest. Therefore, the relatively poor precision of the natural forest carbon stock estimates and the impact of being unable to measure eight out of 28 sites (unsampled areas will be assumed to have the same yield table as sampled areas) will have little impact on the overall stocks and changes for post-1989 forest in New Zealand.

5. Conclusions

Biomass measurements and basal disc diameter increment assessments allowed carbon stock changes to be estimated from a single inventory measurement. Aboveground live biomass comprised the majority of the carbon stock based on inventory data acquired in 2012 and was dominated by two arboreal shrub species, manuka and kanuka. The diameter, height and decay class of dead stems in post-1989 natural forest and assumptions around the stem mortality rate allowed stock estimates for the deadwood and litter pools. Incorrect assumptions around decay rates are not likely to be of importance, because dead organic matter comprised a small proportion of the carbon stock (all pools excluding soil C). An age-based carbon yield table based on vegetation mean age was developed for use within New Zealand's Land Use Carbon Analysis System for reporting and accounting greenhouse gas emissions. The table applies to the natural forest component of post-1989 forest. This table will be used in conjunction with data on the area of post-1989 forest in New Zealand to estimate carbon stocks annually in post-1989 natural forest. The same process is used for the planted component of post-1989 forest. These natural and planted components of post-1989 forest will be combined to calculate national estimates of total carbon stocks and changes in New Zealand's entire post-1989 forest estate.

Acknowledgments

The Ministry for the Environment provided funding for this work and for the pilot study to develop and test the backcasting methodology and to implement the national carbon inventory of post-1989 natural forest. New Zealand Forest Surveys Ltd collected the inventory data.

Author Contributions

Peter N. Beets: Inventory design, development of field manuals, training and auditing of field teams, data checking, calculation methods and writing; Mark O. Kimberley: refinement and implementation of calculation methods, statistical analysis, and writing; Thomas S. H. Paul: inventory design and refinement; Graeme R. Oliver: preparation of field manuals, training and auditing of field teams, biomass calculations, basal disc increment and plant age verification, and writing; Stephen H. Pearce: Remote assessment of vegetation type (planted versus natural) at grid points prior to plot establishment, biomass sample processing, basal disc annual increment measurement, shrub age determination, and writing; Joanna M. Buswell organized the inventory of post-1989 natural forest, is the Ministry for the Environment contact person responsible for ensuring that the yield table and age class distribution are used appropriately in New Zealand's Land Use Carbon Analysis System, and contributed to writing the paper.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Bouwman, A. F. Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. In *Soils and the Greenhouse Effect*; Bouwman, A.F., Ed.; John Wiley and Sons: New York, NY, USA, 1990; pp. 61–127.
2. Silver, W.; Ostertag, R.; Lugo, A. The potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands. *Restor. Ecol.* **2000**, *8*, 394–407.
3. Canadell, J.G.; Raupach, M.R. Managing forests for climate change mitigation. *Science* **2008**, *320*, 1456–1457.
4. Brown, S.; Gillespie, A.J.; Lugo, A.E. Biomass estimation methods for tropical forests with applications to forest inventory data. *For. Sci.* **1989**, *35*, 881–902.
5. Trotter, C.; Tate, K.; Scott, N.; Townsend, J.; Wilde, H.; Lambie, S.; Marden, M.; Pinkney, T. Afforestation/reforestation of New Zealand marginal pasture lands by indigenous shrublands: The potential for Kyoto forest sinks. *Ann. For. Sci.* **2005**, *62*, 865–871.
6. Wardle, P. *Vegetation of New Zealand*; CUP Archive: Cambridge, UK, 1991.
7. Carswell, F.; Burrows, L.; Mason, N. *Above-Ground Carbon Sequestration by Early-Successional Woody Vegetation*; Landcare Research Contract Report: LC0809/083; Department of Conservation: Wellington, New Zealand, 2009.
8. *New Zealand's Greenhouse Gas Inventory 1990–2012*; Ministry for the Environment: Wellington, New Zealand, 2014.
9. *IPCC Guidelines for National Greenhouse Gas Inventories*; Prepared by the National Greenhouse Gas Inventories Programme; IGES: Tokyo, Japan, 2006.
10. Beets, P.; Brandon, A.; Goulding, C.; Kimberley, M.; Paul, T.; Searles, N. The inventory of carbon stock in New Zealand's post-1989 planted forest for reporting under the Kyoto protocol. *For. Ecol. Manag.* **2011**, *262*, 1119–1130.
11. Coomes, D.A.; Allen, R.B.; Scott, N.A.; Goulding, C.; Beets, P. Designing systems to monitor carbon stocks in forests and shrublands. *For. Ecol. Manag.* **2002**, *164*, 89–108.
12. Navarro Cerrillo, R.M.; Blanco Oyonarte, P. Estimation of above-ground biomass in shrubland ecosystems of southern Spain. *For. Syst.* **2008**, *15*, 197–207.
13. Whittaker, R.H.; Woodwell, G.M. Dimension and production relations of trees and shrubs in the Brookhaven Forest, New York. *J. Ecol.* **1968**, *56*, 1–25.
14. Whittaker, R.H. Estimation of net primary production of forest and shrub communities. *Ecology* **1961**, *42*, 177–180.
15. Beets, P.N.; Kimberley, M.O.; Oliver, G.R.; Pearce, S.H. The application of stem analysis methods to estimate carbon sequestration in arboreal shrubs from a single measurement of field plots. *Forests* **2014**, *5*, 919–935.
16. Dymond, J.R.; Shepherd, J.D.; Newsome, P.F.; Gapare, N.; Burgess, D.W.; Watt, P. Remote sensing of land-use change for Kyoto Protocol reporting: The New Zealand case. *Environ. Sci. Policy* **2012**, *16*, 1–8.
17. Van Breugel, M.; Ransijn, J.; Craven, D.; Bongers, F.; Hall, J.S. Estimating carbon stock in secondary forests: Decisions and uncertainties associated with allometric biomass models. *For. Ecol. Manag.* **2011**, *262*, 1648–1657.

18. Beets, P.N.; Kimberley, M.O.; Oliver, G.R.; Pearce, S.H.; Graham, J.D.; Brandon, A. Allometric Equations for Estimating Carbon Stocks in Natural Forest in New Zealand. *Forests* **2012**, *3*, 818–839.
19. McCullagh, P.; Nelder, J.A. *Generalized Linear Models (Monographs on Statistics and Applied Probability 37)*; Chapman Hall: London, UK, 1989.
20. Beets, P.N.; Hood, I.A.; Kimberley, M.O.; Oliver, G.R.; Pearce, S.H.; Gardner, J.F. Coarse woody debris decay rates for seven indigenous tree species in the central North Island of New Zealand. *For. Ecol. Manag.* **2008**, *256*, 548–557.
21. Kimberley, M.; Bergin, D.; Beets, P. Carbon sequestration by planted native trees and shrubs. In *Planting and Managing Native Trees: Technical Handbook*; (Technical Article No. 10.5); Bergin, D., Ed.; Tane’s Tree Trust: Rotorua, New Zealand, 2011.
22. Scott, N.A.; White, J.D.; Townsend, J.A.; Whitehead, D.; Leathwick, J.R.; Hall, G.M.; Marden, M.; Rogers, G.N.; Watson, A.J.; Whaley, P.T. Carbon and nitrogen distribution and accumulation in a New Zealand scrubland ecosystem. *Can. J. For. Res.* **2000**, *30*, 1246–1255.
23. Litton, C.M.; Boone Kauffman, J. Allometric models for predicting aboveground biomass in two widespread woody plants in Hawaii. *Biotropica* **2008**, *40*, 313–320.
24. Spurr, S.H. *Forest Inventory*; Ronald Press: Nova York, NY, USA, 1952; p. 476.
25. Montagnini, F.; Nair, P. Carbon sequestration: An underexploited environmental benefit of agroforestry systems. *Agrofor. Syst.* **2004**, *61*, 281–295.

© 2014 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/3.0/>).