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Planted Forest Carbon Monitoring System – forest carbon model validation study for *Pinus radiata*.

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Abstract

A plot based inventory system in conjunction with models is being used to facilitate predictions of carbon stocks and changes in New Zealand's planted forests. The models include the 300 Index Growth Model for *Pinus radiata* D.Don to predict stem gross and net volume under bark over a rotation using plot data, linked with a wood density model to convert stem volume to carbon, and C_Change to calculate carbon stocks annually in four pools - above-ground biomass, below-ground biomass, dead wood and litter. This linked suite of models is called the Forest Carbon Predictor version 3.

This model validation paper aims to empirically determine the accuracy and precision of carbon stock and change estimates and predictions from the Forest Carbon Predictor, using independent above-ground biomass measurements acquired at permanent plots located in 39 stands throughout New Zealand and dead organic matter measurements from 14 stands. Model error was assessed using plot inventory data acquired in the same year that biomass measurements were made (model estimation error), and using plot measurements made nominally 5 years before or 5 years after the biomass measurement (model prediction error).

Model bias and 95% confidence interval of the bias averaged -1.2% ± 2.6 m^3 ha^{-1} for stem volume, -0.8% ± 1.9 kg m^{-3} for wood density, 3.7% ± 7.9 t ha^{-1} for total carbon (excluding mineral soil carbon), -0.9% ± 5.6 t ha^{-1} for above-ground biomass carbon, and 4.7% ± 12.6 t ha^{-1} for dead organic matter. The model prediction error was similar to the model estimation error over growth projection intervals of ± 5 years. Total carbon stock estimates at the inventory date and stock change projections over a 5 year interval are expected to average within 5% of actual values.

Keywords: carbon stocks; forest carbon sink; inventory; Kyoto Protocol; model testing; national system; *Pinus radiata*.

Introduction

New Zealand's planted forest net stocked area is estimated to cover approximately 1.74 million hectares as at 1st April 2009 (Ministry of Agriculture & Forestry (MAF), 2010). *Pinus radiata* D.Don is the dominant species by area (90%), followed by *Pseudotsuga menziesii* (Mirb.) Franco (6%). The remainder of area includes eucalyptus, cypress, and other minor softwood and hardwood species. Approximately 37 percent of the area was established through afforestation/reforestation activities since 31st December 1989 (MAF, 2010). Under the terms of the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC), New Zealand has agreed to take responsibility for its greenhouse gas

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emissions in the 2008-2012 Commitment Period. The Kyoto Protocol allows for the creation of carbon sinks through afforestation/reforestation post-1989 of non-forested lands, which represents a key category for New Zealand.

Carbon stocks in New Zealand's planted forests have historically been estimated for UNFCCC report purposes from yield tables (stem total volume by age) and stand age- and geographical region-specific wood density using a carbon model developed for *Pinus radiata*, C_Change (Beets et al., 1999). Yield tables and forest area by age class data were acquired by species through voluntary surveys of forest owners and managers, as part of the National Exotic Forest Description (NEFD) (MAF, 2010). The accuracy of the results of these surveys is weakest for the non-professionally managed woodlots that comprise the bulk of the post-1989 forest area, and the survey would, therefore, not meet the Good Practice Guidance for reporting under Article 3.3 of the Kyoto Protocol. The NEFD yield table approach has recently been replaced by New Zealand's Land Use and Carbon Analysis System (LUCAS) (Ministry for the Environment, 2009).

The Land Use and Carbon Analysis System is based on a national inventory of post-1989 and pre-1990 forests, utilising permanent and invisible sample plots, largely following inventory methods used in Europe, Scandinavia, and North America (Beets et al., 2010). The plot assessment procedures provide nationally representative data on stand growth, silvicultural management activities, tree health, and site fertility which, when coupled with the Forest Carbon Predictor, provide estimates of stem volume and carbon in live and dead organic matter pools. Forest inventories with repeated plot measurements, including modelling systems, provide increased certainty around carbon stock and change estimates, and are considered good practice (Intergovernmental Panel on Climate Change (IPCC), 2003).

The modelling concept used in New Zealand has remained largely unchanged since it was described some time ago (Beets et al., 1999), although research has identified and addressed various data gaps and model limitations. Improved component models have been developed to calculate volume yield tables, wood density, and carbon in live and dead organic matter pools on a per hectare basis in a modelling system referred to as the Forest Carbon Predictor (FCP) v3. In particular, the 300 Index national growth model uses inventory plots directly (Kimberley et al., 2005), and a national volume function (Kimberley & Beets, 2007), to calculate yield tables, replacing various regional growth models and volume functions used previously (Whiteside, 1990; West, 1993). A new wood density model that incorporates soil fertility, temperature, and stem diameter growth rate was developed to improve the accuracy of wood density predictions for fertile Kyoto compliant forest (Beets, Kimberley, & McKinley, 2007; Kimberley & Beets, 2010). Information on root/shoot ratios has been improved following the acquisition of new root biomass data (Beets, Pearce, et al., 2007). Finally, recently completed research programmes have provided data for modelling dead wood and litter decay rates in *P. radiata* plantations in relation to site factors, and data on the carbon content of live *P. radiata* biomass components, dead wood (decayed stems and roots) and litter material (Garrett et al., 2008; Garrett et al., 2010; Jones et al., 2011; Oliver et al., 2011). The Forest Carbon Predictor provides an integrated, consistent carbon estimation and projection system for planted forests in New Zealand.

A comparison of methods for estimating forest carbon sinks for national reporting purposes found a lack in transparency, consistency, and completeness between EU Members States (Lowe et al., 2000). For example, expansion factors differed depending on whether the forest inventory provided estimates of merchantable or total stem volume, and also depended on which live and dead organic matter components of the trees and understory vegetation were included. Assuming such issues are being addressed, there is still a need to test the accuracy and precision of the carbon stock and change estimates derived from models that are linked to national inventory systems. Reliable and affordable protocols for testing the validity of forest carbon monitoring systems are required.

The objective of this paper is to document the accuracy and precision of the stem volume, wood density, and carbon estimates per hectare obtained using a modelling system referred to as the Forest Carbon Predictor v3.

Materials and Methods

Model description

The Forest Carbon Predictor is a stand level modelling system developed for *P. radiata* that delivers plot summary data, silvicultural activity data, and site information to the 300 Index growth model and a wood density model, which together provide the data required by C_Change to calculate carbon stocks per ha on an annual basis over a rotation from a single plot measurement (Figure 1).

The 300 Index Growth Model (Kimberley et al., 2005) generates a volume productivity index from plot summary statistics. These include stand age, mean top height, basal area, stocking, and the stand silvicultural history, which were calculated for each plot following standard protocols developed for New Zealand's Permanent Sample Plot system (Dunlop, 1995). The productivity index is specific to each plot

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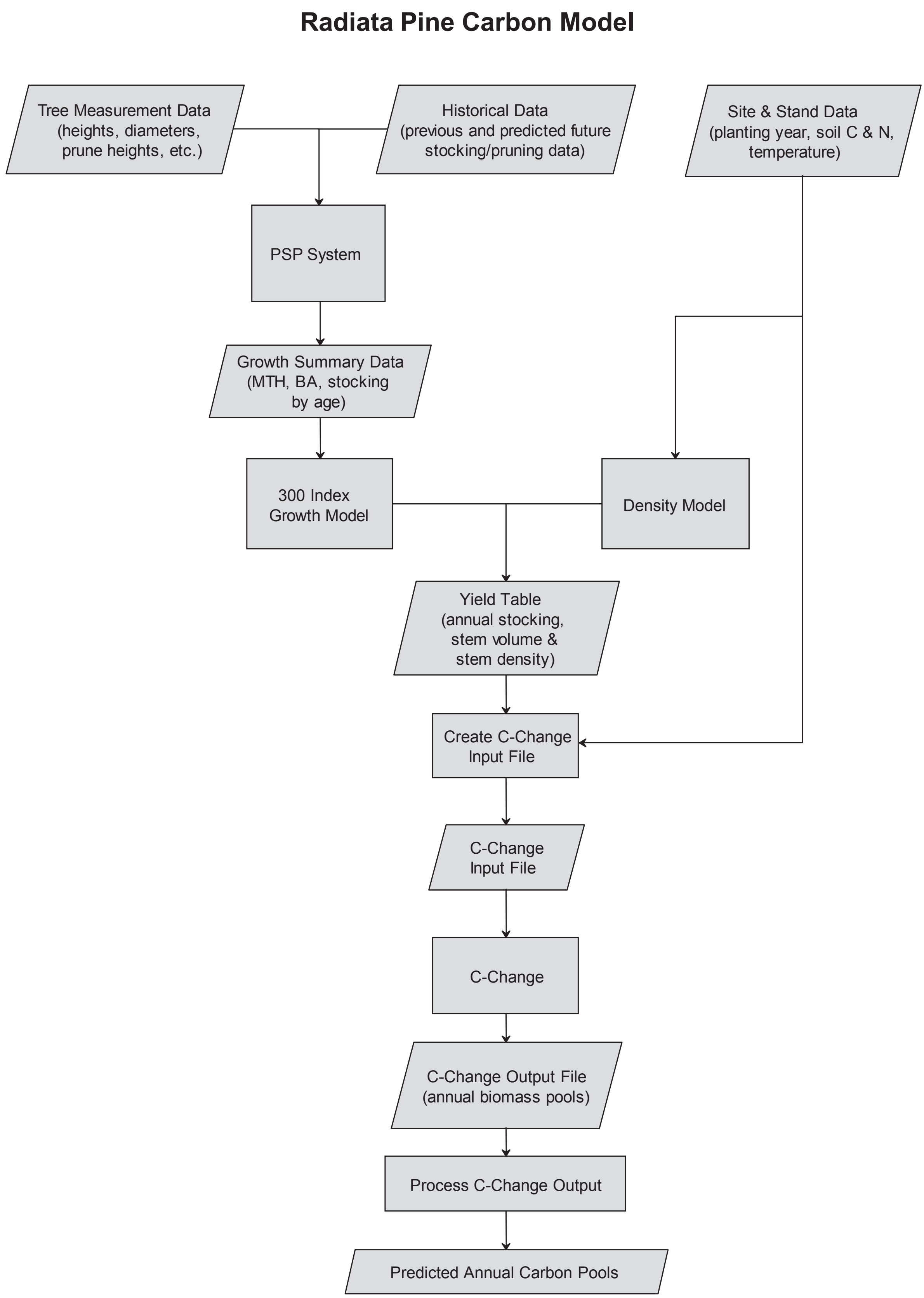

FIGURE 1: Flowchart outlining the Forest Carbon Predictor version 3, which delivers stand growth data, including basal area (BA), mean top height (MTH), stocking (trees ha^{-1}), and silvicultural information extracted from a permanent sample plot system (PSP) and site data acquired at plots to a volume model (300 Index Growth model), a wood density model (Density model), and a carbon partitioning model (C_Change), to predict carbon stocks by GPG pool in *Pinus radiata* stands.

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and measurement date, and ensures that the annual predictions from the 300 Index model pass through the measured basal area and mean top height at the plot measurement date. Stem volume per hectare is estimated from the plot basal area and mean top height using a nationally applicable volume function that applies from soon after planting to harvesting age (Kimberley & Beets, 2007). The annual predictions of gross and net stem volume under bark from the 300 Index model are combined with the wood density of annual growth sheaths (Beets, Kimberley, & McKinley, 2007; Kimberley & Beets, 2010), and the silvicultural regime, to provide annual predictions of carbon stocks in live biomass components (needles, live and attached dead branches, stem wood, stem bark, coarse roots, fine roots, cones), and dead organic matter (needle litter and stem, branch, and root debris) using C_Change (Beets et al., 1999). Density estimates from the wood density model were reduced by 2.6%, to reflect the results of a validation study undertaken previously of breast height outerwood (0-5 cm depth) density (Beets, Kimberley, & McKinley, 2007).

The C_Change model uses growth partitioning functions to allocate carbon to live biomass components, an "accounting" approach to estimate carbon flows to dead organic matter pools, and component specific decay functions to estimate losses of carbon to the atmosphere. Instantaneous decreases in live biomass pools match increases in dead pools following for example natural mortality due to disease effects on needle retention, competition effects on branch mortality, and management activities such as crown pruning, thinning, and harvesting (Beets et al., 1999). The Forest Carbon Predictor amalgamates detailed outputs from C_Change into above-ground biomass, below-ground biomass, dead wood, and litter (four of the five Good Practice Guidance (GPG) pools (IPCC, 2003)). Biomass extracted off-site following harvest operations is based on merchantability parameters (70% of total stem volume following production thinning and 85% of total stem volume following clearfelling), and is treated as an instant emission, following Kyoto Protocol rules.

Trial sites

Biomass measurements suitable for calculating above-ground biomass were acquired in stands located throughout the North Island and in the northern part of the South Island of New Zealand (Table 1), and covered a range of stand ages and silvicultural regimes. Stands at Kinleith, Tarawera, and Puruki included repeated biomass measurements suitable for calculating the periodic mean annual increment in volume and above-ground biomass carbon. Mean annual air temperature and nitrogen fertility at each site were required model inputs, to predict basic density of annual growth sheaths from breast height outer wood density (Beets, Kimberley, & McKinley, 2007). Temperature was predicted for each site from climate surfaces from the National Institute of Water and Atmospheric Research (NIWA), and nitrogen fertility was determined from the carbon/nitrogen (C/N) ratio in soil samples collected from each site.

Measured volume and carbon in above-ground biomass and dead organic matter

The growth plots associated with the biomass studies were typically 0.04 ha in area. The DBH of all trees in the plot, and the total height and pruned height of a sample of from 10 – 15 or more trees spanning the range of DBH were measured in the year the biomass study was undertaken. Stand biomass carbon was determined by measuring and weighing a random sample of trees from the stand at a given stand age and applying stand-specific basal area ratios from sample trees to the plot basal area. Using stand-specific basal area ratios ensures that biomass estimates per plot were statistically independent of each other, and were unbiased (Madgwick, 1981). Stand-specific basal area ratios were unbiased because they directly incorporate the effects of silvicultural activities such as pruning and thinning operations on crown/stem relationships, which is not achievable using general allometric equations for *P. radiata* (Moore, 2010).

Biomass measurement procedures varied widely among studies. These included, in decreasing order of precision, estimates based on: (1) full crown weighing of individual trees; (2) weighing of representative sample branches and scaling to a tree basis using a complete enumeration of branch diameters made on the sample trees; and (3) weighing a random selection of sample branches and scaling to a unit area basis using branch counts obtained from a number of randomly selected trees from within the stand. The number of trees available for developing statistically independent stand biomass estimates also varied among biomass studies. In general, the sample size was small in studies involving full crown weighing, and large in studies involving the branch count method. At some sites stem volume under bark had been measured and disk samples cut at regular intervals along the stem of biomass trees and oven-dried, which provided data to calculate whole stem density.

The biomass studies compiled for this validation study included data from 39 stands in six forests with the requisite biomass and site data to run the Forest Carbon Predictor (Appendix A). Biomass measurements for replicate plots within a stand were averaged by treatment, to minimise pseudo-replication. Appendix A also gives the sample size (n) per stand, and the number of biomass trees sampled for either crown or stem parameters. The total number of biomass trees can be determined by multiplying the number of stands by the number of sample trees per stand. Dead organic matter pools were assessed in six

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TABLE 1: Location of biomass study sites and land use history, site mean air temperature (MAT) and soil fertility, based on soil samples obtained from within each stand. Low carbon/nitrogen ratios reflect high nitrogen fertility.

Site ID	Land-use History	Latitude	Longitude	MAT[1]	C/N ratio[2]
Golden Downs	Forest	41°36´S	172° 53´E	10.1	25.4
Kinleith	Forest	38° 14´S	175° 58´E	11.3	19.1
Puruki	Pasture	38° 26´S	176° 13´E	10.6	16.6
Shenstone	Forest	34° 33´S	172° 52´E	16.0	36.2
Tarawera	Forest	38° 13´S	176° 00´E	13.5	23.2
Tikitere	Pasture	38° 03´S	176° 21´E	12.3	13.8
Wanganui	Pasture	39° 40´S	175° 02´E	11.8	15.1
Huntly	Pasture	37° 37´S	175° 01´E	13.9	12.8
Taumaranui	Pasture	38° 41´S	175° 11´E	12.0	10.7
Bennydale	Pasture	38° 37´S	175° 27´E	11.5	11.5
Taihape	Pasture	39° 43´S	175° 58´E	10.4	11.5
Rotorua	Pasture	37° 58´S	176° 40´E	12.3	12.2
Gisborne	Pasture	38° 20´S	178° 04´E	12.3	11.3
East Cape	Pasture	38° 02´S	178° 19´E	13.6	15.3
Overall mean				***12.3***	***16.8***

[1]Mean annual air temperature (MAT) obtained from climate surfaces (Wratt et al., 2006).
[2]Surface (0 – 5 cm) mineral soil carbon/nitrogen (C/N) ratio.

second-rotation stands at Tarawera and Kinleith that had undergone different experimental treatments (including forest floor manipulation between rotations (Oliver et al., 2011)). Dead organic matter on site arose primarily from thinning operations undertaken 5 years prior to the biomass studies. The largely fragmented residues from pruning and thinning operations undertaken 10 years prior to the biomass studies were measured as part of the humus pool. Residual stumps and roots from harvested trees from the previous rotation were evident but not measured, however dead wood and litter from the previous rotation, if present, were indistinguishable from material arising from the current rotation, so would have been included (Oliver et al., 2011). Dead wood and litter pools were also measured at 8 post-1989 LUCAS plots with the requisite site and silvicultural history data to run the Forest Carbon Predictor. Methods used largely following procedures reported in Oliver et al. (2011).

Model validation approach

The accuracy of predictions made using empirical models such as the Forest Carbon Predictor depends on the precision of the estimated model parameters, as well as on the validity of underlying model assumptions. Model parameters were estimated from experimental data and generally their standard errors and the correlations between them were known. It is, therefore, possible to determine model prediction accuracy by propagating the errors of the model parameters. However, this becomes less feasible when the predictions are made using a linked series of fairly complex models. Therefore, to establish the accuracy of the Forest Carbon Predictor, an alternative approach of validating the model predictions directly using independent data was adopted. The disadvantage of this approach is that it requires a significant quantity of independent data. Its advantage is that it is simple to apply, and provides a comprehensive test of the model, including both the effects of parameter errors and of underlying modelling assumptions.

Following Beets et al. (1999), plot summaries of basal area, mean top height and stocking were extracted from the New Zealand Forest Research Institute Ltd Permanent Sample Plot (PSP) system. For modelling purposes, plot summaries were calculated using plot measurements made at the same time biomass studies were undertaken, which we denoted as “Ref” for reference year. We refer to the modelled data as “estimates”, because plot basal area, mean top height, and stocking were directly measured. In addition, plot summaries were calculated using plot measurements made nominally five years before (Bf) or five years after (Af) the biomass studies were undertaken. We refer to

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the modelled data as "predictions", because the plot basal area, mean top height, and stocking were based on projections to the date of the biomass study. If plots were not measured exactly five years before or after the biomass study, then the closest measurement was used, provided that it was no less than three years from the nominated date. Hence, recently completed biomass studies do not include "Af" model predictions.

It is intended that New Zealand's post-1989 planted forest plots will be measured at both the beginning and end of the first commitment period of the Kyoto Protocol, although some plots will be measured only once, at the end of the period. The accuracy of estimates is relevant when stock changes per plot are calculated from measurements acquired in 2008 and 2012. The accuracy of predictions is relevant when stock changes per plot are calculated from a measurement in 2012 and the prediction in 2008.

The following steps were followed to create a carbon yield table for each plot and measurement date of interest:

Step 1 The plot basal area, mean top height and stocking at a given measurement date and the associated stand tending history data were input to the 300 Index model, which predicts annual gross and net stem volume inside bark tables over a rotation.

Step 2 The surface mineral soil carbon (C) and nitrogen (N) concentration (g per 100 g mineral soil), temperature, and basal area growth rate from the 300 Index model were input to the density model, which predicts the density of annual stem wood growth sheaths by ring age (Beets, Kimberley, & McKinley, 2007; Kimberley & Beets, 2010).

Step 3 The gross and net stem volume yield tables, stand silvicultural history, wood density of annual growth sheaths, and needle retention score (a default value of 2.1 was used when forest health was not assessed) were input to C_Change. In second rotation stands with dead organic matter pool measurements (Tarawera and Kinleith), the Forest Carbon Predictor was run over two successive rotations, to ensure that dead wood and litter that persisted following harvesting of the first rotation to the time of the biomass study in the second rotation was modelled.

Step 4 The volume and carbon yield tables were identified by plot and measurement date (i.e. Ref, Bf, Af).

Comparison of modelled with measured carbon stocks

The above-ground biomass and dead organic matter stock estimates (Ref) and predictions (Bf, Af) from the Forest Carbon Predictor were compared with data from biomass studies. Above-ground biomass carbon is comprised of needles, live branches, dead branches, stem wood, stem bark, and reproductive parts. Dead wood is comprised of dead stems and coarse roots arising from thinning operations and natural mortality. Litter is comprised of the Litter/Fermenting/Humus (LFH) layer from pruning and thinning operations and natural litter fall. To aid in model testing, the modelled stem total volume under bark and whole stem wood density were also compared with measurements from biomass studies.

Assessing model accuracy and precision

The accuracy of the model predictions was assessed by plotting the modelled plot means against measurements from biomass studies. A zero-intercept regression model, measured = a × modelled, was fitted using the SAS Version 9.2 REG. The slope parameter a provided an estimate of the model bias which was expressed as a percentage, i.e. bias = 100 × (1 - a). Using the standard error of a, a t-test was constructed to test whether the model was significantly biased (i.e. whether the slope differed significantly from one), and to obtain a 95% confidence interval of the bias. Estimates of model bias were made for the model estimates made at the biomass measurement date and for predictions obtained from tree measurements made five years prior to and five years following the biomass measurement.

Results and Discussion

Measured volume, above-ground biomass and dead organic matter stocks

Stem total volume inside bark, whole stemwood density, above-ground biomass carbon, dead wood and litter carbon data for testing the Forest Carbon Predictor are summarised by site in Table 2. Not all variables were measured at each site, which explains why there are gaps in the table. Stands ranged in age between 5 – 23 years old, stem volume ranged between 45 – 429 m^3 ha^{-1}, whole stemwood density ranged between 324 – 380 kg m^{-3}, and above-ground biomass ranged between 10 – 114 t C ha^{-1} (Table 2). In stands with dead organic matter measurements dead wood averaged 15.7 t C ha^{-1} and litter averaged 13.2 t C ha^{-1} (Table 2).

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TABLE 2: Stem volume, above-ground biomass carbon, dead wood, and litter from biomass studies in *Pinus radiata* stands across a range of sites and stand ages. N is number of stands assessed per site, with a total of 39 stands with above-ground biomass data, 14 stands with dead organic matter data, and 28 stands with whole stem wood density data.

Forest site	N	Age (yrs)	Stem Total Volume inside bark (m^3 ha^{-1})	Total Carbon (excluding soil) (t ha^{-1})	Above-ground biomass Carbon (t ha^{-1})	Dead wood (t ha^{-1})	Litter (t ha^{-1})	Whole Stem Wood Density (kg m^{-3})
Golden Downs	6	5	52.9	-	20.7	-	-	324
Kinleith	3	5	45.1	-	19.5	-	-	-
Kinleith	3	15	299.1	125.8	79.4	16.7	13.8	358
Puruki (first rotation)	1	16	220.5	-	58.7	-	-	340
Puruki (first rotation)	3	17	429.3	-	113.9	-	-	354
Puruki (first rotation)	1	22	237.8	-	72.3	-	-	363
Puruki (first rotation)	1	23	253.4	-	84.6	-	-	380
Puruki (second rotation)	10	9	155.3	-	39.1	-	-	325
Shenstone	2	11	-	-	56.2	-	-	-
Tarawera	3	5	56.4	-	22.5	-	-	-
Tarawera	3	16	396.7	164.7	105.6	23.3	14.6	361
Tikitere	3	6	-	-	9.6	-	-	-
Post-1989 LUCAS sites	8	10 – 17				7.2	11.2	
Overall	**47**	**5 – 23**	**196.9**	**142.3**	**50.4**	**15.7**	**13.2**	**341**

Accuracy of model estimates

Estimates from the Forest Carbon Predictor are shown in relation to measured values in Figures 2 – 6.

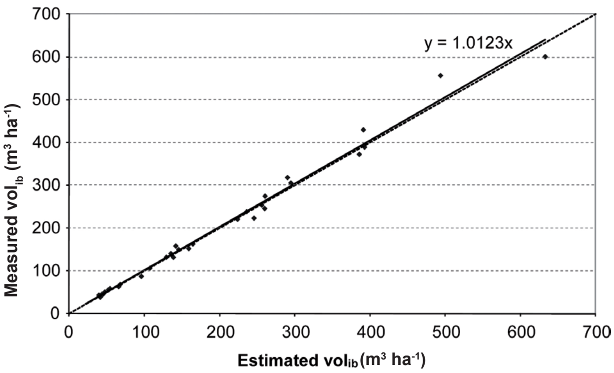

FIGURE 2: Modelled estimate (“Ref” age) versus measured stem total volume inside bark, vol$_{ib}$. The linear regression (solid line) can be compared with the one-to-one relationship (extended dashed line in this and following figures).

Stem total volume under bark

Modelled estimates of stem volume under bark per hectare, from the 300 Index model, were generally very similar to values reported from biomass studies (Figure 2). It should be remembered that the 300 Index model gives the identical basal area, mean top height, and stocking to those obtained from the PSP system in the year that the biomass study (“Ref” year) was undertaken. The variation in Figure 2 also reflects biomass sampling error associated with estimating stem volume using a relatively small set of sample trees.

Whole stemwood density

A comparison of the predictions of whole stemwood density from the wood density model with the mean whole stemwood density estimates based on the biomass trees showed only moderate strong agreement (Figure 3). Biomass sampling variation is likely to be large for wood density.

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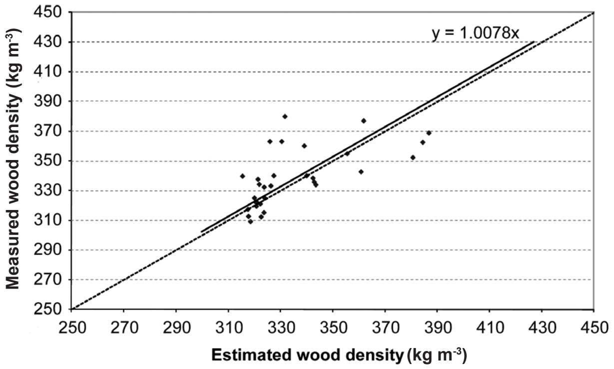

FIGURE 3: Modelled estimate versus measured whole stemwood density.

Above-ground biomass carbon

Model estimates of above-ground biomass carbon were generally similar to the values reported from biomass studies, although more variation was evident for biomass carbon than found for stem volume (Figure 4).

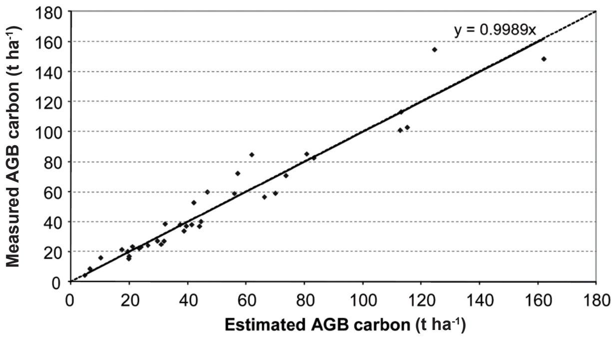

FIGURE 4: Modelled estimate versus measured above-ground biomass carbon.

The likely magnitude of the biomass sampling error can be inferred from an analysis undertaken by Madgwick (1991), who showed that biomass studies based on 12 – 17 trees yield estimates within 5% of the actual stand biomass, with error increasing markedly when fewer than 5 trees were measured (Madgwick, 1991).

Dead wood and litter carbon

The model tended to overestimated dead organic matter per hectare on the forest floor (Figure 5). In intensively managed stands, dead wood arises predominantly during tree felling operations associated with thinning to waste. The forest floor material includes branch residues arising from pruning and thinning operations and from natural branch mortality and needle shedding. Biomass studies did not measure needle litter that was trapped by dead branches within the lower canopy. Furthermore, the model assumes that shed needles fall to the forest floor. The field measured carbon stock estimate for the LFH pool may therefore be an underestimate. The difficulties involved in accurately measuring and modelling dead organic matter presumably partly explain why the model appears to overestimate the dead organic matter pool, although the apparent bias is quite small and was not statistically significant.

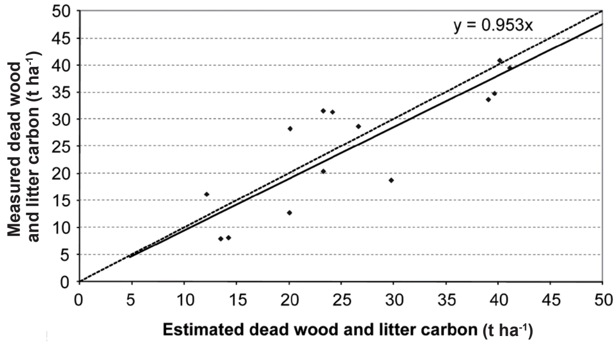

FIGURE 5: Modelled estimate versus measured dead wood & litter carbon.

Total carbon pool

Modelled estimates of the total carbon stock (excluding carbon in the mineral soil) were compared with measurements undertaken at Kinleith and Tarawera (Oliver et al., 2011), (Figure 6). The model tended to overestimate total carbon stocks at Tarawera, while stocks at Kinleith Forest were similar to measured values (Figure 6), although too few sites had complete carbon budgets, and the overall accuracy of the model is therefore best inferred from Figures 4 and 5.

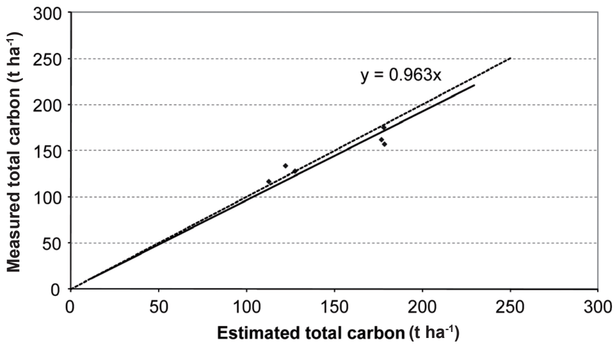

FIGURE 6: Modelled estimate versus measured total carbon.

Accuracy of stock change estimates

The periodic mean annual increments (PMAI) in stem volume and above-ground carbon from the Forest Carbon Predictor were compared with stock changes calculated for a subset of stands with repeated biomass measurements (Figures 7 & 8). PMAI estimates for these stands apply to increment periods that ranged between 5 and 11 years duration, with an average increment period of 8 years duration between plot re-measurement dates. The same calculation approach

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will be possible in future to provide carbon sequestration estimates for post-1989 planted forest over the first commitment period, once plots measured in 2008 are remeasured in 2012.

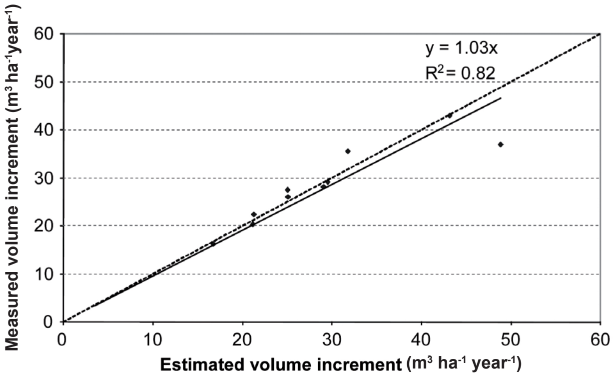

FIGURE 7: Modelled estimate versus measured volume increment.

The modelled sequestration rates average 4% higher than the stock changes from repeated biomass measurements (Figure 8), which is a small difference given that biomass sampling variation will likely be relatively large.

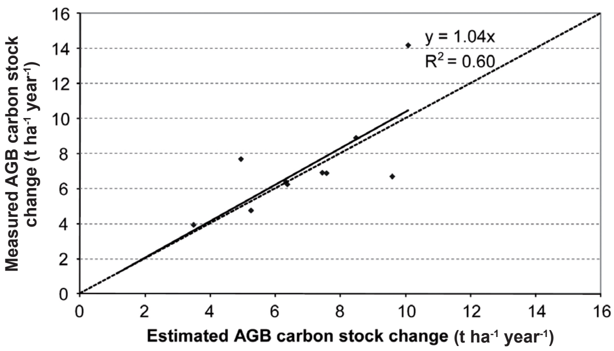

FIGURE 8: Modelled estimate versus measured carbon sequestation.

Accuracy of model projections

The model prediction errors are shown graphically (with Bf and Af predictions combined) only for volume and above-ground biomass carbon per ha (Figures 9 & 10). Predictions based on model projections were slightly more variable than estimates obtained using the "Ref" year, nevertheless the model prediction (Bf and AF combined) error averaged less than 4% for above-ground biomass carbon.

Accuracy and precision of the Forest Carbon Predictor

Model bias and confidence intervals are summarised in Table 3. Plot measurement date (five years before "Bf", at "Ref", or five years "Af" the biomass study) did not significantly influence either stem volume or

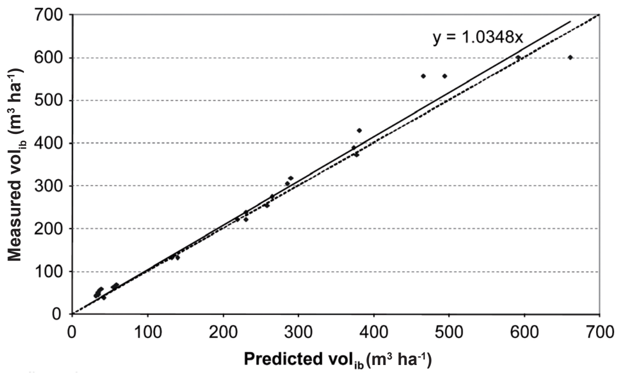

FIGURE 9: Modelled prediction ("Bf" and "Af") versus measured stem total volume under bark.

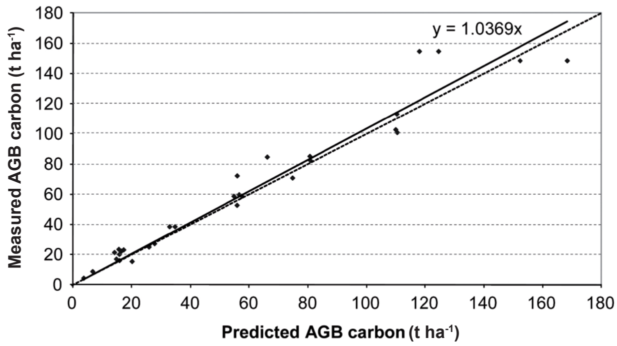

FIGURE 10: Modelled prediction ("Bf" and "Af") versus measured above-ground biomass carbon.

carbon pools (*p*-values in Table 3 were not statistically significant), which indicates that the Forest Carbon Predictor can be calibrated using plot measurements acquired 5 or more years prior to or following the date when carbon stock estimates are required. For example, a plot measurement in 2012 can be used to estimate carbon stock in 2012 and also predict the carbon stock in 2008, and carbon sequestration over this period can be calculated by difference.

Advantages of the Forest Carbon Predictor

Replacing the set of regional volume growth models used in STANDPAK (Beets et al., 1999) with one growth model, the 300 Index model, has greatly simplified carbon predictions using the Forest Carbon Predictor. Furthermore, the 300 Index model allows for the effects of pruning and thinning operations on growth, whereas pruning required the use of the EARLY model followed by the appropriate regional growth model in STANDPAK (Beets et al., 1999). The 300 Index model also does not require linear interpolation between ages 0 and 4 years to predict carbon at early ages. Compared with results reported in Beets et al. (1999), it is evident that the Forest Carbon Predictor confers benefits in terms of simplicity in use and transparency without a loss in model accuracy or precision.

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TABLE 3: Model mean error and 95% confidence intervals for stem volume inside bark, mean wood density, total carbon in four GPG pools (excluding mineral soil), carbon in above-ground biomass and combined dead wood and litter pools, obtained using the Forest Carbon Predictor. Model errors are shown using plot measurements made five years before (Bf), at (Ref), and five years after (Af) the biomass measurement, along with the *p*-value testing the significance of the bias for the measurement year.

Stock	Measurement Year	Number of stands	*p*-Value for Measurement Year	Forest Carbon Predictor v3 Estimate	Model Mean Error and 95% Confidence Interval
Volume inside bark (m^3 ha^{-1})	Bf	12		332.4	-1.6% ± 5.7
	Ref	31	0.33	195.0	-1.2% ± 2.6
	Af	13		136.5	-7.9% ± 5.9
Wood Density (kg m^{-3})	Bf	12		353.2	-1.2% ± 4.3
	Ref	31	0.40	335.3	-0.8% ± 1.9
	Af	13		333.8	0.0% ± 2.7
Total Carbon (t ha^{-1})	Bf	6		153.5	1.2% ± 6.6
	Ref	6	0.28	156.9	3.7% ± 7.9
	Af	-		-	-
Above-ground biomass Carbon (t ha^{-1})	Bf	14		84.8	-1.2% ± 8.1
	Ref	36	0.75	48.3	-0.9% ± 5.6
	Af	16		30.0	-12.2% ± 12.0
Dead wood plus litter carbon (t ha^{-1})	Bf	-		-	-
	Ref	14	0.44	26.2	4.7% ± 12.6
	Af	-		-	-

Limitations

The Forest Carbon Predictor requires accurate data to calibrate the model to each plot. This was not always the case, for example, needle retention (NR) data were not available for all biomass studies used in this validation study. Needle retention was assessed as part of the LUCAS forest inventory. The Tikitere stands were pruned while the biomass study was underway, with some biomass sample trees unpruned while other were pruned, while the Forest Carbon Predictor used plot measurements acquired after the pruning operation had been completed. At Shenstone the “Reference” date was in June (winter-measurement date), however, the biomass study was undertaken in November. At Kinleith and Tarawera, thinning occurred several months after the winter measurement was completed, by which time the thinned trees would have grown a little. The biomass sampling error also varied from study to study, which contributed to the variation between modelled and measured values. Root/shoot biomass ratios applicable to *P. radiata* were reviewed recently, and were therefore not addressed in this paper (Beets, Pearce, et al., 2007).

Conclusions and Recommendations

The use of the Forest Carbon Predictor model, where the estimates of stand basal area, mean top height, and stocking are conditioned to be equal to the plot data at time of measurement, provides an integrated estimation and projection system. The most recent version at the time of finalising this paper is FCP v3.

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Based on this model validation study, the following conclusions and recommendations are made:

1. Forest Carbon Predictor v3 provides estimates of total carbon stocks with an overall accuracy of approximately 5%, or approximately 1% when only above-ground biomass carbon is required.

2. Carbon stock change (sequestration) in above-ground biomass was estimated with an accuracy of approximately 5%, when linked to plot growth data acquired at both the start and end of each period, the average length of which corresponded reasonably closely with the length of the first commitment period of the Kyoto Protocol.

3. A model-based approach for estimating carbon stocks based on plot measurements at one point in time and projecting growth forwards or backwards over an approximately five year period showed considerable promise for predicting carbon sequestration in *Pinus radiata*. This approach is necessary when only one plot measurement is available, and can be applied when stand silvilcultural operations have been completed.

4. The plot data associated with biomass studies reported here were in most cases measured on a two-yearly basis, and therefore the timing of silvicultural operations was known to within a few months. LUCAS plots will likely be measured on a five yearly basis, and the timing of operations may not be known precisely. Sensitivity analysis of the Forest Carbon Predictor to various model inputs is an important next step for improving forest carbon inventories.

5. The development of new temperature dependent functions for estimating the decay rates of dead wood, litter, and dead roots allow carbon stocks to be estimated on both a national and regional basis. This is an important improvement, because models can be expected to estimate carbon stocks and changes in situations where dead material is costly or impractical to measure accurately using field methods (e.g. slash piles, windrows, or plots with heavy understory vegetation) - the timing of silvicultural operations needs to be known.

Underpinning research continues to improve methods of carbon assessment in planted forests. A recent focus involves calibrating the FCP model to improve estimates of carbon stocks in minor planted tree species. Carbon in understorey vegetation was excluded from the analysis presented here, although research is underway to improve this part of the carbon assessment methodology. Carbon stocks in forest soils are currently not estimated using the FCP, although research is underway to examine the impacts of afforestation and forest site preparation techniques such as ripping and mounding on mineral soil carbon stocks.

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APPENDIX A: Above-ground biomass studies used to test the Forest Carbon Predictor.

Site	Trial	Stands	Plant year	Rotation	Stand Age	Stems per hectare	BA (m^2)	Mean Top Height (m)	N[1] stem	N[1] crown	Method[2]	Reference
Tarawera	FR41	3	1989	2	5	1900 – 2512	12.9 – 20.5	7.4 – 7.8	20	40	BC	Oliver et al. (2011)
	FR41	3	1989	2	16	500 – 563	38.9 – 40.1	29 – 30	8	8	BWt	Oliver et al. (2011)
Kinleith	FR188	3	1992	2	5	1900 – 2419	13.5 – 16.0	6.2 – 6.5	20	40	BC	Oliver et al. (2011)
	FR188	3	1992	2	15	531 – 600	31.0 – 34.9	24 – 25	8	8	BWt	Oliver et al. (2011)
Golden Downs	FR220	6	1994	2	5	2340 – 2450	14.8 – 19.5	6.0 – 6.8	20	40	BC	Beets et al. (unpub)
Puruki	RO1050	1	1973	1	17	1145	65.7	25.4	5	5	BD	Beets (unpub)
		1	1973	1	17	560	53.3	25.1	5	5	BD	Beets (unpub)
		1	1974	1	16	160	26.0	25.1	5	5	BD	Beets (unpub)
		1	1973	1	17	63	14.6	26.2	5	5	BD	Beets (unpub)
		1	1973	1	22	62	22.1	32.0	10	10	BD	Beets (unpub)
		1	1973	1	23	62	23.5	32.0	10	10	BD	Beets (unpub)
	RO443/5	10	1997	2	9	1000	21.0 – 48.9	11.6 – 14.6	5	5	BWt	Beets et al. (2011)
Shenstone	AK976	2	1979	1	12	1029 – 1078	22 – 25	11.1 – 13.0	3	3	BD	Parfitt et al. (1994)
Tikitere	RO382	1	1973	1	6	100	6.2	7.8	8	8	BWt	Madgwick (unpub)
		1	1973	1	6	200	8.7	7.7	8	8	BWt	Madgwick (unpub)
		1	1973	1	6	400	15.5	7.7	8	8	BWt	Madgwick (unpub)

[1] Number of sample trees per stand. Total number of trees per site is N x Stands.
[2] Biomass method: Branch count (BC); branch diameter (BD); or full crown weighing (BWt).

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