# DESCRIPTION AND VALIDATION OF C_CHANGE: A MODEL FOR SIMULATING CARBON CONTENT IN MANAGED *PINUS RADIATA* STANDS

P. N. BEETS, K. A. ROBERTSON, J. B. FORD-ROBERTSON, J. GORDON, and J. P. MACLAREN

New Zealand Forest Research Institute,
Private Bag 3020, Rotorua, New Zealand

## ABSTRACT

A model has been developed that predicts the amount of carbon contained in the stem, crown, roots, forest floor, and understorey of managed *Pinus radiata* D. Don stands at any age over a rotation. A key concept underlying the C_change model is that, with current knowledge of growth partitioning, mortality, and decay of tree components, stem volume production can be used to predict carbon content of forest biomass components. The advantage of taking this approach is that data input requirements for predicting forest carbon are minimised, given a system for determining stem volume growth and mortality over time. The Stand Growth module of STANDPAK predicts *P. radiata* stem volume for each of the major forest-growing regions in New Zealand, based on an extensive network of permanent sample plots (PSP). By linking the Growth Partitioning module with Stand Growth, a minimum set of data inputs is required to calibrate C_change to the region.

The utility of this approach was tested by running C_change to make predictions of stem volume and carbon at several sites where stand biomass measurements had been made. These sites covered a range in nitrogen fertility, stocking, stand ages, and climate. Across all studies, actual above-ground stand carbon content (i.e., excluding understorey and forest floor) was highly correlated with that predicted by C_change ($r^2 = 0.97$, $n = 25$, $p < 0.01$). Assuming that suitable regional growth models are available for predicting stem volume and that growth relationships are constant across regions, these results give confidence in the use of C_change for prediction of carbon on a stand and regional scale in New Zealand.

**Keywords**: carbon; plantation forest; modelling; New Zealand; *Pinus radiata*.

## INTRODUCTION

### Model Objective

The purpose of C_change is to predict the carbon content of managed *Pinus radiata* stands from the predetermined stem growth rate, as reflected by growth measurement plots or conventional stand growth models.

The carbon content of *P. radiata* stands depends on growth, mortality, and decay rates, which vary with the silvicultural system (e.g., stocking, pruning, thinning, harvesting,

rotation number), site factors (e.g., climate, soil fertility, soil type, disease), and stand age. The approach that was developed to deal with this complexity is based on having time series estimates of stem total volume which are converted to stand dry matter production and component carbon content.

This report describes the concept underlying the C_change model, explains why this approach is useful, tests the model using independent biomass data sets, and, from an assessment of model limitations, maps out possible directions for research. The way in which the C_change module is linked to STANDPAK, which is a computer-based modelling system widely accepted by industry (Whiteside 1990), is also summarised.

## Modelling Concept

The Growth Partitioning module is derived from DRYMAT, which is in turn a simplification of a process-based compartment model (Beets 1982). The dry matter (and carbon) content of living (needles, branches, stems, reproductive parts, and roots) and non-living tree components and litter (but excluding carbon in the mineral soil) are represented as boxes (compartments), and the inter-compartmental flows as arrows (Fig. 1). The Growth Partitioning module simulates the oven-dry weight of model compartments, on a unit area basis, using a system of conservative flow equations (called state transition equations) which are solved simultaneously (Beets 1982).

Process-based models, when suitably simplified, are proving useful for predicting spatial variation in productivity, particularly over large areas (*see*, for example, Landsberg & Waring 1997), and are likely to be increasingly important for projecting productivity into the future as systems are developed to forecast environmental drivers determining productivity. The increase in atmospheric greenhouse gas concentrations has provided impetus for understanding and predicting the effects of climate change on future temperature and rainfall patterns on a regional basis. These systems are more advanced than systems for predicting the effects of silvicultural management (genotype, site preparation, fertiliser application, weed control, rotation number, harvesting system, incidence and severity of disease) on sustainable productivity. The drivers of long-term site productivity are not sufficiently well understood to permit the exclusive use of process-based models to forecast growth.

The preferred option for accurately predicting carbon sequestration for short-rotation plantation species such as *P. radiata* is based on a hybrid approach involving conventional growth models to predict stem volume, coupled to a process-based model to expand to other stand components.

A key concept underlying the C_change model is that, given current knowledge of growth partitioning, mortality, and decay of tree components, stem volume production and mortality can be used, in conjunction with the silvicultural regime, to calculate dry matter (and carbon) gains and losses of other forest biomass components. Gross gains in tree components necessarily sum to net primary production from photosynthesis and respiration. Stem dry matter content can be obtained from stem volume and wood density data, which are required as model inputs (predicted using the Stand Growth module in STANDPAK). This approach is useful because stem volume growth data, together with other model inputs, are the basis for calibrating C_change to the site, and so make it possible to by-pass the difficult and error-prone task of having to simulate actual photosynthesis and respiration rates from historical environmental factors.
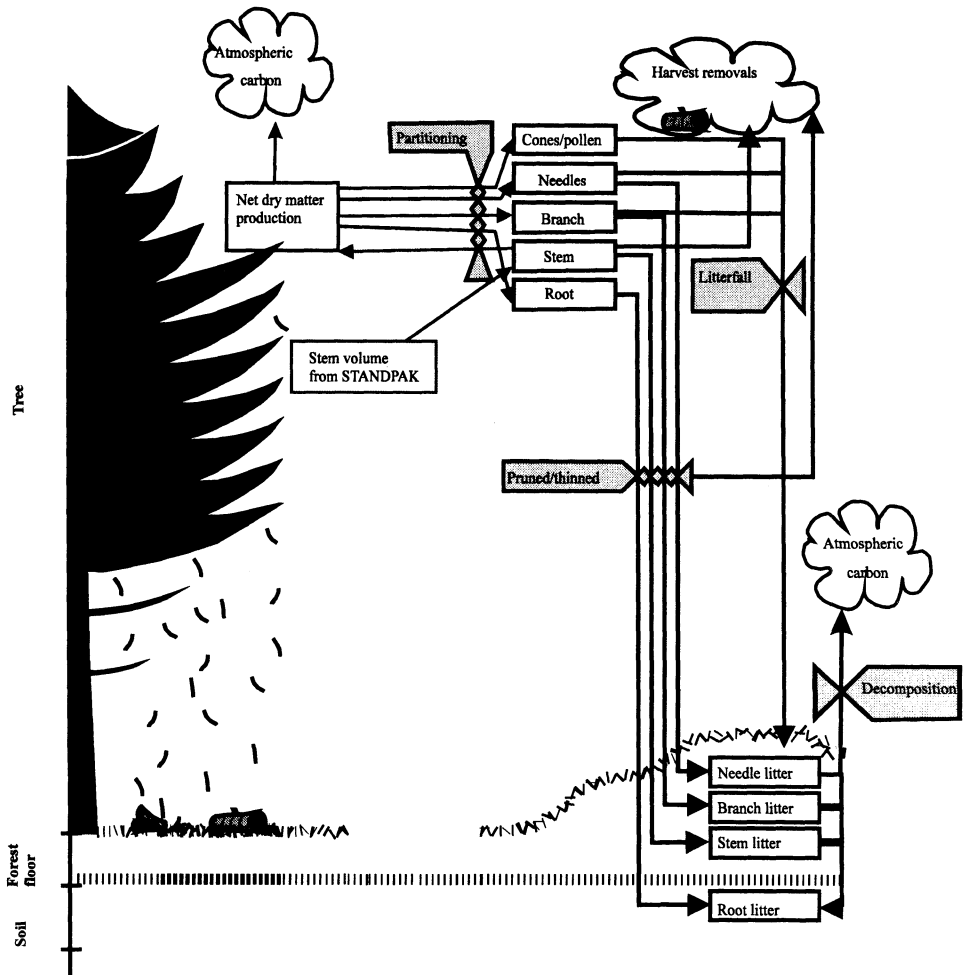
FIG. 1–Growth partitioning module of C_change.

## Linkages to STANDPAK

STANDPAK is a computer-based stand modelling system widely accepted by industry. It is used to predict volume, size, and quality of logs from pine stands grown on a range of sites in New Zealand, Australia, and Chile, and managed under a wide range of silvicultural regimes (Whiteside 1990; West 1993). The Stand Growth module of STANDPAK predicts gross and net stem total volume under bark (among other things) for *P. radiata*, given management information specific to a particular stand, allowing the calculation of stem volume growth and mortality. A number of empirical growth models are currently installed in the Stand Growth module of STANDPAK, allowing growth predictions to be made for different growth regions. These regional growth models are derived from data from a nationwide network of over 23 000 permanent sample plots.

The data inputs and resulting growth predictions of the Stand Growth module are required by the Growth Partitioning module (stand age, volume, height, basal area, pruned height,

stocking, harvest removals) for predicting stand carbon content. Hence, the Growth Partitioning module has been linked with the Stand Growth module, and together they are referred to as C_change. Additional inputs not provided by the Stand Growth module are entered by the user in forms within the Stand Growth and Growth Partitioning modules.

The current version of C_change allows carbon to be simulated over two successive rotations of *P. radiata*, following identical stand management regimes. This facility provides information on longer-term trends in carbon storage, as it is assumed that slash and forest floor carbon arising from the first rotation becomes the initial carbon for the subsequent rotation.

## GROWTH PARTITIONING MODULE
### Partitioning Data

The relationship between stem growth and that of other tree components has been examined in a number of comprehensive biomass studies (Madgwick *et al*. 1977; Beets & Pollock 1987; Beets & Madgwick 1988). Biomass time series measurements were used to calculate annual dry matter production and its partitioning to needles, branches, stem, and roots in relation to tree age, thinning intensity, and site fertility following methods given by Beets & Whitehead (1996). Previous analysis of these biomass data sets has shown the following facts regarding partitioning of production, and these apply in stands where the current annual stem volume increment (CAI) in closed stands ranged between 15 and 52 m³/ha:

- Partitioning of above-ground production to needles and stems is determined primarily by tree (physiological) age (Beets & Pollock 1987; Madgwick *et al*. 1977; Madgwick 1985).
- Partitioning of above-ground production to needles, branches, and stems does not appear to be influenced by stocking, although stocking × nitrogen fertility interactions warrant further investigation with regard to branch *versus* stem growth, because branch growth is poorly estimated in most studies (Beets & Madgwick 1988).
- Partitioning of above-ground production to needles is not significantly influenced by tree nitrogen status, although partitioning to branches increases at the expense of partitioning to stem, with increasing nitrogen status (Beets & Whitehead 1996).
- Partitioning of total production to roots decreases with improved nitrogen nutrition, owing primarily to an apparent reduction in partitioning of carbon to fine roots, mycorrhizas, and exudates, although few data exist to confirm this (Beets & Whitehead 1996).

In C_change, existing regional stem volume growth models are linked to the Growth Partitioning module, and so the primary effect of variation in stem growth rate on carbon sequestration by other components of the stand is automatically taken into account. When the partitioning functions were being developed, it was assumed that changes in above-ground growth partitioning were related only to stand age, because stand age is included in existing regional growth models, and age is a major source of variation in above-ground growth partitioning. More elaborate partitioning equations incorporating the effects of nitrogen fertility on root/shoot and branch/stem partitioning (e.g., following Beets & Whitehead 1996), would be difficult to apply when linked to existing regional growth models, because in the latter nitrogen fertility effects are confounded with other factors such as moisture supply and defoliation by fungal diseases.

In the Growth Partitioning module the growth of individual crown components (needles by age class, live branches, dead branches, cones) is predicted as a function of stand age, stem volume, wood density region (Cown *et al.* 1991), and partitioning equations, with the latter based on above-ground biomass measurement in stands aged 2–22 years (Madgwick *et al.* 1977), 29 years (Webber & Madgwick 1983), and 2–12 years (Beets & Pollock 1987). Based on these data, partitioning of above-ground production ranged between 12% and 40% for needles, 30% and 72% for stem wood plus bark, and was approximately 20% for branches and reproductive parts (cones), with partitioning depending on stand age (Fig. 2, Table 1). Partitioning below ground (including coarse and fine root production and turnover) was assumed to be a constant 30% of total production, irrespective of stand age and fertility, of which from 15% to 20% accumulates in live root biomass, depending on stand age. While it is acknowledged that partitioning below ground can exceed 30% (e.g., at nitrogen-deficient sites—Beets & Whitehead 1996), higher values are associated with fine roots, mycorrhizas, and root exudates which turn over and also decay rapidly, and consequently represent a relatively small pool of biomass carbon.

TABLE 1–Parameter values and error estimates of logistic curve used in C_change to describe partitioning as a function of tree age*.

Predicted partitioning (to components, Y) at stand age (t)
$$Y(t) = [(A-D)/(1.0+(t/C)^B)+D]$$

| Component | Parameter | Value | SE |
|---|---|---|---|
| Needles | A | 39.58 | 2.85 |
| | B | 3.337 | 0.82 |
| | C | 7.867 | 0.74 |
| | D | 12 | 0.0 |
| Stem wood plus bark | A | 72.0 | 0.0 |
| | B | −2.938 | 0.88 |
| | C | 8.710 | 0.91 |
| | D | 33.850 | 4.14 |
| Stem wood | A | 65.0 | 0.0 |
| | B | −2.947 | 0.89 |
| | C | 8.331 | 0.95 |
| | D | 28.521 | 4.26 |
| Reproductive parts | A | 2.597 | 0.60 |
| | B | −3.816 | 1.72 |
| | C | 12.542 | 2.27 |
| | D | 0.0 | 0.0 |

* Growth to branches is by difference (i.e., above-ground production minus needle, stem, and reproductive growth). Root production is assumed to be 30% of total production.

## Mortality Data (Needle, Branch, and Tree)

Natural needle loss is determined by needle retention and consumption by herbivores. Needles not retained on the tree enter the forest floor as needle litter and decompose, while needle consumption represents a carbon loss from the stand. Needle retention was determined from the age-class distribution of cohorts of needle fascicles, which had been remeasured
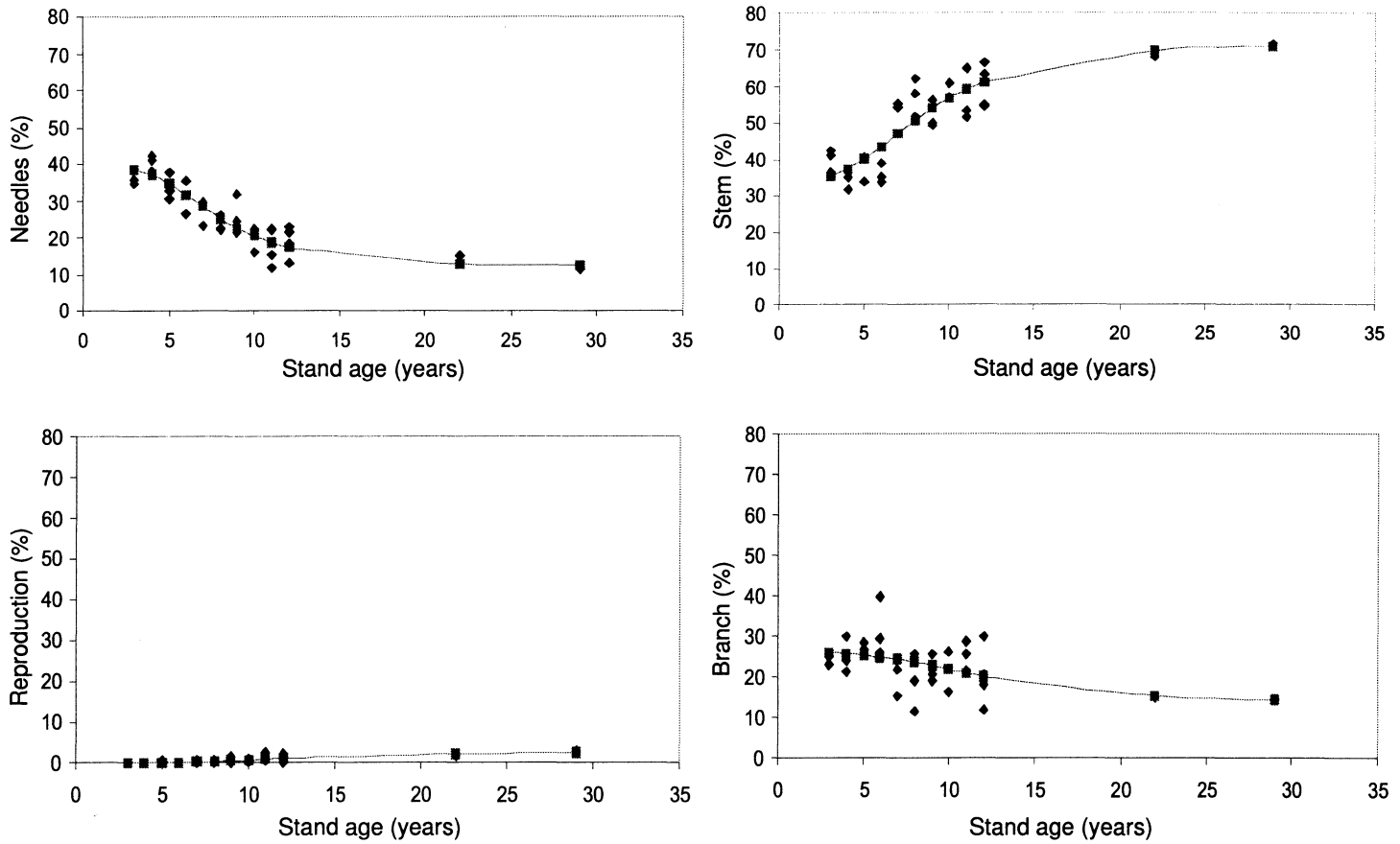
FIG. 2–Proportion of current annual above-ground dry matter production partitioned to needles, stem, reproductive parts, and branch at sites of moderate to high nitrogen status covering a wide range in stocking, shown in relation to stand age. ♦ = actual data points, ■ = predictions.

over time (Beets & Pollock 1987). Needle retention and consumption parameters are required as model inputs. Needle retention is likely to vary spatially. However, for simplicity, in C_change these are set at default values (0.7 is the fraction of 1-year-old needles retained for a second year, and 0.05 is the fraction of 1-year-old needles consumed).

Branch mortality normally occurs when the live branch content increases above the maximum (stocking dependent) amount possible in *P. radiata* stands (Madgwick 1985). Branch mortality then matches branch production. Dead branches begin decomposing while still attached to the stem, unless crown pruning occurs, which results in the deposition of branch and foliage matter on to the forest floor.

Tree mortality can occur throughout the life of the tree crop, owing to competition, windthrow, and breakage. In stands with minimum tending, natural tree mortality from competition can be high, but is generally low in intensively managed stands. Natural tree mortality is modelled within the Stand Growth module of STANDPAK. STANDPAK predicts the gross and net stem volume, enabling the calculation of mortality. The carbon contained in the dead trees is transferred to the forest floor pool, where it decomposes.

Pruning, thinning, and clearfelling operations are the major cause of mortality in intensively managed stands, and result in the transfer of foliage, branch, stem, and root carbon from live to dead pools throughout the rotation. The direct effects of pruning and thinning operations on foliage, branch, root, and stem carbon are predicted in the Growth Partitioning module of C_change. Pruning functions were based on biomass data giving the vertical distribution of foliage and branches within the canopy (Madgwick *et al.* 1977). Trees are pruned up to a specified average crown height, and thinned to a specified stocking based on the silvicultural information from Stand Growth. Prunings and thinnings are normally transferred to litter pools after allowing for possible extraction of harvested materials off site. Extraction of stem carbon occurs during production thinning operations, and at the end of the rotation through clearfelling, and is represented as an instantaneous loss of carbon. Carbon retained in live trees is modelled as a function of crown length remaining after pruning, and basal area remaining after thinning. Crown displacement can occur during harvesting operations; however, crown extraction is rare. Allowance can be made for possible removal of crown material off site.

Slash reduction through burning represents a loss of carbon from the site, although currently burning is rarely practised in New Zealand (Robertson 1998). Nevertheless, allowance can be made for possible losses of carbon off site after burning.

In summary, carbon from living tree components eventually enters the forest floor compartment (litter), depending on needle retention parameters and information on the frequency and intensity of pruning, thinning, and harvesting operations, or is extracted off the site as harvested material (which is specified as a model input). Litter decay rates (component specific parameters for needles, branches, stems, and roots) determine the rate at which carbon is released from the stand back to the atmosphere. Some litter eventually becomes part of the soil organic matter pool, which is not simulated here.

## Losses of Carbon Through Decomposition

Decomposition data have been obtained mostly from central North Island (CNI) sites (Will *et al.* 1983; Santantonio & Santantonio 1987a, b) and were used to calculate average

annual decay rates of needles (0.22), fine roots (0.52), and stems (0.18). Branch decomposition rates were assumed to be midway between needle and stem decomposition rates. Coarse root and attached dead branch decomposition rates were assumed to be equal to the stem decomposition rate. It is expected that attached branches decompose more slowly than branches on the forest floor. Several research programmes are looking at decomposition rates and these figures could be improved in future. Central North Island decomposition rates are expected to be representative of national average rates but may not necessarily be accurate for specific regions in New Zealand (e.g., it is expected that Northland sites will have higher rates, and Southland sites lower rates than CNI sites).

## Understorey Data

Shrub biomass data from an age series of stands in Kaingaroa Forest (G.Oliver, unpubl. data) were used to estimate pine forest understorey carbon content. The function operates as an add-on in C_change (i.e., an empirical equation running independently from the Stand Growth module, and therefore not interacting with silvicultural regime). This add-on is run independently due to lack of data about the relationship between forest and understorey growth.

After the trees have been harvested, understorey carbon and forest floor and slash from the pines are used as initial conditions for the subsequent simulation. The pine residues exclude crown and stem matter that is specified to have been removed during harvesting.

Initial vegetation on site is assumed to be killed when pines are established (with an allowance possible for loss of carbon owing to site preparation—e.g., burning). Remaining carbon is assumed to be lost at a rate equal to that of pine branches decomposing on the forest floor.

## Summary of Model Inputs

The inputs to run the Growth Partitioning module, as implemented in C_change, include:

- Rotation parameters (number of rotations and rotation age);
- Stand parameters (wood density region—low, medium, or high; stand age; mean top height; basal area; stem volume; needle retention (fraction of 1-year-old needles retained for second year; 1-year-old needle loss owing to consumption; defaults);
- Silviculture/harvesting regime (timing and intensity of pruning, thinning, and harvesting operations are inputs from the Stand Growth module), including parameters giving the percentage of crown and stem removed from the site during harvesting (stem carbon loss defaults to 80% after production thinning and 85% at clearfelling age, unless set by the user);
- Initial conditions: default seedling weights, with simulations starting at stand age 0, from a given stocking;
- Initial vegetation and loss parameter (to allow for site preparation effects).

These inputs allow the model to simulate stand carbon content from time of establishment to rotation age, by calculating total dry matter production and partitioning of production to tree components. The model assumes that dry matter is 50% carbon (Matthews 1993). Carbon in the forest floor and in slash from the first rotation are used as initial conditions for the second rotation.

## Summary of Model Outputs

The C_change model output includes a list of the Stand Growth models used, the starting values, and the predicted carbon content of the stand, as shown in Table 2. While a greater level of detail was necessary for modelling stand carbon, the level of detail reported is that considered appropriate for carbon accounting purposes. Options are available for including inputs from the Stand Growth module (i.e., age, stocking, height, stem volume, and basal area) in the output file produced by C_change.

## VALIDATION OF C_CHANGE

Biomass data sets for *P. radiata* stands world-wide were recently catalogued by Madgwick (1994). The data sets of Madgwick *et al.* (1977), Webber & Madgwick (1983), and Beets & Pollock (1987) were used to develop the growth partitioning, crown mortality, and pruning and thinning functions in the Growth Partitioning module, and so were excluded from the following tests. Stand information from independent biomass studies in New Zealand (Table 3) was used to test the accuracy of the C_change predictions, including data sets of Mead *et al.* (1984), Beets & Madgwick (1988), Dyck *et al.* (1991), Smith *et al.* (1994), Fang *et al.* (in prep. a,b), and recently acquired data sets from Kinleith and Tarawera (A.Lowe, unpubl. data), and Puruki Forest (P.Beets, unpubl. data). These validation data sets cover a wide range of growth regions, stand ages, and stocking levels.

To test the accuracy of the C_change predictions, stand management information was obtained for each study site, including initial stocking, pruning, and thinning history. The effect of site on stand growth rate was taken into account by first running the EARLY model (West *et al.* 1982), followed by the appropriate regional growth model to predict stand volume through to the end of the rotation. The stand management information and resulting stem volume predictions were used in the Growth Partitioning module in C_change to predict crown and stem carbon content. These predictions were compared with actual biomass estimates from the biomass studies, after grouping of minor components (e.g., crown includes needles, branches, cones).

The EARLY growth model was used to predict the effects of silviculture on growth up to stand age 18 years. EARLY must be used if pruning is carried out. When using EARLY it is necessary to specify a basal area level, which is usually set based on experience or validation plots. For this validation exercise, the basal area level specified when running the EARLY growth model was based on the early basal area development of the stands for which biomass data were available.

## Woodhill (Using EARLY and SANDS Growth Models)

Beets & Madgwick (1988) measured above-ground *P. radiata* biomass in an intensively monitored trial (AK287) installed on a large nitrogen-deficient coastal dune at Woodhill Forest in 1968. The lupin treatment was selected to test C_change as the appropriate regional Stand Growth model (SANDS) was based on this site management practice. The normal site preparation procedure at that time involved over-sowing the site with lupin, which was crushed prior to tree planting and allowed to regrow after planting. The experimental stand was initially stocked at 2224 stems/ha, and plots were either left unthinned, or thinned to final-crop nominal stockings of 1483 stems/ha, or 741 stems/ha. In C_change, the EARLY

TABLE 2–C_change output.

| Growth model: | 23 EARLY | DOS fn.: | Standard |
|---|---|---|---|
| Basal area fn: | High | Crown fn.: | Beekhuis |
| Basal area adj. | 0.00% | DOS adj. | 0.0 |
| Height model: | 3 | Site Index: | 32.0 m |
| Stand volumefn. | 3 | Start date: | 1979 JUL |
| Monthly growth fn.: | 1 | Mean top height : | 7.1 m |
| | | | |
| Growth model: | 19 KGM3 | Monthly growth fn.: | 1 |
| GF rating: | 9 | | |
| Height model: | 34 | | |
| Stand volume fn. | 3 | | |

| Age (yr) | Stand total | Shrubs | Crown | Stem | Root (L&D) | Forest floor | Stems/ha | BA (m²/ha) | Ht (m) | GCL (m) | Vol. (m³/ha) | Pruned height (m) | Extract (t C/ha) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | - - - - - - - - - - - - - - - - - carbon (t/ha) - - - - - - - - - - - - - - - - | | | | | | | | | | | | |
| 1 | 1.5 | 0.1 | 0.6 | 0.3 | 0.4 | 0 | 2220 | 4.9 | 0.4 | 0.4 | 1.7 | | |
| 5 | 42.3 | 0.5 | 15 | 12 | 11.1 | 3.7 | 2220 | 27.4 | 4.6 | 4.6 | 62.1 | | |
| 10 | 107.5 | 1.2 | 18.1 | 32.9 | 24.2 | 31 | 550 | 31.5 | 13.3 | 10.5 | 160.9 | | |
| 15 | 192.6 | 2.1 | 33.5 | 93.8 | 39.8 | 23.5 | 535 | 52.3 | 22.9 | 17.1 | 431.7 | | |
| 20 | 264.1 | 3.1 | 39 | 150.3 | 53.7 | 17.9 | 510 | 62.7 | 30.5 | 22.2 | 660.1 | | |
| 25 | 332.5 | 4.2 | 40.5 | 204.6 | 66.9 | 16.3 | 484 | 69.7 | 37.1 | 26.5 | 868.1 | | |
| 30 | 392.4 | 5.5 | 39.6 | 252.4 | 78.4 | 16.4 | 458 | 74.4 | 42.8 | 30.3 | 1045.2 | | |

TABLE 3—Stand parameters of the data used for validation.

| Site | Rotation | Stand age | Stocking | Basal area (m$^2$) | Height (m) | n* | Average temperature (°C) | Annual rainfall (mm) | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Woodhill | 1 | 7.0 | 2224 | 20.3 | 9.3 | 6 | 14.3 | 1330 | Beets & Madgwick (1988) |
| AK287 | 1 | | 1483 | 17.5 | 9.0 | 6 | | | |
| | 1 | | 741 | 11.6 | 8.7 | 6 | | | |
| | 1 | 10.5 | 2224 | 29.6 | 14.2 | 6 | | | |
| | 1 | | 1483 | 27.2 | 13.4 | 6 | | | |
| | 1 | | 741 | 20.0 | 12.9 | 6 | | | |
| | 1 | 14.0 | 2224 | 36.1 | 16.2 | 6 | | | |
| | 1 | 17.0 | 2224 | 39.2 | 18.2 | 6 | | | |
| Woodhill | 1 | 42.0 | 270 | 56.0 | 33.8 | 7 | 14.6 | 1330 | Dyck *et al.* (1991) |
| AK1029 | 2 | 5.0 | 2500 | 15.3 | 6.4 | 15 | | | Smith *et al.* (1994) |
| Tarawera | 1 | 27.0 | 401 | 53.4 | 38.2 | 10 | 14.0 | 1820 | Lowe (unpubl. data) |
| | 2 | 5.0 | 2500 | 11.9 | 6.0 | | | | Fang *et al.* (in prep. a,b) |
| Kinleith | 1 | 25.0 | 300 | 43.1 | 33.6 | | 13.2 | 1420 | Lowe (unpubl. data) |
| | 2 | 5.0 | 2500 | 16.1 | 5.3 | 40/12 | | | Fang *et al.* (in prep. a,b) |
| Puruki | 1 | 17.0 | 2220 | 65.7 | 25.4 | 5 | 10.0 | 1500 | Beets (unpubl. data) |
| | 1 | 17.0 | 550 | 53.3 | 25.1 | 5 | | | |
| | 1 | 17.0 | 160 | 26.0 | 25.1 | 5 | | | |
| | 1 | 17.0 | 50 | 14.6 | 26.2 | 5 | | | |
| | 1 | 22.0 | 50 | 22.1 | 32.0 | 10 | | | |
| Eyrewell | 2 | 7.0 | 1540 | 9.1 | 5.3 | 12 | Range 4.6–16.2 | 871 | Mead *et al.* (1984) |
| control | 2 | 8.0 | 1540 | | | 6 | | | |
| | 2 | 9.0 | 1540 | | | 6 | | | |
| | 2 | 11.0 | 1540 | 28.0 | 12.1 | 6 | | | |
| | 2 | 8.0 | 770 | | | 12 | | | |
| | 2 | 9.0 | 770 | | | 6 | | | |

*n = number of trees sampled for crown/stem biomass.

growth model was used until the mean top height of the plot attained 18 m; the growth model was then changed to SANDS. Since stand carbon calculations are based on stem volume from the Stand Growth models, the C_change predictions are compared firstly in terms of actual stem volume and secondly in terms of carbon.

Plots of actual stem volume in relation to predicted volume (Fig. 3) show that the Stand Growth models selected for this simulation predicted stem volume within 7% of actual values measured at this site. Above-ground carbon was measured at stand ages 7, 10.5, and 17 years. The Growth Partitioning module, using outputs from the Stand Growth module, predicted above-ground carbon within 5% of measured values at this site (Fig. 4, $R^2 = 0.88$).



FIG. 3–Stand actual and predicted stem volume from three different stockings at Cpt 138 of Woodhill Forest.
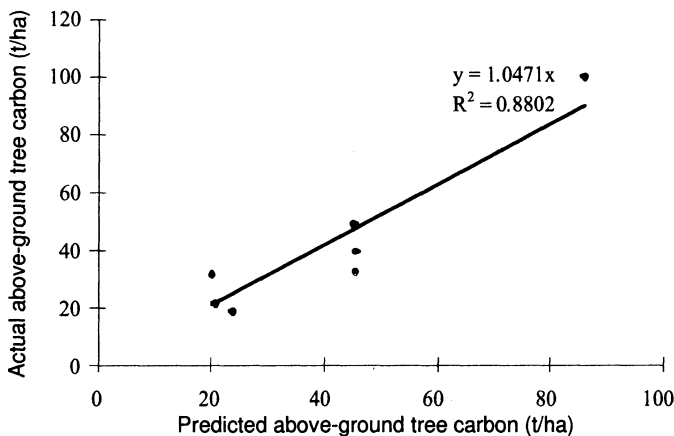


FIG. 4–Actual and predicted stand carbon in above-ground *P. radiata* components in Cpt 138 of Woodhill Forest.

## Central North Island (Using EARLY and INTERIM PUMICE PLATEAU Growth Models)

Above-ground biomass was measured in first- and second-rotation *P. radiata* stands with moderate to high nitrogen fertility at Tarawera and Kinleith Forests. Site characteristics have been given by Smith *et al.* (in prep.). The first-rotation stands were aged 27 and 25 years respectively (unpubl. data), and second-rotation stands were both aged 5 years (Fang *et al.* in prep. a,b). The two 5-year-old stands followed the same management regime, with stands stocked initially at 2500 stems/ha and no thinning or pruning undertaken by stand age 5 years (Table 3). The 5-year-old stands were control plots without fertiliser in intensively monitored trials.

First-rotation stands at Puruki Forest were established on improved pasture of high nitrogen fertility. Site characteristics have been given by Beets & Brownlie (1987). Biomass measurements at stand ages 17 and 22 years (Beets, unpubl. data.) were not used to develop the Growth Partitioning module, and were therefore included as model validation data. The Puruki stands were initially stocked at 2200 stems/ha and either left unthinned, or thinned to 550, 160, or 60 stems/ha, and pruned to 2.2 m height, following the management schedule given by Beets & Brownlie (1987). The biomass at age 17 was measured at each stocking rate, while the biomass at age 22 was measured in the stand stocked at 60 stems/ha.

Actual and predicted stem and crown carbon contents are given in Fig. 5. The Growth Partitioning module slightly over predicted carbon in this region (actual carbon = predicted carbon × 0.98).
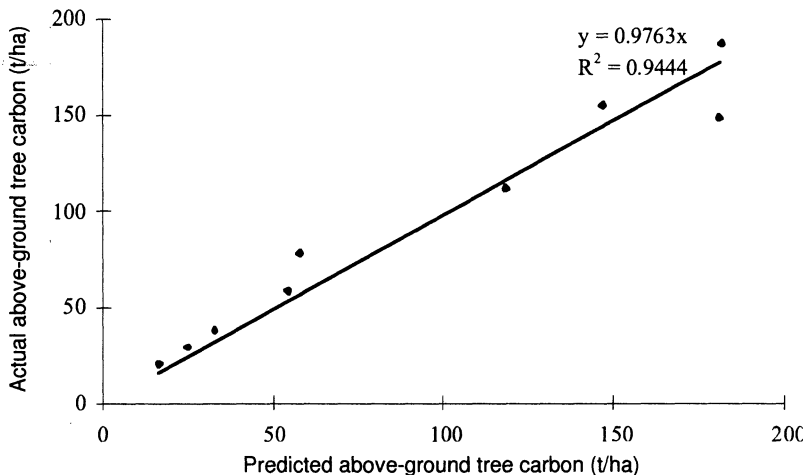


FIG. 5–Actual and predicted stand carbon from *P. radiata* at Kinleith, Tarawera, and Puruki.

## Eyrewell ( Using EARLY Growth Model)

Above-ground biomass was measured at a dryland site with moderate nitrogen fertility in Canterbury, where seasonal drought occurs periodically (Mead *et al.* 1984). Data from the controls without fertiliser were used to test the Growth Partitioning module predictions.

Above-ground biomass was measured at stand ages 7, 8, 9, and 11 years. Actual and predicted stem and crown carbon were within 10% ( Fig. 6, $R^2$ = 0.90).
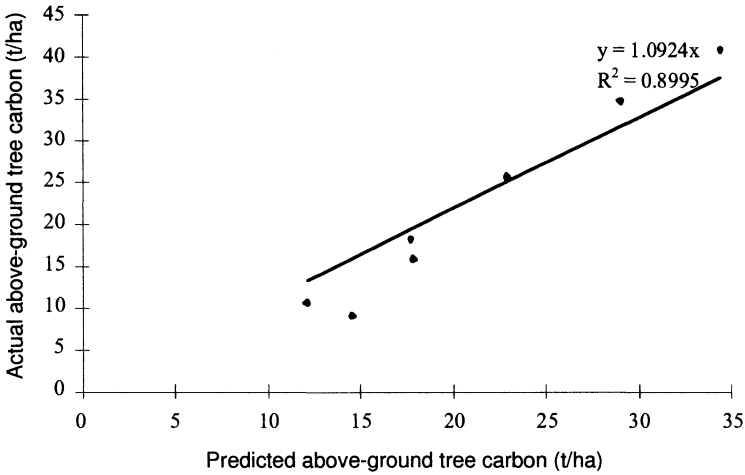


FIG. 6–Actual and predicted stand carbon from *P. radiata* at Eyrewell.

## Synthesis

Across all sites, the measured carbon in above-ground tree components was not significantly different from that predicted by C_change (i.e., excluding understorey, forest floor, and roots, for which validation data are extremely limited). Data from the Woodhill, Kinleith, Tarawera, Puruki, and Eyrewell sites described above were used in Fig. 7, together with data from a first-rotation stand aged 42 years (Dyck *et al.* 1991) and a 5-year-old second-rotation stand (Smith *et al.* 1994) in Woodhill Forest. The regression was fitted with an intercept, and included the 95% and 99% confidence intervals (CI).
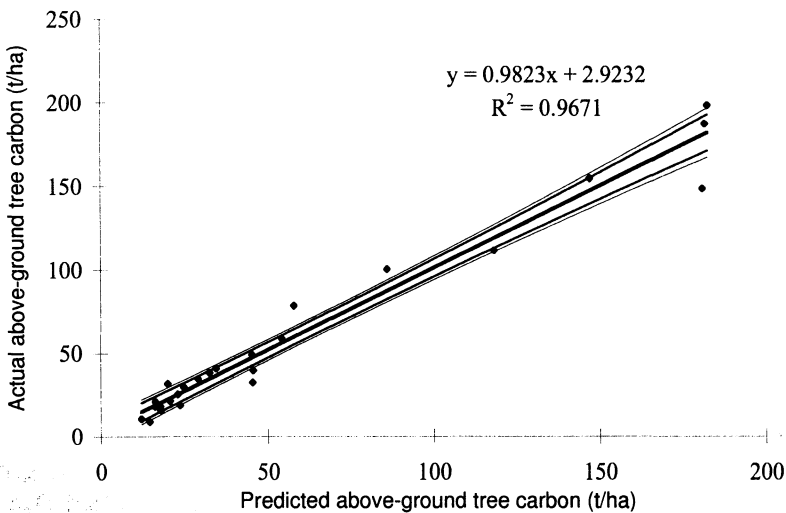


FIG. 7–Actual and predicted stand above-ground tree carbon for all validation sites.

Shrub biomass data from two *P. radiata* stands were used to assess the validity of this component of the model (Table 4). However insufficient validation data were available to test the shrub component adequately.

TABLE 4–Actual and predicted understorey carbon.

| Site | Actual carbon (t/ha) | Predicted carbon (t/ha) |
|---|---|---|
| Kaingaroa | 2.4 | 4.5 |
| Ngaumu | 4.6 | 3.5 |

# DISCUSSION
## Performance of the Model

C_change is a user-friendly package that enables the calculation of above-ground *P. radiata* stand carbon rapidly and accurately. Stand information required as model inputs (e.g., stocking, timing and intensity of pruning or thinning operations, rotation age, extraction) is generally readily available to forest managers. However, in some instances modelling assumptions were made to keep data input requirements to a minimum.

In assessing the performance of C_change, as reflected by the graphs of actual *versus* predicted stand carbon content in above-ground tree components, three classes of factors were considered, including (1) accuracy of volume predictions from the Stand Growth module, (2) precision of the validation data, and (3) assumptions influencing the accuracy of the Growth Partitioning module. These factors are discussed in turn.

### Volume predictions from C_change

The Stand Growth module commenced at stand age 4 years, but the Growth Partitioning module requires stem volume data from the beginning of the rotation. To overcome this limitation, volume is linearly interpolated between ages 0 and 4 years for use by the Growth Partitioning module. The resulting predictions of crown carbon content at stand ages less than 4 years are likely to be over-estimates using this approach; however, the effect of this limitation is likely to be small as only small amounts of carbon have accumulated by that age.

Between-tree differences in stem form factor are large, and a minimum of 20 trees is considered essential to estimate the mean form factor of a stand. The validation data sets typically comprised from five to 10 trees each, and deviations from the stand mean form factor of 20% and more can be expected; this would be evident as an increase in random error using C_change.

The effect of climate change on regional productivity is currently not incorporated into regional growth models. Gains in volume production owing to genetic improvement are addressed through the use of multipliers which are applied in C_change according to the level of genetic improvement. Direct effects of climate change (rainfall, elevated carbon dioxide) on stand productivity are likely to be small, except where moisture supply is currently inadequate for maximum growth, and plantation forests in New Zealand are located in areas where rainfall is not limiting. The possible effects of factors such as the incidence and

severity of diseases and catastrophic events (storms, fire) on productivity are not predictable. Continued monitoring of permanent sample plots in conjunction with updating of growth models would seem essential.

### Precision of the biomass validation data

The stand actual carbon content data used to test C_change predictions are estimates obtained using biomass methods. Biomass measurement procedures vary greatly from study to study, with errors of estimation depending both on the number of sample trees used and on tree size. The estimates of stand carbon content included in this validation exercise were based on biomass studies with from five to 10 sample trees per study (Table 2), and trees ranging in size from less than 10 cm to over 90 cm dbh, depending on stand age and tree stocking. The errors associated with biomass estimates have been studied elsewhere. For example, in an 8-year-old stand studied by Ovington *et al.* (1967), individual crown components (foliage, live branches, dead branches) were found to be poorly estimated, with errors of estimation ranging from –42% to 23% when five or 10 biomass trees were used. Consequently, the carbon output file reports the combined weight of components (foliage, live and dead branches, and reproductive parts), as some compensation of random errors among crown components can be expected to occur. Large trees are normally subsampled for logistical reasons, with only four branches taken per sample tree in the study of Beets & Madgwick (1988). In other studies, full-crown weighing was used. The inclusion of many studies was therefore considered to be essential for this validation exercise, and the slope of the relationship between actual and predicted total above-ground carbon is of primary interest for carbon accounting purposes.

### Error estimates

The mean error of C_change predictions was obtained by calculating confidence limits on the regression line relating actual above-ground tree carbon (in tonnes per hectare) to the predictions from the C_change model (confidence limits in Fig. 7 are 95% and 99%). These confidence limits include measurement error associated with the actual biomass data, and so will over-estimate the limits within which the true mean stand carbon will lie. This regression indicates that the C_change predictions are within 5% of the actual mean value (using 95% CI), except when the predicted carbon is low. For example, when the carbon prediction is only 50 t C/ha, the confidence interval for actual mean carbon is 47.6 to 56.4 t C/ha, or –14% to +5%.

### Calibrating the model for other species

Although C_change was parameterised using data for *P. radiata* in New Zealand, it may be possible to adjust predictions for other species. Representative stand data of total carbon would be obtained, and related to C_change predictions using a regression equation similar to that in Fig. 7. The C_change model predictions could then be corrected to allow for species differences. The resulting correction procedure would only require estimates of total carbon, without requiring more complex data collection procedures which would be needed for full reparameterisation of C_change. This approach may also be advisable if C_change is applied to *P. radiata* in countries where climatic conditions are markedly different from those in New Zealand.

*C_change model assumptions*

   To keep data input requirements for running the model to a minimum, some simplifying assumptions were made, which influence the accuracy of the carbon predictions.

(1) Partitioning to branches *versus* stems varies in relation to nitrogen supply, and inclusion of this fertility effect will improve the accuracy of the model. However, the model predictions at a site with moderately low nitrogen status (Woodhill) were only 5% less than measured. In terms of carbon accounting, the accuracy to be gained by improving this aspect of the model, needs to be balanced against the additional requirement for site fertility information. Planned improvements to the modelling system relate to broader issues of sustainability.

(2) Needle retention is known to vary both spatially and temporally, depending on genotype, soil fertility, and climate (Madgwick 1994). Regional differences in retention may prove to be important for carbon accounting purposes in the future, particularly when predictions of forest floor carbon content are being tested. At this stage, the assumption that retention of 1-year-old needles for a second year is 70% does not appear to be particularly important, because needles contain a relatively small proportion of crown carbon.

(3) Dead branches are poorly estimated in most biomass studies, particularly in mature stands where dead matter will have accumulated to the greatest extent. Improved biomass measurement procedures will be required before this aspect can be much improved. In this validation exercise, the stands were intensively managed, and branch mortality was less important than it would be in stands receiving minimum tending.

(4) Partitioning in relation to moisture supply has not been studied closely, and inclusion of moisture effects will probably improve the accuracy of the model. The model predictions at the dryland site (Eyrewell) differed from measured values by 10%, suggesting that improvements to the modelling system with respect to moisture supply are warranted.

## Limitations Owing to Lack of Validation Data

   In addition to carbon in live trees, the Growth Partitioning module predicts carbon in roots, forest floor, and understorey shrubs. Few suitable data sets were available to test fine root predictions; however, this is considered to be a minor limitation as fine roots represent a small fraction of stand total carbon content in *P. radiata* (Santantonio & Santantonio 1987b).

   Shrub biomass in production forests is highly dependent on site and stand management. In New Zealand plantations the contribution by shrubs is usually small (less than 2%), and can be ignored in terms of carbon accounting purposes, though it may be important in some situations elsewhere.

   The forest floor carbon pool is large and expected to be predictable. Two comprehensive national data sets exist for testing forest floor carbon predictions for New Zealand. One deals with decomposition rates in relation to site factors, and the other is a survey of forest floor weights at characterised sites. Both data sets cover a range of sites and silviculture regimes. Results of this testing will be reported when a suitable system has been developed for including the effects of site on component decomposition rates.

## Future Directions

The model parameters in C_change are based on *P. radiata*, but the modelling concept can be applied to other species if suitable mensuration growth models and biomass and growth partitioning data sets are available for other species. Alternatively, simple regression equations using stand total carbon could be developed to correct C_change predictions, possibly facilitating carbon sequestration calculations in other species.

Systems for monitoring soil carbon on a regional basis in New Zealand are currently being developed; however, soil carbon could be included as a component of the Growth Partitioning model, by representing the incorporation of forest floor and fine root dry matter into the soil. Although fine roots comprise only a small proportion of the stand total carbon content, they represent an important input to the mineral soil organic matter pool, and influence the soil carbon content. Our ability to predict the productivity of *P. radiata* stands from environmental factors, and to simulate the effectiveness of nitrogen fertilisers, depends on being able to forecast changes in the forest floor carbon and nitrogen pools and the surface soil carbon/ nitrogen balance both within and between each harvesting cycle.

## REFERENCES

BEETS, P.N. 1982: Modelling dry matter content of a managed stand of *Pinus radiata* in New Zealand. Ph.D. thesis, University of Georgia, Athens.

BEETS, P.N.; BROWNLIE, R.K. 1987: Puruki experimental catchment: site, climate, forest management and research. *New Zealand Journal of Forestry Science 17(2/3)*: 137–160.

BEETS, P.N.; MADGWICK, H. A. I. 1988: Above-ground dry matter and nutrient content of *Pinus radiata* as affected by lupin, fertiliser, thinning, and stand age. *New Zealand Journal of Forestry Science 18*: 43–64.

BEETS, P.N.; POLLOCK, D. S. 1987: Accumulation and partitioning of dry matter in *Pinus radiata* as related to stand age and thinning. *New Zealand Journal of Forestry Science 17*: 246–271.

BEETS, P.N.; WHITEHEAD, D. 1996: Carbon partitioning in *Pinus radiata* stands in relation to foliage nitrogen status. *Tree Physiology 16*: 131–138.

COWN, D.J.; McCONCHIE, D.L.; YOUNG, G.D. 1991: Radiata pine wood properties survey. *New Zealand Forest Research Institute, FRI Bulletin No. 50*. rev. ed.

DYCK, W.J.; HODGKISS, P.D.; OLIVER, G.R.; MEES, C.A. 1991: Harvesting sand-dune forests: impacts on second rotation productivity. Pp. 163–176 *in* Dyck,W.J.; Mees,C.A. (Ed.) "Long Term Field Trials to Assess Environmental Impacts of Harvesting". Proceedings IEA/BE T6/ A6 workshop, Florida, USA, February 1990. IEA/BE T6/A6 Report No. 5. *New Zealand Forest Research Institute, FRI Bulletin No. 161*.

FANG, S.Z.; LOWE, A.T.; SMITH, C.T.; BEETS, P.N.: Biomass and nutrient accumulation in second-rotation *Pinus radiata* after harvest residue management and fertiliser treatment of Tarawera gravel (in prep. a)

————: Biomass, productivity, and nutrient accumulation of *Pinus radiata* following harvest disturbance and fertiliser treatment of Taupo sandy loam (in prep. b)

LANDSBERG, J.J.; WARING, R.H. 1997: A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology and Management 95*: 209–228.

MADGWICK, H.A.I. 1985: Dry matter and nutrient relationships in stands of *Pinus radiata*. *New Zealand Journal of Forestry Science 15*: 324–346.

————1994: "Pinus *radiata*—Biomass, Form and Growth". H.A.I.Madgwick, Rotorua, New Zealand. 428 p.

MADGWICK, H.A.I.; JACKSON, D.S.; KNIGHT, P.J. 1977: Above-ground dry matter, energy, and nutrient contents of trees in an age series of *Pinus radiata* plantations. *New Zealand Journal of Forestry Science 7*: 445–468.

MATTHEWS, G. 1993: The carbon content of trees. *Forestry Commission, Edinburgh, Forestry Commission Technical Paper 4*. 9 p.

MEAD, D.J.; DRAPER, D.; MADGWICK, H.A.I. 1984: Dry matter production of a young stand of *Pinus radiata*: Some effects of nitrogen fertiliser and thinning. *New Zealand Journal of Forestry Science 14(1)*: 97–108.

OVINGTON, J.D.; FORREST, W.G.; ARMSTRONG, J.E. 1967: Tree biomass estimation. Pp. 3–31 in Young, H.E. (Ed.) "Symposium on Primary Productivity and Mineral Cycling in Natural Ecosystems". University of Maine Press, Orono, Maine.

ROBERTSON, K. 1998: Loss of organic matter and carbon during slash burns in New Zealand exotic forests. *New Zealand Journal of Forestry Science 28(2)*: 221–228.

SANTANTONIO, D.; SANTANTONIO, E. 1987a: Effect of thinning on production and mortality of fine roots in a *Pinus radiata* plantation on a fertile site in New Zealand. *Canadian Journal of Forest Research 17*: 919–928.

——1987b: Seasonal changes in standing crops of live and dead fine roots during two successive years in a thinned plantation of *Pinus radiata* in New Zealand. *New Zealand Journal of Forestry Science 17(2/3)*: 315–328.

SMITH, C.T.; DYCK, W.J.; BEETS, P.N.; HODGKISS, A.T.; LOWE, A.T. 1994: Nutrition and productivity of *Pinus radiata* following harvest disturbance and fertilisation of coastal sand dunes. *Forest Ecology and Management 66*: 5–38.

SMITH, C.T.; LOWE, A.T.; SKINNER, M.F.; BEETS, P.N.; SCHOENHOLTZ, S.H.; FANG, S.: Response of radiata pine forests to residue management and fertilisation across a fertility gradient in New Zealand (in prep.)

WEBBER, B.; MADGWICK, H.A.I. 1983: Biomass and nutrient content of a 29-year-old *Pinus radiata* stand. *New Zealand Journal of Forestry Science 13(2)*: 222–228.

WEST, G.G. 1993: A review of the development and use of the New Zealand stand modelling system: STANDPAK. International symposium on "System Analysis and Management Decisions in Forestry", Valdivia, Chile, March. 8 p.

WEST, G.G.; KNOWLES, R.L.; KOEHLER, A.R. 1982: Model to predict the effects of pruning and early thinning on the growth of radiata pine. *New Zealand Forest Service, FRI Bulletin No. 5*.

WHITESIDE, I.D. 1990: STANDPAK stand modelling system for radiata pine. Pp. 106–111 in James, R.N.; Tarlton, G.L. (Ed.) "New Approaches to Spacing and Thinning in Plantation Forestry". Proceedings of a IUFRO symposium, 10–14 April 1989, Forest Research Institute, Rotorua. *New Zealand Ministry of Forestry, FRI Bulletin No. 151*.

WILL, G. M.; HODGKISS, P. D.; MADGWICK, H. A. I. 1983: Nutrient losses from litterbags containing *Pinus radiata* litter: Influences of thinning, clear felling, and urea fertiliser. *New Zealand Journal of Forestry Science 13*: 266–304.