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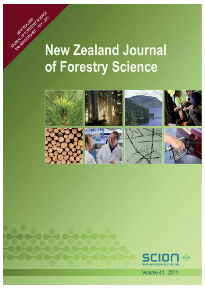

Carbon accumulation in two *Pinus radiata* stands in the North Island of New Zealand

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Abstract

Carbon stocks in two *Pinus radiata* (D.Don) stands in the North Island of New Zealand were determined at 5-years-old and again at mid-rotation (15-years-old at Kinleith; 16-years-old at Tarawera). Above-ground tree biomass was measured at both ages. At the mid-rotation, dead organic matter pools were also assessed. Below-ground live roots were not directly measured but estimated from a published root/shoot ratio to indicate the relative sizes of the stand carbon pools.

At Kinleith (15-years-old) and Tarawera (16-years-old), carbon in the four pools: above-ground biomass; live below-ground biomass; dead wood; and forest floor litter; were estimated to be 79.4 t/ha and 105.6 t/ha, 15.9 t/ha and 21.1 t/ha, 17.2 t/ha and 23.6 t/ha, 13.7 t/ha and 14.6 t/ha, respectively. The total carbon stocks at Kinleith (15-years-old) and Tarawera (16-years-old) were 126 (± 5.1) t/ha and 165 (± 5.5) t/ha, respectively.

At mid-rotation, 63 – 64% of total carbon stock at both sites was in live above-ground biomass plus attached dead branches; 16% was in stems, live and dead stumps, dead roots and branch woody debris from the second thinning operation, 7 – 8% was in the forest-floor litter, and 13% was estimated to be in live roots. Carbon (C) accumulation in above-ground biomass averaged 5.3 t C/ha/year by age 15-years at Kinleith and 6.6 t C/ha/year by age 16-years at Tarawera, and increased to 6.4 t C/ha/year at Kinleith and 7.9 t C/ha/year at Tarawera when *Pinus radiata* live root biomass was included. Further, when dead organic matter pools were included with the *Pinus radiata* biomass, the mean C accumulation rate increased to 8.4 t C/ha/year at Kinleith and 10.4 t C/ha/year at Tarawera.

Overall weighted mean carbon concentration of above-ground biomass was estimated as 51.4 g/100 g and 52.0 g/100 g of dry matter at Kinleith and Tarawera, respectively.

At Kinleith (15-years-old) and Tarawera (16-years-old) respectively, mean diameter at breast height was 27.1 cm and 30.8 cm, mean total height was 22.7 m and 28.2 m, mean basal area was 33.1 m^2/ha and 39.4 m^2/ha, and mean volume inside bark was 299 m^3/ha and 397 m^3/ha.

Keywords: biomass; carbon stocks; *Pinus radiata*; woody debris.

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Introduction

New Zealand is obligated under the Kyoto Protocol and the United Nations Framework Convention on Climate Change to report on carbon (C) sinks and emissions for forestland, and land subject to afforestation, reforestation, and deforestation activities. Carbon stocks need to be estimated annually. The Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC, 2003) has defined five separate carbon pools: live above-ground biomass; live below-ground biomass; litter; dead wood; and soil.

The IPCC pools do not explicitly state where dead branches attached to live trees belong. Attached dead branches are most easily measured along with the rest of the live tree at the time of felling and are included in the “above-ground” tree pool in this study.

We did not estimate carbon content of the soil pool but measured soil carbon and nitrogen (N) concentrations in the 0 – 5 cm mineral soil layer for wood density and carbon modelling purposes (Beets et al. 2007a).

The New Zealand Land Use and Carbon Analysis System (LUCAS) provides a national estimate of the carbon stocks present in various biomass pools for plantation forests. This system involves a network of permanent plots installed at each intersect of a grid placed across New Zealand. The silvicultural regime and mensurational data for each plot is used to estimate the amount of carbon in each of the four pools (excluding soil). These estimates are generated using a combination of two models, the “300 Index” growth model (Kimberley et al., 2005) which uses the stem volume mean annual increment at stand age 30 years of a regime of 300 stems per hectare as a measure of productivity, and the “C_Change” model (Beets et al., 1999); which now also incorporates a nationwide wood density model (Beets et al., 2007a) that predicts stem biomass and carbon sequestration from volume increments and wood density of annual growth sheaths.

The biomass partitioning model, C_Change, was developed using biomass data, predominantly from fertile, ex-pasture sites (Beets et al., 1999). This data represented part of a larger biomass data set acquired previously by Madgwick (1994) for *Pinus radiata* (D.Don) covering a wide range of stand age and stocking, from stands mostly on fertile sites in the central North Island of New Zealand. The C_Change model was then validated using a compilation of independent datasets (Beets et al., 1999) drawn from stands with known silvicultural history over a range of tree ages, stocking levels, soil fertility, and mean annual air temperature, from sites in both the North Island and northern South Island of New Zealand.
The dominant species planted in production forests in New Zealand is *Pinus radiata*, which is intensively managed and clearfelled on an approximately 28-year rotation. For any given stand, the total carbon stock at a given time depends on the balance between tree growth, mortality, and decay. Stand growth rates vary spatially and temporally, depending on initial stocking, tree age, site productivity, and silvicultural activities such as pruning, thinning, and harvesting. Thus, pruning and non-commercial thinning operations result in the transfer of some above-ground biomass to the dead organic matter pools, of dead wood and litter while harvesting (clearfelling) normally results in the transfer of all crown material, tree stumps, roots and other logging waste to dead pools. Since dead organic matter pools represent a carbon source, it is necessary to take into account the timing and intensity of silvicultural operations over multiple rotations in order to accurately estimate forest carbon stocks and stock changes over time at the national level. While an independent nationwide study by Carey et al. (1982) measured the dead organic matter pool of forest floor litter across a wide range of first and second rotation stands, comprehensive measurement of both the live and dead carbon pools under known silvicultural regimes has not been undertaken previously in New Zealand.

This paper provides estimates of live biomass and dead organic matter pools (wood and litter), based on measurements undertaken at two trials installed in second-rotation *Pinus radiata* stands in Kinleith Forest and Tarawera Forest. Both trials were of the same standard design, and included various levels of residue retention, following harvesting of the first rotation *Pinus radiata* stands.

The main objective of this study was to produce carbon pool data from the two trials in a form suitable for input into the C-Change model. We achieved this by:

1. determining the carbon stock in above-ground tree biomass components of 5-year-old second rotation *Pinus radiata* stands following three levels of residue retention at both Kinleith and Tarawera forests; and

2. determining the carbon stock in both above- and below-ground tree biomass components and dead organic matter pools of 15- and 16-year-old *Pinus radiata* stands in the same three residue treatments at Kinleith and Tarawera forests, respectively.

A comparison of the different residue retention treatments was not an objective here but data from the different treatments provide an indication of the variation possible in empirical data.

An additional objective was to provide associated stand data and silvicultural history at the treatment level, which together with the above estimates of carbon at

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Kinleith and Tarawera would allow independent testing of predictions of biomass and organic matter carbon pools using the C_Change model.

2. Materials and Methods

2.1. Location of sites

The Tarawera and Kinleith sites are part of a national Long Term Site Productivity trial series originally located at three sites (Smith et al., 2000) and later expanded to six. The Tarawera site is located in the Tarawera valley at latitude 38° 13′ S and longitude 176° 00′ E near Kawerau in the Bay of Plenty, and the Kinleith site is located on the Mamaku plateau at latitude 38° 14′ S and longitude 175° 58′ E near Tokoroa in the central North Island. The Tarawera and Kinleith sites were planted in 1989 and 1992, respectively, as second rotation *Pinus radiata* stands to determine the impacts of various harvest residue management practices on site productivity.

The Tarawera site is 90 m a.s.l., on a river terrace slope of less than 5 degrees and has a mean annual rainfall of 1968 mm and mean annual air temperature of 13.5 °C (Leathwick et al., 2003). The soil is classified as a Typic Tephric Recent Soil in the New Zealand Classification System (Hewitt, 1998). The parent material originated from the 1886 Mount Tarawera eruption and overlies pumiceous river terrace material. The soils are moderately well drained, with gravely, sandy loam and sand textures.

The Kinleith site is 490 m a.s.l., on a slope of mostly less than 10 degrees (but includes some steeper mounds associated with ignimbrite tors) and has a mean annual rainfall of 1764 mm and mean annual air temperature of 11.5 °C (Leathwick et al., 2003). The soil is classified as an Orthic Pumice Soil in the New Zealand Classification System (Hewitt, 1998). The parent material of Taupo pumice originated from the Taupo volcanic centre (1860 $\underline{+}$100 BP) and includes some older ash showers. The soils are moderately well drained, with sandy loam and sand textures.

2.2. Experimental design

At each trial site, four harvest residue retention treatments (Smith et al., 2000) were established, each replicated in 4 blocks, with 32 20 x 20 m plots (horizontal area basis) planted with 2500 stems/hectare, in a split plot (± fertiliser) design, giving nominally 100 trees per plot. The three non-fertilised treatments, common to both trials, and used for our assessments were: conventional stem removal with normal residues remaining (SO); whole tree removal with forest floor left intact (WT); and whole tree and forest floor removal (FF). Four replicate plots of each treatment were selected for measurement of carbon stocks in 1994 and 2005 at Tarawera and 1997 and 2007 at Kinleith.

Neither trial was pruned but both were thinned to waste (Maclaren, 1993), between 5- and 6-years-old (first thinning), and again between 10- and 11-years-old (second thinning). The first thinning, in 1994 and 1998 at Tarawera and Kinleith, respectively, aimed to systematically remove every second tree. The second thinning, in 2000 and 2002 at Tarawera and Kinleith, respectively, aimed to remove 50% of the plot basal area at each event randomly whilst maintaining reasonably uniform spacing. In fact, some adjustments were made to ensure that badly malformed trees were removed. Trees were directionally felled in a non-random orientation, which prevented the crowns of fertilised-plot trees contaminating unfertilised treatments.

Only live branches (i.e. no live stems were felled) were sampled from one plot of the SO treatment at Kinleith at stand age 5-years because tree stocking was low due to early tree mortality. To maintain the sample size, additional trees were measured from other replicate plots of the SO treatment. This plot was omitted from biomass sampling at 15-years-old because remaining trees had atypical large crowns.

2.3. Data collection and use

Some differences occurred in data collection (especially bulking of samples) between sites as the methodology evolved over the course of the study.

2.3.1 Diameter at breast height

As part of a normal regular measurement programme (annually to 1998, and less frequently thereafter), diameter at breast height (1.4 m, DBH) of every plot tree was measured just prior to each biomass assessment so that total basal area per plot could be calculated. From this, the total above-ground biomass and its carbon content could be estimated using the basal area ratio method (Madgwick, 1981).

2.3.2 Height

The height of all plot trees were measured when the stands were 5-years-old. At the mid-rotation age (15- and 16-years-old at Kinleith and Tarawera, respectively), the heights of 12 trees per plot were measured, with trees selected across the diameter range to construct a height diameter curve from which the plot mean height and mean top height (MTH) were determined.

2.3.3. Above-ground tree biomass at 5-years-old (both sites)

The total above-ground tree biomass at age 5 was calculated by summing the biomass of live branches, dead branches, foliage, stem wood and stem bark.

Branches:

Crowns of ten randomly selected live standing trees were sampled in each plot at both sites prior to thinning. Tree crowns were subdivided into three zones, each with approximately the same number of branch whorls (including dead whorls). One randomly selected sample branch was removed (by climbing) from each zone. This generated a total of three sample branches per tree (30 branches per plot) for processing. The sample branches were bulked by plot, as either live foliated branches or dead branches. The total fresh weight of each category and the fresh weight of a subsample (selected by repeated quartering) were measured in the field. All samples were oven-dried (70 °C to constant weight) and live foliated branches were then separated into needles and branch, re-dried and weighed. The number of branches was counted in each whorl from which sample branches were taken, and the number of branch whorls per zone was counted for each tree that was sampled. The total dry weight of the ten sample tree crown components was calculated by multiplying the oven dry weight of sample branch components by the sub-sampling fraction and then by the total branch count of sampled trees.

Stems (wood and bark):

At Kinleith, tree stems were sampled by randomly selecting three trees from each of four WT and FF plots (plus four stems from each of three SO plots), giving a total of 36 stems. At Tarawera, five stems were randomly selected from each of the twelve sample plots, giving a total of 60 stems.

Stems at both sites were felled 10 cm above ground level and diameter over bark (DOB) measured by tape at the base of the tree (0.15 m height), 1.4 m height, at base of green crown, and at 1 m intervals up the stem to the top of the tree for volume determination. Total height and the height to the base of the green crown were also recorded. A 2.5 cm thick disc was cut from the base of the tree, and 5 cm thick discs were cut at 1 m height intervals to the top of the tree. Measurements were made of: DOB (by tape); disc thickness at four equidistant points around the disc perimeter (using a pair of callipers); and diameter inside bark (DIB) by tape, after the bark was removed from each disc. Disc components collected from Kinleith were combined into one bulk sample of wood and one bulk sample of bark per plot. The bark and de-barked discs from individual trees at Tarawera were kept separate and used for individual tree oven-dry weight determination (70 °C to constant weight). In this case, the total dry weight of stem components was calculated for each tree by multiplying the oven-dry weight of the disc component by the stem volume sampling ratio (i.e. the volume of wood or bark of the 1 m stem section that the disc samples represent divided by the total wood or bark volume of the sample). At Kinleith, the stem volume sampling ratio was applied to bulk samples of wood and bark.

2.3.4. Above-ground tree biomass at 15- (Kinleith) and 16-years-old (Tarawera)

The total above-ground tree biomass at age 15/16 years was calculated by summing the biomass of live branches, dead branches, foliage, cones, stem wood and stem bark.

Stems (wood and bark):

The atypical SO plot at Kinleith was excluded so an additional two trees were selected randomly for biomass measurement from the other three SO plots to give a total of eight trees per treatment). Two trees from each of the four plots of the WT and FF treatments (i.e. eight trees per treatment) were selected to give a total of 24 trees for biomass measurement based on standard procedures developed previously for *Pinus radiata* (Beets & Pollock, 1987). At Tarawera, two trees from each of the four plots per treatment (total 24 trees) were selected. Total height, height to base of green crown, and DOB (at base height of 0.15 m, 0.7 m, 1.4 m, and at 3 m intervals along the stem) were measured by tape for determination of total stem volume. A 2.5 cm thick disc was cut from the tree base and 5 cm thick discs were cut at 3 m intervals along the stem dividing the tree into 3 m zones. The disc DOB, thickness (at four to eight points around disc perimeter) and DIB were measured as for 5-year-old trees, to determine sample disc volume with and without bark.

Stem disc wood from Kinleith and Tarawera and disc bark samples from Kinleith were oven dried (70 °C to constant weight) and individually weighed but disc bark samples from Tarawera were bulked per tree before weighing. The total weight of stem components was calculated by the same volume ratio method as for 5-year-old trees.

An additional disc was cut at 1.4 m height to determine outerwood basic density, by cutting two diametrically opposite radial strips by bandsaw and separating these into outerwood (outer five rings) and inner wood, as described for cores in survey trees. The fresh wood volume of samples was determined by displacement, and oven-dry weight determined after drying for 48 hours at 104 ºC (Clifton, 1994).

Branches, foliage and cones:

Branch dry weight in the dead crown zones (below base of live crown) of each tree was based on two typical dead branch samples collected from each zone, bulked per tree and weighed fresh. Remaining dead branches were removed, weighed fresh and discarded. In each live crown zone, two (Kinleith), or three (Tarawera), live undamaged sample branches representative of the foliage to branch wood ratio of that zone were collected, bulked and weighed fresh. One typical dead branch (if present) was also collected from each live zone and weighed fresh. Stem needles (foliage) were removed and included in the top crown zone. All branch and stem cones were collected and weighed fresh as one bulked sample per tree. Remaining live branches were then removed, weighed fresh by zone, and discarded. Any samples over approximately 10 kg fresh weight were reduced in size by careful mixing and subsampling, and subsample fresh weights recorded.

All biomass samples were oven-dried (70 °C to constant weight) and live foliated branches were then separated into needles and branch, re-dried and weighed. The total dry weight of crown components was calculated by multiplying the oven-dry weight of the component by the fresh weight sampling ratio for each zone and summed by tree.

2.3.5. Outer wood basic density survey

The sample size (8) of trees used in the biomass calculation was relatively small. A double-sampling procedure was, therefore, used to improve the accuracy of the estimate of the whole-stem wood density on a stand basis (Beets et al., 2008). Outer wood was defined here as the five outermost annual rings. Outerwood cores were extracted with an increment borer at 1.4 m (breast height) from eight randomly selected trees in each plot prior to biomass sampling. The cores were all refrigerated until wood basic density was determined using the maximum moisture content method (Smith, 1954). Treatment means of breast height core outerwood basic density for both sites were determined from weighted plot means obtained from individual core weights and lengths. The whole-stemwood density estimate of each treatment on a stand basis was estimated by a double sampling technique outlined in Beets et al. (2008). In this method the density ratio estimate ($\overline{D}_R$) was calculated from the following equation:

$$\overline{D}_R = R\overline{D}_O \qquad [1]$$

where (R) is the ratio of the mean whole stemwood density ($\overline{d}_T$) over the mean outerwood basic density ($\overline{d}_O$) of the eight biomassed trees and $\overline{D}_O$ is the mean outerwood basic density of the 32 survey trees.

2.3.6. Above-ground biomass carbon pool

The above-ground biomass at stand age 5-years-old at both Kinleith and Tarawera was assumed to be 50% carbon. At mid-rotation carbon concentration was measured on bulked samples of six tree components per tree: live branches; needles; stem wood; stem bark; cones; and dead branches) from each site by chipping and grinding to pass a 2 mm sieve and analysis of total carbon with a LECO FPS-2000 CNS thermal combustion furnace (LECO Corp., St Joseph, MI, USA).

The carbon contained in the above-ground biomass (t/ha) was estimated from sample tree weights, by component, using the basal area ratio method developed by Madgwick (1981) adjusted to a horizontal area basis. Madgwick, (1991) also showed that increasing the number of trees sampled in any given plot from five to ten markedly reduces variation of stand dry weight estimates from the actual stand value. We maximised the practicable sample size by combining the two or three sample trees measured in each plot to provide eight trees per treatment when estimating stand weights at mid-rotation. This method provides unbiased (Madgwick, 1981) estimates of stand weights given the basal area of the stand, and the weight and basal area of a randomly selected sample of trees from the stand.

2.3.7. Live below-ground tree biomass pool

Root biomass was not directly measured but was estimated using a root/shoot (R/S) ratio of 0.2 (Beets et al., 2007).

2.3.8. Dead wood pool

Carbon stock in dead wood was expressed on a horizontal area basis.

Stem debris from second thinning - no diameter limits:

At mid-rotation, the residual volume of stems from the second thinning operation five years earlier was assessed using two line-transects per plot. These line-transects were installed by laying length tapes across the two plot diagonals and measuring the diameter (at right angles to the central axis) of every stem intersected by the lines, following the method of Van Wagner (1968). Stem volume per plot was then calculated from the formula:

$$V = (\pi^2 \sum d^2)/8L \qquad [2]$$

where: V is residual stem volume (m^3/ha), d is stem residual diameter (cm), and L is total length (cm) of transects.

Several assumptions were made. The most important of these was that the stems intersected were randomly orientated. Stems were also assumed to be horizontal (because plot terrain was generally flat and stems were mostly in contact with the ground) and to have no taper at the measurement point, with both these factors being considered of minor significance in this study.

The volume of stem woody-debris at Kinleith was converted to weight of dry matter based on the density of a disc sample collected from each of the two stems nearest to each of 12 litter quadrats per plot described below in Section 2.3.9. The resulting 24 discs were assessed for: the proportion of bark remaining; diameter (by tape); and disc thickness (using a pair of callipers), at four to eight equidistant points around the disc perimeter to estimate disc volume. Individual-disc dry weight was determined by drying at 70 °C to constant weight. Mean disc density per plot was then calculated from the sum of individual-disc dry weights divided by the sum of disc volumes. Total dry weight of thinned stems was then calculated by multiplying the mean disc density by the volume of thinned stems measured by transect in each plot and calculated using Equation [2] above.

For each plot in the SO-treatment at Kinleith, the carbon concentration was measured in a bulk sample of discs taken at 2 m intervals up each of 10 additional stems, selected randomly as part of a decay study (Garrett et al., 2010). Stem disc samples were chipped and ground to less than 2 mm before analysis of total carbon using a LECO thermal combustion analyser. The range in carbon concentration of individual trees was assumed to be the same in all residue retention treatments so the mean carbon concentration of stem discs in the decay study was applied to the thinned-stem dry weight for all Kinleith plots where dry matter estimates were made.

At Tarawera, nine discs (one per litter quadrat) were collected from each plot and combined into a single bulk sample before determination of oven dry weight (70 °C to constant weight) and carbon concentration. Total stem dry weight in each plot was estimated from thinned stem volume and mean disc density as for the Kinleith plots.

Live and dead stump debris remaining after thinning:

> Garrett et al. (2010) measured heights and residual diameters of all (live and dead) stumps remaining from the first and second thinning operations in the three plots of the SO treatment at the Kinleith site and a sample of stumps in four plots of the SO treatment at the Tarawera site (Garrett et al. 2008). The stump total dry matter and carbon stock at Tarawera were both estimated by first applying the ratio of basal area of all felled stems to sample tree basal area, multiplied by the residual sectional area (SA) of the sample stumps, to estimate the total stump residual sectional area. The total stump residual SA at Kinleith was simply the sum of the measured stump sectional areas. At both sites, total volume, dry matter, and carbon stock of stumps in plots of the SO treatment were calculated, by multiplying total stump SA by average stump heights, and allowing for the proportions of live and dead stumps, with their respective densities and carbon concentrations (Garrett et al., 2008, Garrett et al., 2010). To estimate the carbon content of stumps remaining from the second thinning in the FF and WT treatments the stump carbon : stem carbon ratio of the SO treatment was applied to the mean thinned stem carbon content measured by transects in those treatments.

Dead roots:

> Biomass and carbon in dead roots resulting from thinning operations were estimated from decay constants developed from data collected at both the Tarawera and Kinleith sites (Garrett et al., 2008; Garrett et al., 2010).

2.3.9. Litter pool (no diameter limit)

Carbon stock in the litter pool (including dead branches lying on the forest floor) was expressed on a horizontal area basis. Dead branches attached to live standing trees are classified by the IPCC as litter but are reported in the above-ground biomass pool in this study. No maximum diameter limit was applied to any of the dead branches.

By the time of the mid-rotation measurement, residues from harvesting the first rotation had almost completely decayed. Dead woody debris remaining from stems felled during the first thinning operation at 5-years-old had mostly merged with the forest floor and had insignificant mass, so was collected and measured as part of the forest floor layer.

At the mid-rotation measurement, branch debris from natural litterfall and branches attached to stems arising from the second thinning operation five years earlier were collected in 12 (Kinleith) and 9 (Tarawera) systematically located 0.25 m^2 quadrats in every plot except for the atypical SO plot at Kinleith. These quadrats were also used to estimate the forest floor needle litter (L) and fermenting humus material (FH) as part of forest floor/soil related studies at Tarawera (Jones et al., 2008), and Kinleith (Jones et al., unpublished data). Branch debris that could be measured for diameter was collected as branch litter (as defined by the IPCC). Unsound decayed branch portions were measured as part of the FH layer. Dead branches collected as litter were chipped and ground to less than 2 mm before analysis of total carbon using a LECO thermal combustion analyser.

2.3.10. Soil pool

Soil carbon (C) and nitrogen (N) ratio (C/N) is a required input for validation of the C_Change model. This ratio was determined at each site by collecting soil cores from 0-5 cm depth with Hoffer tube samplers (JBK Manufacturing and Development Co. Ohio, USA). Initially, 60 cores were taken per plot from Tarawera in 2005 at the same time as the 16-year biomass measurements (data not shown). This process was repeated at Tarawera in 2006 using 100 cores per plot to confirm the 2005 results. One hundred cores per plot were also taken at Kinleith in 2007 at the same time as the 15-year biomass measurements. Soil samples were air-dried, ground to pass a 2-mm sieve, and analysed for carbon and nitrogen concentrations with a LECO thermal combustion analyser.

3. Statistical Analysis

The effect of both harvesting and residue retention treatment on tree stocking, mean top height, basal area, and soil C/N ratio were tested using the GLM procedure in SAS (SAS Institute, 2000). Wood density of survey trees was examined between treatments and sites. The effect of residue retention treatment on stand dry weight and carbon stocks could not be tested statistically because sample trees were combined by treatment and plots were, therefore, not statistically independent.

4. Results

4.1. Stand growth

At stand age 5-years there was no difference in overall mean stocking between forests (sites), however, the SO treatment had significantly lower stocking (p = 0.0035) than other treatments, due to early mortality, at both sites (Tables 1 & 2). Basal area and mean height at 5-years-old were both significantly (p = 0.0147 and p < 0.0001, respectively) higher at Tarawera (17.50 m^2/ha and 6.7 m) than at Kinleith (15.12 m^2/ha and 5.4 m) after allowing for treatment

TABLE 1: Stand characteristics of *Pinus radiata* at two ages for three harvest residue treatments at Kinleith Forest.

Age (y)	**Treatment**	**Stocking (stems/ha)**	**Mean DBH (±se) (cm)**	**Mean height (±se) (m)**	**MTH[2] (±se) (m)**	**Basal Area (±se) (m^2/ha)**	**Vol_ib[1] (m^3/ha)**	**Vol_ob[1] (m^3/ha)**
5	FF	2419	9.2 (0.3)	5.6 (0.2)	6.6 (0.2)	16.0 (1.0)	49.2	59.1
	WT	2300	9.1 (0.4)	5.4 (0.3)	6.3 (0.2)	15.1 (1.2)	44.4	52.5
	SO	1900	9.2 (0.6)	5.3 (0.5)	6.2 (0.3)	13.5 (3.5)	41.8	49.7
15	FF	575	26.3 (0.4)	23.0 (0.4)	24.6 (0.3)	31.0 (1.0)	274.3	324.0
	WT	600	27.2 (0.1)	22.2 (0.2)	24.1 (0.1)	34.9 (0.7)	305.2	356.1
	SO	531	29.0 (1.4)	22.6 (0.3)	24.4 (0.5)	34.8 (1.7)	317.8	371.5

[1] Tree volume (Vol) inside (ib) and over bark (ob) based on tree sectional measurements.

[2] Mean Top Height

TABLE 2: Stand characteristics of *Pinus radiata* at two ages for three harvest residue treatments at Tarawera Forest.

Age (y)	**Treatment**	**Stocking (stems/ha)**	**Mean DBH (±se) (cm)**	**Mean height (±se) (m)**	**MTH[2] (±se) (m)**	**Basal Area (±se) (m^2/ha)**	**Vol_ib[1] (m^3/ha)**	**Vol_ob[1] (m^3/ha)**
5	FF	2512	10.2 (0.2)	7.1 (0.1)	7.8 (0.1)	20.5 (0.9)	68.2	81.2
	WT	2381	10.3 (0.1)	7.1 (0.1)	7.9 (0.2)	19.8 (1.0)	63.0	75.8
	SO	1900	9.3 (0.2)	6.0 (0.1)	7.6 (0.3)	12.9 (0.9)	38.0	45.4
16	FF	563	29.8 (0.4)	28.3 (0.2)	29.8 (0.2)	39.2 (0.6)	388.8	457.4
	WT	525	30.8 (0.5)	28.4 (0.2)	29.5 (0.3)	38.9 (2.3)	372.0	443.5
	SO	500	32.0 (0.4)	27.8 (0.2)	28.7 (0.2)	40.1 (1.0)	429.3	504.1

[1] Tree volume (Vol) inside (ib) and over bark (ob) based on tree sectional measurements.

[2] Mean Top Height

differences due to stocking. The SO treatment had significantly lower basal area ($p = 0.0183$) and mean height ($p = 0.0282$) than the FF treatment at 5-years after allowing for growth differences between forests. As a result of two thinning operations, stocking was significantly higher at Kinleith age 15 years than at Tarawera age 16 years (575 stems/ha and 529 stems/ha, respectively; $p = 0.01$). There were no significant differences in Mean Top Height (MTH) and basal area between treatments at either Kinleith or Tarawera at mid-rotation but differences between sites was highly significant ($p < 0.001$). Volume comparisons between treatments and sites at both 5-years-old and mid-rotation reflect differences in stand basal areas as a result of the basal area ratio method of stand estimates.

4.2. Basic density and whole stem density

The mean breast height outerwood basic density of survey trees was significantly ($p < 0.0001$) higher at Tarawera (440 kg/m^3) than Kinleith (411 kg/m^3), however, treatment differences were not statistically significant at either site (Table 3).

Breast height outerwood basic density of biomass trees was higher than survey trees at Tarawera and tended to be lower in corresponding treatments at Kinleith. Standard errors of outerwood basic density were generally less in survey trees than biomass trees particularly at Kinleith confirming the value of the double sampling method. Adjusted and unadjusted whole stem densities and adjustment ratios are also shown in Table 3, to indicate the impact on the biomass based estimate of applying the survey outerwood basic density data.

Only unadjusted stem weights are given in this paper, because it is intended that the survey data provide a direct measure of the plot mean outer wood density as input to the C_Change Model.

4.3. Tree carbon concentrations

Mean unweighted carbon concentrations of the mid-rotation above-ground biomass samples from Kinleith and Tarawera varied from 51 – 55 g/100 g of dry matter in all tree components at both sites with lowest and highest values found in stem wood and stem bark,

TABLE 3: Wood density of *Pinus radiata* trees from Kinleith (age 15 years) and Tarawera (age 16 years) Forests.

Forest	**Treatment**	**Basic density at breast height of outerwood (0 – 5 rings) (kg/m^3) and (±se)**		**Whole stem density_ib (kg/m^3)**		**Ratio (R)[1] of $\bar{d}_T$ to $\bar{d}_O$**
		Survey trees $\bar{D}_O$	**Biomass trees** $\bar{d}_O$	**Unadjusted** $\bar{d}_T$	**Adjusted** $\bar{D}_R$	
Kinleith	FF	406 (10.1)	405 (18.0)	342	342	0.844
	WT	422 (3.9)	409 (7.9)	365	376	0.893
	SO	405 (9.8)	407 (21.3)	356	355	0.876
Tarawera	FF	446 (5.5)	465 (4.6)	382	366	0.822
	WT	444 (8.4)	457 (17.5)	368	357	0.805
	SO	430 (10.6)	465 (9.9)	379	350	0.814

[1] *See Equation [1].*

TABLE 4: Unweighted carbon concentrations (g/100 g oven-dry basis) of six above-ground biomass components at Kinleith (age 15 years) and Tarawera (age 16 years).

Forest	**Age (y)**	**Treatment**	**Stem wood**	**Stem bark**	**Dead branches**	**Live branches**	**Foliage**	**Cones**
Kinleith	15	FF	50.7	54.2	53.0	51.6	51.1	52.5
		WT	50.7	54.6	52.9	51.2	51.5	52.8
		SO	51.4	54.6	52.6	51.3	51.4	52.3
Tarawera	16	FF	51.3	55.0	51.4	52.5	52.9	53.1
		WT	51.5	55.3	51.6	52.5	53.0	53.3
		SO	51.6	54.9	51.7	52.5	52.8	53.0

respectively (Table 4). Mean carbon concentrations at Tarawera were slightly higher than corresponding components at Kinleith except for dead branches, which had lower values at Tarawera.

4.4. Above-ground biomass carbon

Total above-ground biomass carbon at 5-years-old ranged from 20 to 23 t/ha at Kinleith and 15 to 27 t/ha at Tarawera (Tables 5 and 6). Biomass of the SO treatment at Tarawera lagged behind the two other treatments consistent with lower height and basal area.

At mid rotation ages, total above-ground biomass carbon ranged from 71 to 85 t/ha at Kinleith and 101 to 113 t/ha at Tarawera; with greatest biomass found in the SO treatment at both sites (Tables 5 & 6). However the differences could not be tested for significance because of the method of calculation.

4.5. Live below-ground biomass carbon

Applying the root/shoot ratio of 0.2 suggested by Beets et al. (2007) would add 4.3 and 4.5 t/ha of carbon in live roots to the 5-year-old mean biomass carbon stock, and 15.9 and 21.1 t/ha of carbon in live roots to the mid-rotation mean biomass carbon stock at Kinleith and Tarawera, respectively.

4.6. Combined above- and live below-ground biomass carbon

The mean annual increment (MAI) of the combined above-and live below-ground tree carbon stock averaged 5.2 t C/ha at Kinleith and 5.4 t/ha at Tarawera by stand age 5-years and increased to 6.4 and 7.9 t/ha, respectively, by mid-rotation.

4.7. Dead wood pool

4.7.1 Volume of thinned stems from the second thinning

Treatment mean thinned stem volumes based on two transects per plot, for both Kinleith and Tarawera are shown in Table 7. Mean site volume estimates (±se) averaged across the three treatments were 109 (± 3) m^3/ha and 143 (± 7) m^3/ha for Kinleith and

TABLE 5: Carbon stock (t/ha) in above-ground biomass components of 5- and 15-year-old *Pinus radiata* stands at Kinleith Forest.

Age (y)	Treatment	Stem wood[1]	Stem bark	Dead branches	Live branches	Foliage	Cones	Total above-ground biomass
5	FF	8.01	1.32	0.82	8.27	4.94	0	23.36
	WT	7.27	1.12	0.55	6.46	4.67	0	20.07
	SO	6.87	1.27	0.54	7.36	5.27	0	21.31
15	FF	47.45	6.54	4.65	7.80	3.48	0.85	70.77
	WT	56.54	6.98	4.01	9.17	5.04	0.69	82.43
	SO	58.28	7.65	4.26	9.67	4.77	0.50	85.13

[1] *Stem wood carbon is calculated using unadjusted whole stem density, as required by the C_Change model.*

Table 6. Carbon stock (t/ha) in above-ground biomass components of 5- and 16-year-old *Pinus radiata* stands at Tarawera Forest.

Age (y)	Treatment	Stem wood[1]	Stem bark	Dead branches	Live branches	Foliage	Cones	Total above-ground biomass
5	FF	11.39	1.68	0.86	7.38	5.82	0	27.12
	WT	10.65	1.61	0.69	6.75	5.20	0	24.90
	SO	6.37	0.92	0.29	4.00	3.77	0	15.36
16	FF	76.36	9.34	4.77	7.05	4.37	0.89	102.79
	WT	70.38	10.10	4.92	9.12	4.43	1.93	100.88
	SO	83.96	9.88	5.46	7.66	5.31	0.91	113.18

[1] *Stem wood carbon is calculated using unadjusted whole stem density, as required by the C_Change model.*

Tarawera, respectively. The mean percentage bark remaining on the thinned stems, assessed at points where transects intercepted the debris, averaged 67% and 62% at Kinleith and Tarawera, respectively. There was large variance in volume (maximum 2-fold difference) between transects within plots due to the non-random orientation of thinned stems, with transects sometimes running more-or-less parallel with the thinned stems (small volume) while others were mostly perpendicular (large volume) to the thinned stems.

4.7.2. Dry matter and carbon in thinned stems

Dry matter in stem debris from the second thinning operation ranged from 27 – 29 t/ha at Kinleith and from 33 – 43 t/ha at Tarawera (Table 7). Carbon concentrations were only analysed on woody debris disc samples from the SO treatments and averaged 49.4 g/100 g of dry weight at Kinleith and 50.7 g/100 g at Tarawera. The site mean (± se) carbon stock of thinned stems was 13.9 (± 0.3) t/ha at Kinleith and 19.1 (± 1.4) t/ha for the one year older stems thinned at Tarawera.

4.7.3. Dry matter and carbon in live and dead stumps

Stumps were directly assessed in the SO treatment only. At both sites, stumps included a small number (2 – 3%) remaining from the first thinning, kept alive and evidently preserved from decay for an unknown period, by root grafting (Garrett et al., 2008; Garrett et al., 2010). Between 8 and 9% of stumps from the second thinning appeared alive when both sites were assessed during the biomass studies. The ratio of stump dry matter to thinned stem dry matter measured by transect in the SO treatment was applied to stem dry matter in the WT and FF treatments to estimate the corresponding stump dry matter and carbon stock at both sites (Table 8). Dry matter and carbon content

TABLE 7: Volume, dry matter, and carbon stock of thinned stems (dead wood) at Kinleith and Tarawera Forest.

Forest	**Debris time on ground (y)**	**Treatment**	**Volume (m^3/ha) (±se)**	**Dry weight (t/ha) (± se)**	**Carbon stock (t/ha) (± se)[1]**	**% bark remaining**
Kinleith	5.3	FF	106.6 (19.1)	27.6 (5.2)	13.6 (2.6)	68
		WT	105.9 (19.4)	27.3 (5.2)	13.5 (2.6)	67
		SO[2]	116.4 (9.5)	29.5 (2.0)	14.6 (1.0)	69
Tarawera	5.6	FF	132.3 (15.4)	33.4 (3.7)	16.9 (1.8)	53
		WT	156.3 (12.0)	42.7 (2.7)	21.7 (1.4)	62
		SO	139.3 (14.7)	36.7 (4.4)	18.6 (2.2)	71

[1] *Calculated from mean carbon concentration measured on discs from SO treatment only by Garrett et al. (2008) and Garrett et al. (2010) (49.4% C and 50.7% C for Kinleith and Tarawera, respectively).*

[2] *Only 3 replicates were measured in SO treatment at Kinleith.*

TABLE 8: Dry weight and carbon stock (t/ha) (± se) in all stumps (live and dead) at Kinleith and Tarawera Forest.

Forest	**Treatment**	**Total Stump dry weight[1]**	**Total Stump carbon stock**
Kinleith	FF	0.99	0.52
	WT	0.98	0.51
	SO	1.06 (0.03)	0.55 (0.02)
Tarawera	FF	1.64	0.85
	WT	2.09	1.09
	SO	1.80 (0.09)	0.94 (0.05)

[1] *Stumps were measured in the SO treatment and the stump/stem ratio generated was used to estimate stump dry weights in the WT and FF treatments; se only applicable to SO treatment.*

stump/stem ratios were respectively 0.036 and 0.038 at Kinleith and 0.049 and 0.050 at Tarawera. The total dry matter in remaining stumps was nevertheless minor, with carbon stocks averaging between 0.5 t/ha (Kinleith) and 1 t/ha at Tarawera (Table 8). Carbon concentrations in dead stumps at Tarawera ranged from 51 to 53 g/100 g of dry weight and in live stumps averaged 58 g/100 g (Garrett et al., 2008).

4.7.4. Dry matter and carbon in dead roots of thinned trees

Dead roots resulting from the first thinning operation would have been minor considering stem mass and time of decay. Root mass at the time of the second thinning can be estimated for the mean of SO treatments of both forests by applying a root/shoot ratio of 0.2 to above-ground biomass estimates. At Tarawera, Garrett et al (2008) estimated from DBH and height data corrected to time of thinning that the initial mass of stem plus stump debris was 75 t/ha. At Kinleith, 58.2 and 2.2 t/ha of dry matter in stems and stumps respectively was estimated by the same method. After allowing for crown weights, the amount of carbon in initial root dry matter resulting from the second thinning was estimated to be 8.5 tC/ha and 7.0 tC/ha for Tarawera and Kinleith, respectively. Root grafting of 8% of the stumps was not applied, because, the reduction in these figures would have been matched by an increase in the live root carbon pool. Using root decay constants reported by Garrett et al. (2008) (k = 0.1571/y) for Tarawera and by Garrett et al. (2010) (k = 0.1688/y) for Kinleith, carbon in decayed roots remaining at the time of the mid-rotation biomass was estimated to be 3.5 tC/ha and 2.8 tC/ha for Tarawera and Kinleith, respectively.

4.8. Litter pool

4.8.1. Dry matter and carbon in dead branch debris

The dry weight of dead branch debris on the forest floor ranged from 4.9 to 8.9 t/ha over all treatments at Kinleith and Tarawera (Table 9). Carbon concentration of dead branches was 51 g/100 g at Kinleith and 52 g/100 g at Tarawera. Dead branch carbon stocks averaged 3.3 (± 0.6) t/ha at Kinleith and 2.8 (± 0.1) t/ha at Tarawera.

4.8.2. Carbon in needle litter (L) and fermenting humus (FH) layers

Site mean (± se) forest floor carbon stocks (L(needles) + FH) amounted to 10.4 (± 0.7) t/ha at Kinleith (Jones et al., unpublished) and 11.9 (± 1.1) t/ha at Tarawera (Jones et al., 2008). The FH layer contained about 2 (Kinleith) to 4 (Tarawera) times the amount of carbon found in the L (needle) layer. Data was adjusted for slope but not for loss on ignition.

4.9. Total carbon in combined above-and live below-ground biomass and dead organic matter (dead wood and litter) pools

The mean (± se) mid-rotation total carbon stock (excluding that in the mineral soil) at Kinleith and Tarawera was estimated to be 126 (± 5.1) and 165 (± 5.5) t/ha, respectively, with combined total above-and live below-ground biomass contributing 95 (± 5.3) t/ha at Kinleith and 127 (± 4.6) t/ha at Tarawera (Table 10). Carbon in the forest floor, live and dead stumps, dead roots and woody debris (stem plus branch) remaining from thinnings amounted to 31 (± 0.9) t/ha at Kinleith and 38 (± 2.0) t/ha at Tarawera.

Mean mid-rotation annual carbon accumulation rates were 8.4 and 10.3 t/ha for all live and dead carbon pools at Kinleith and Tarawera, respectively.

4.10. Soil C/N ratio

The most up-to-date soil data is required by the C_Change model and is shown for Tarawera (2006) and Kinleith (2007) in Table 11. Mineral soil carbon and nitrogen concentrations at Kinleith were 2 – 3 times higher than Tarawera values. The mean site nitrogen fertility index, (calculated as C/(N-0.014)), as given in Beets et al. (2007), was significantly higher (p = 0.04) at Tarawera (26) than at Kinleith (23), but did not differ significantly among treatments at either site (least square means of ratios).

TABLE 9: Dry matter and carbon stock (t/ha) (± se) in dead branch debris (litter) at Kinleith and Tarawera Forest.

Forest	Treatment	Dead branch dry weight	Dead branch carbon stock
Kinleith	FF	8.87 (1.77)	4.46 (0.88)
	WT	6.62 (0.93)	3.31 (0.47)
	SO	5.02 (0.97)	2.26 (0.40)
Tarawera	FF	5.30 (0.36)	2.76 (0.19)
	WT	4.91 (1.24)	2.54 (0.65)
	SO	5.65 (0.68)	2.92 (0.35)

TABLE 10: Distribution of carbon stocks by IPCC pool (t/ha) in mid second-rotation *Pinus radiata* at Kinleith (15-years-old) and Tarawera forest (16-years-old).

Forest	Treatment	IPCC Carbon pool				Total carbon stock excluding soil [5] (t/ha)
		Above-ground biomass[1]	Below-ground biomass[2]	Dead wood[3]	Litter[4]	
Kinleith	FF	70.8	14.2	17.0	14.9	116.8
	WT	82.4	16.5	16.8	12.4	128.1
	SO	85.1	17.0	17.9	13.9	134.0
Tarawera	FF	102.8	20.6	21.3	12.9	157.5
	WT	100.9	20.2	26.3	14.3	161.7
	SO	113.2	22.6	23.1	16.7	175.6

[1] *Live: stem wood, stem bark, branches, needles, and cones. Dead: attached branches. Modified IPCC category includes dead attached branches as defined in methods.*

[2] *Live roots estimated from R/S ratio. Estimate was included to indicate the relative sizes of the other carbon pools. See Section 2.3.7.*

[3] *Dead thinned stems, live and dead stumps and dead roots.*

[4] *Forest floor (LFH), including dead branches. Data from Jones et al. (2008) (Tarawera) and Jones et al. (unpublished data) (Kinleith).*

[5] *Total carbon not always equal to sum of columns due to decimal rounding.*

TABLE 11: Mineral soil carbon and nitrogen concentrations (oven-dry basis) and C/N ratios of 0 – 5 cm depth at Kinleith (2007) and Tarawera (2006).

Forest	Treatment	Carbon (g/100 g)	Nitrogen (g/100 g)	C/N ratio	C/N ratio (adjusted)[1]
Kinleith	FF	6.5	0.30	21.7	22.8
	WT	7.9	0.35	22.5	23.4
	SO	8.0	0.39	20.8	21.6
Tarawera	FF	2.2	0.10	22.1	25.7
	WT	2.9	0.13	22.7	25.5
	SO	4.1	0.19	22.2	24.1

[1] *C/N ratio (adj.) = C/(N-0.014).*

5. Discussion

5.1. Stand growth

By stand age 5-years, trees at the Tarawera site had outgrown those at Kinleith by about 1.5 m in height and 1 cm in diameter, reflecting the difference in site index of 34 m at Tarawera verses 31 m at Kinleith (Smith et al., 2000). This is presumably because of the warmer climate at the substantially lower elevation of the Tarawera site and higher rainfall, although Kinleith is inherently a more fertile site (Smith et al., 2000). By mid-rotation, the trees at Tarawera showed greater growth in all parameters even after allowing for the age difference. Highest growth rates, particularly in terms of stem volume and basal area increment, were recorded in the SO treatment at both sites, presumably because of a beneficial effect from more harvest residues being retained on site, although treatment differences were not statistically significant. (The SO treatment simulates the majority of harvesting operations).

Mid-rotation tree height at both sites was 50 – 80% more than a 16-year-old Australian *Pinus radiata* stand at higher altitude (720 m) near Canberra (Guo et al., 2008) and mean DBH in the two New Zealand stands

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studied here was about 5 – 20% greater than the Australian site. Growth differences probably reflect low rainfall (623 mm) at the Australian site more so than temperature difference.

5.2 Basic density and whole stem density

The adjustment ratios of whole stem density at Tarawera (Table 3) were about 11% lower than expected values based on the mean ratio of 0.91 found for stem growth increments of 15 – 20-year-old stands on high density sites throughout New Zealand (Beets et al., 2007). This suggests that at Tarawera wood density declined more with height up the stem than expected. Derived ratios of whole stem density/ breast height outerwood density decreased with increasing site mean outerwood density and ranged from 0.88 to 0.95 for the validation dataset in Beets et al. (2007) which included the Tarawera trial site. However, the results presented here confirm the high density status of the Tarawera site associated with a relatively warm mean annual temperature and high C/N ratio (Beets et al., 2007). At Tarawera, breast height mean outerwood density was consistently lower in survey trees compared to biomass trees in contrast to the Kinleith data. The reasons for this are attributed to the small sample size of two biomass trees per plot and the effect of stocking on density of the outer rings. With survey data to adjust treatment whole stem wood density estimates, the accuracy of the stand weight estimate was improved, overcoming the tree-to-tree density variation found by only sampling 8 biomass trees in each treatment.

5.3. Above-ground biomass carbon concentrations

Live above-ground biomass component carbon concentration (excluding dead branches) is often assumed to be 50% of dry weight, and is the IPCC default value although 51% has been recommended for *Pinus radiata* in Spain (Balboa-Murias et al., 2006). The overall weighted average above-ground biomass carbon concentration (including dead branches) was 51.4 and 52.0 g/100 g of dry matter at Kinleith and Tarawera, respectively in this study. These results suggest that above-ground carbon stocks in post-1989 New Zealand *Pinus radiata* plantation forests could be up to 4% higher than carbon stocks calculated with the IPCC default values, especially in younger stands which have a higher proportion of weight in crown components.

5.4 Above- and below-ground biomass carbon stocks

Pinus radiata stands accumulated 79 t/ha of above-ground biomass carbon (including dead branches) on 570 stems/ha over 15 years at Kinleith, which was similar to the above-ground standing biomass (including dead branches) for a 16-year-old Canberra (Australia) stand with 800 stems/ha (Guo et al., 2008). The mean rate of carbon accumulation of 6.6 t/ha/year in above-ground tree components at Tarawera exceeded the rate of carbon accumulation (5.9 t/ha/year) in a 30-year-old *Pinus radiata* stand in north-western Spain (Balboa-Murias et al., 2006). The Spanish stand was grown on fairly acid soils with the best site quality in climatic conditions not unlike the central North Island plateau of New Zealand.

Above-ground carbon accumulation in Tarawera trees was less than net annual above-ground carbon increment over 22 years (7.2 t/ha, assuming carbon was 50% of the dry weight) in an age series of *Pinus radiata* stands in Kaingaroa Forest (Madgwick et al., 1977). Gross annual above-ground carbon increment in the Kaingaroa stands between 10- and 22-years-old (12.3 t/ha) exceeded our estimated mid-rotation MAI of combined above-and live below-ground plus dead organic matter carbon pools (which included the forest floor) at Kinleith (8.4 t/ha.) and Tarawera (10.3 t/ha). This anomaly may be due to the large sample error at Kaingaroa where a chronosequence (space for time substitution) approach was used, compared with our more accurate age series (plots remeasured) approach. The above-ground carbon accumulation rates of our unfertilised *Pinus radiata* stands growing in the central North Island of New Zealand achieved about half the MAI of 13.5 t C/ha (assuming carbon was 50% of dry matter) exhibited by 17-year-old *Eucalyptus regnans* in this area (Frederick et al., 1985). This suggests that although carbon sequestration in New Zealand's exotic forests is dominated by industrial *Pinus radiata* plantations, there are alternative faster growing species such as eucalypts to consider, if forests are grown specifically for carbon storage.

5.5. Dead wood volume and mass in thinned stems

From comparison of stem diameter measurements including and excluding bark, a 100% bark loss was estimated to reduce the measured volume over bark of the second thinnings by 11% at Kinleith and by 13% at Tarawera. Given that about 70% of the stem bark was still present at the biomass assessment date, it is reasonable to expect that the volume of the thinned stems should closely match the original volume of the stems when they were felled, had they been randomly orientated. To test this, an independent estimate of dry matter in thinned stem debris was, therefore, made as follows: Garrett et al. (2008), estimated that 72 t/ha of dry matter was felled in stems of the SO treatment at the second thinning at Tarawera. We applied the stem decay constant (k) of 0.1260/y from Garrett et al. (2008) and estimated 35 t/ha of residual dry matter would remain in those stems after 5.6 years of decay. This is very close to the mean value obtained by converting thinned stem volume from the line intersect method to dry matter for the SO treatment at Tarawera (Table 7) giving confidence in the transect method for measuring dead wood volume at Tarawera. The same calculations for Kinleith thinned stem dry matter (58.2 t/ha) after 5.4 years of decay using the stem decay constant 0.0949/y (Garrett et al. 2010), estimated that 34.9 t/ha of stem dry matter would remain. This is 24% higher than the mean stem mass measured by transect (Table 7) which is attributed to the large variance between transect volumes at Kinleith and the different methods used to collect transect sample discs for density verses stem discs collected for density and carbon analyses in the separate decay study by Garrett et al. (2010).

5.5.1. Dry matter and carbon in thinned stems and dead branches

Guo et al. (2006) measured 6.06 t/ha of dry matter in stem-plus-branch woody-debris down to less than 5 mm diameter (3.1 t/ha carbon) with the line intersect method in a 16-year-old stand at the dry, high altitude (720 m a.s.l) Canberra site in Australia, which had been pruned and thinned down to 800 stems/ha at 8-years-old. They did not specify the proportion of the stem total volume that had been felled. There was six times less carbon in thinned stems and branch debris at the Australian site than was measured at either the Kinleith or Tarawera sites, showing the potential for woody debris to accumulate in our intensively managed *Pinus radiata* plantations.

5.5.2. Dry matter and carbon in stumps

A small proportion of stumps from the second thinning at both sites were still alive with very high carbon concentration due to root grafting and resin accumulation after cutting (Garrett et al., 2008). However, the carbon stock of stumps from thinning operations was found to be relatively unimportant compared to carbon in stem woody-debris. Remnants of the large stumps from the first rotation were not included in the mid-rotation assessment at Tarawera because the wood was in an advanced stage of collapse, (except for a few stumps with resin impregnated heartwood), with an outer shell of bark. The situation at Kinleith was different to Tarawera in that many stumps from both the first and second thinnings (and some thinned stem debris) had been partially or completely fragmented by feral pigs (*Sus scrofa*) searching for food, presumably, larvae of the Huhu beetle (*Prionoplus reticularis* White). In the SO treatment, the proportion of dry matter remaining as intact stumps to that remaining in thinned stems was 3.6% at Kinleith compared to 4.9% at Tarawera. Some carbon in fragmented stumps would have been measured as litter and/or fermenting humus, compensating for possible losses, although respiration losses of carbon from an increased decay rate may also have occurred at Kinleith as fragmentation increased.

5.6. Carbon in the litter pool

Fine litter (mainly dead needles) under a 16-year-old *Pinus radiata* stand with 800 stems/ha in Australia (Guo et al., 2008) contained 4.8 t/ha of carbon which is less than half of the carbon mass found in the same material at our sites. A higher needle decay rate at their site seems unlikely given the low rainfall and reported fine litter residence time (95% mass loss), which was estimated to be 7.5 years (Guo et al., 2008). Both of the New Zealand stands studied here carried a similar mass of foliage carbon (4 – 5 t/ha) to the Australian stand which suggests less litterfall occurs in the Australian stand than occurs at our sites. Carbon in the forest floor (L + FH) layer at both our sites was only half that found by Ballard and Will (1981) in a 16-year-old naturally regenerated second rotation *Pinus radiata* stand in Kaingaroa Forest, New Zealand assuming carbon was 40% of their total litter layer. This difference is presumably due to the high stocking (950 stems/ha) of the Kaingaroa stand (carrying a high foliar mass) and maybe a greater amount of residues left from the first rotation giving a mean total litter depth of 7.5 cm, almost twice that measured for the forest floor (3.8 cm) at Tarawera by Jones et al. (2008). Differences in needle litterfall and decay rate between New Zealand *Pinus radiata* stands may also be associated with different levels of the foliar disease *Dothistroma pini* Hulbary and its subsequent control with aerial applications of copper-based sprays (Ballard & Will, 1981).

5.7. Overall distribution of carbon at Kinleith and Tarawera

At mid-rotation, approximately 64% of total carbon stock (excluding mineral soil) at Kinleith and Tarawera accumulated in the above-ground biomass with the stemwood plus bark contributing about 80% of the above-ground carbon. The fraction of carbon in above-ground trees in a 16-year-old Australian stand (Guo et al., 2008) was higher at 76% due to less carbon in coarse and fine debris on the forest floor compared with the New Zealand stands. After five years of decay, thinned stem-plus-branch woody-debris from the second thinnings still amounted to 14% of total carbon, slightly more than the proportion in live roots which was estimated to be 13% of the total carbon. The remaining 9% of carbon was mainly in the forest floor L and FH layers with the smallest component measured in stump debris (<1%) remaining from the second thinning. Carbon in dead roots from thinned trees at Tarawera and Kinleith was estimated to be, respectively, three and five times the mass of carbon remaining in live and dead stumps. The mean total above- and below-ground biomass carbon at Tarawera (165 t/ha) far outweighed total biomass carbon in a 16-year-old Australian stand (103 t/ha) (Guo et al., 2008). Also, total biomass carbon at Kinleith (126 t/ha) was almost three times the equivalent stock (45 t/ha) in a 15-year-old white pine (*Pinus strobus* L.) plantation in Ontario, Canada (Peichl & Arain, 2006) which reinforces the high rate of carbon accumulation of *Pinus radiata* plantations in New Zealand's temperate climate.

6. Conclusions

Biomass and carbon content of post-1989 *Pinus radiata* plantation stands in Kinleith and Tarawera Forest were measured at 5-years-old and at mid-rotation (15- and 16-years-old, respectively). In addition, stand parameters including mean top height, basal area, stocking, and nitrogen fertility were measured and tending history documented. Significant differences in surface mineral soil C/N ratio, breast height outerwood basic density and stocking were found between sites at mid-rotation. There were no significant differences in outerwood basic density, basal area and mean top height between the harvesting residue retention treatments at either site. Although Tarawera was a less fertile site, growth rates exceeded those at Kinleith because of a more benign climate and higher rainfall.

Total carbon stocks above- and below-ground, including live and dead vegetation but excluding soil, were 126 t/ha and 165 t/ha at Kinleith and Tarawera, respectively, with the largest proportion, approximately 64%, found in above-ground biomass. Mean annual accumulation rate of carbon in above-ground biomass at Tarawera and Kinleith exceeded that reported in for *Pinus radiata* in either Australia or Spain, and was similar to a *Pinus radiata* age series in Kaingaroa Forest.

Mean weighted carbon concentration of all mid-rotation above-ground live tree components plus attached dead branches was 51.4 and 52.0 g/100 g of dry matter at Kinleith and Tarawera, respectively, suggesting that post-1989 *Pinus radiata* plantation carbon stocks in New Zealand may be underestimated using the IPCC default value of carbon concentration as 50% of dry matter.

The data provided in this study may be used to test and further improve the C-Change model of Beets et al. (1999).

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