Above- and below-ground carbon in *Eucalyptus fastigata* in the central North Island of New Zealand

MAF Technical Paper No: 2011/44

Full report prepared for Ministry of Agriculture and Forestry
By Scion
October 2009

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ISSN 2230-2794 (online)
ISBN 978-0-478-38414-7 (online)

June 2011

Ministry of Agriculture and Forestry
Te Manatū Ahuwhenua, Ngāherehere

BIOSECURITY NEW ZEALAND

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CLIENT REPORT (Confidential)

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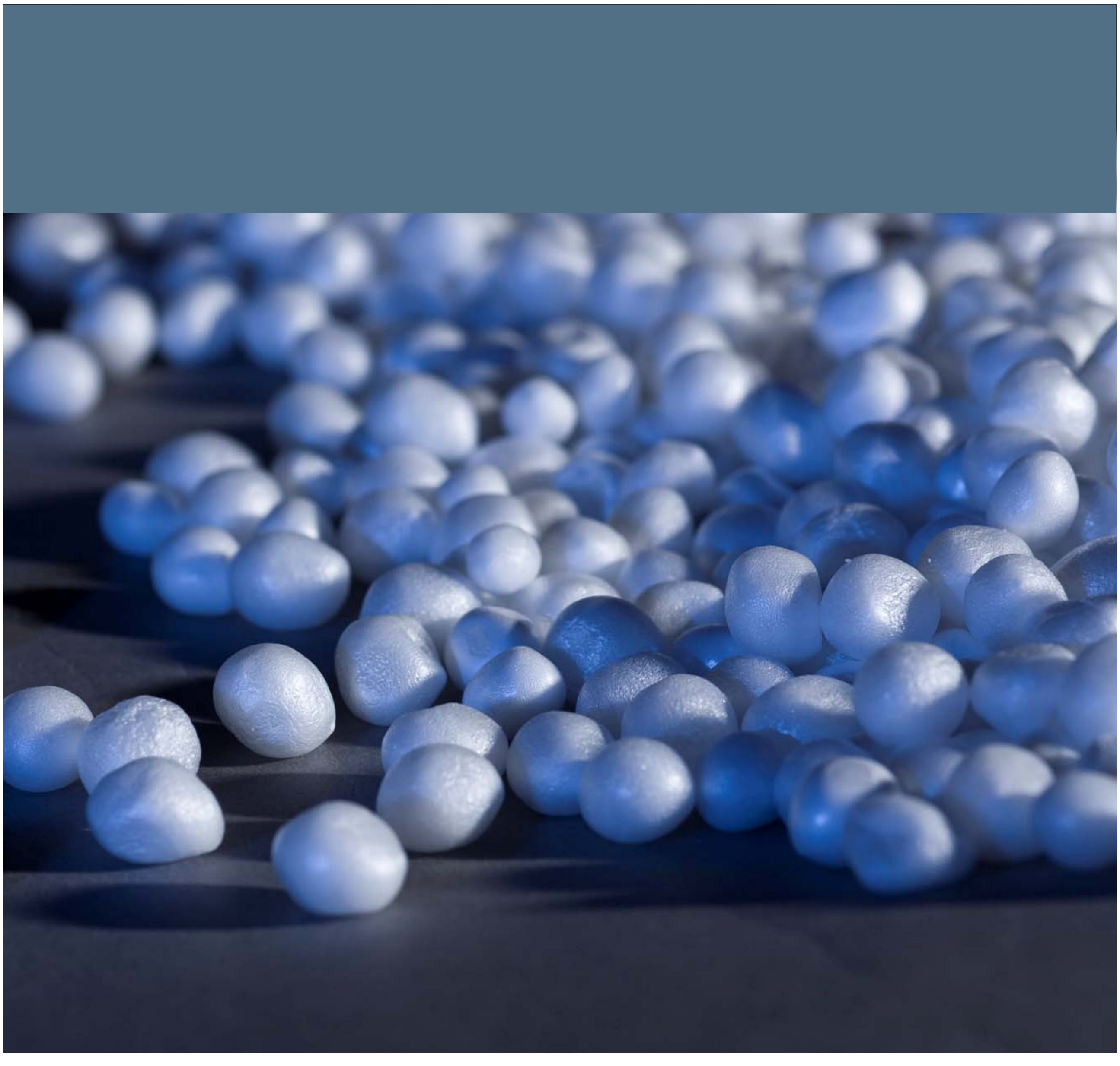

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REPORT TITLE	ABOVE- AND BELOW-GROUND CARBON IN EUCALYPTUS FASTIGATA IN THE CENTRAL NORTH ISLAND OF NEW ZEALAND
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CLIENT	MAF
CLIENT CONTRACT NO:	
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EXECUTIVE SUMMARY

The problem
Knowledge of tree carbon stocks in New Zealand's exotic forests for species other than *Pinus radiata* and Douglas fir is required under our obligations to the Kyoto Protocol consistent with IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (IPCC 2003).

There is very little biomass data available for stands of *Eucalyptus fastigata* for the development of robust nationally representative carbon growth models and wood density functions. Information is especially limited for below-ground biomass for any *eucalyptus* species in New Zealand.

Client Initiatives
The primary objective of this work was to gather new above-and below-ground biomass and wood density data for *E. fastigata* for carbon model development. The biomass work described in this report was done in conjunction with a survey of wood density and soil nitrogen fertility undertaken in *E. fastigata* trials of various ages throughout New Zealand. The entire data set will be used to develop a national carbon growth model for *E. fastigata* in New Zealand.

This project
New above- and below-ground biomass data were obtained from an 8-year-old *E. fastigata* stand planted on an improved pasture site at Kapenga near Rotorua in addition to above-ground biomass in a contrasting 30-year-old *E. fastigata* stand planted in a Nelder trial in Kaingaroa forest near Murupara. Both stands are growing on pumice soils formed on ash showers from various volcanic centres. The results can be summarised as follows:

- The first rotation *E. fastigata* plantation at Kapenga on an improved ex-pasture site accumulated 127 and 20.5 t/ha of above- and below-ground dry matter respectively over 8 years with stemwood plus bark comprising 73% of the above-ground total.
- A 30-year-old *E. fastigata* Nelder trial at Kaingaroa accumulated 218 t/ha of above-ground biomass with 93% found in stemwood plus bark and only 1% in foliage.
- Rate of above-ground carbon accumulation in the vigorous young stand at Kapenga averaged 7.9 t/ha/yr, more than twice the mean rate (3.6 t/ha/yr) of carbon accumulation of above-ground trees in the Kaingaroa Nelder.
- Above- and below-ground carbon accumulation at Kapenga totalled 73.6 t/ha.
- Root/shoot ratio in the young *E. fastigata* at Kapenga was estimated to be 0.16 on a stand area basis and was consistent across individual trees, ranging from 0.14 to 0.16. Shoot weight of *E. fastigata* at Kapenga explained 98% of the variation in root weight.
- Outerwood basic density at Kapenga and the Kaingaroa Nelder was 430 kg/m^3 and 491 kg/m^3 respectively.
- Soil C/N ratios reflect the difference in nitrogen fertility status of an improved ex-farm site at Kapenga (12.4) compared to the low fertility of a forest site in the Kaingaroa Nelder (25.7).

Implications of Results for Client
- The above- and below-ground biomass partitioning data collected here is the most robust information currently available for *E. fastigata* in New Zealand.
- The below- and above-ground biomass accumulation results have been used to parameterise a new carbon web tool for *E. fastigata* in New Zealand, enabling robust carbon sequestration rates to be estimated.

- Carbon sequestration rate information will be able to be utilised by MAF and by investment companies to assess the relative potential of this species for carbon farming on a range of sites.
- Biomass accumulation measured in this study of *E. fastigata* was below the published rates for *E. regnans* and similar to *E. saligna* in the central North Island. Further refinement of the *E. fastigata* carbon model would require more data for the mid-rotation age ranges similar to published data for *E. regnans*

Above- and below-ground carbon in *Eucalyptus fastigata* in the Central North Island of New Zealand

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Scion

OCTOBER 2009

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Introduction

Knowledge of tree carbon stocks in New Zealand's exotic forests for species other than *Pinus radiata* and Douglas fir is required under our obligations to the Kyoto Protocol consistent with IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (IPCC 2003).

An initial attempt has been made on modelling above-ground biomass of hardwood species in New Zealand with DRYMAT, using data from 23 stands, the majority of them eucalypts from the central North Island (Beets and Oliver 2007). An alternative approach using the 300 index growth model and C_Change model (Beets et al. 1999) has been recommended by Beets and Oliver (2007).

The ash group of eucalypts including *Eucalyptus fastigata* Deane & Maiden and *E. regnans* F. Muell. have long been an important, albeit minor, hardwood resource in the New Zealand forest industry either as farm woodlots or industrial plantations. *E. fastigata* was planted widely in the North Island south of Waikato in the first half of the 20th century (Clifton 1990) although the largest single resource was *E. regnans* planted for pulpwood (Haslett 1988). There is renewed interest in growing *E. fastigata* for both short fibre and sawlog production (Berrill and Hay 2005) due to its relatively stable wood properties, (after appropriate drying techniques) (Haslett 1988), its attractive pale brown timber and apparent lack of health problems. A growth and yield model has been developed for *E. fastigata* which gives an indication of potential volume growth depending on age, site index and stocking (Berrill and Hay 2005).

There is very little biomass data available for stands of *E. fastigata* for the development of robust nationally representative carbon growth models and wood density functions, and information is especially limited for below-ground biomass for any eucalyptus species in New Zealand. While above-ground biomass methods are well established and follow standard procedures (Oliver et al. 2009), below-ground biomass measurements are relatively scarce and protocols are often developed for specific tasks and locations depending on the site and soil texture (Beets et al. 2007a).

Above-ground biomass has been measured in a highly stocked (7250 live stems/ha) 4-year-old stand of *E. fastigata* in Rotoehu forest in the Bay of Plenty central North Island (Madgwick et al. 1981) which could simulate a plantation established for carbon sequestration or fuelwood production.

This report presents new biomass and wood density data for two *E. fastigata* stands in the central North Island which are expected to vary in site fertility and are widely different in age and stocking.

In conjunction with the biomass work described in this report, surface soil samples and outerwood density cores were also collected to examine the relationship of site fertility to wood density. In the central North Island, post-1989 plantings of *E. fastigata* have included ex-pasture sites which would be expected to have a fertiliser history and therefore enhanced nitrogen status compared to typical forest sites. Elevated foliar and soil nitrogen levels have been shown to produce a reduction in wood density in *P.radiata* (Beets et al. 2001) and Douglas fir (Brix 1993).

New above- and below-ground biomass data were obtained from an 8-year-old *E. fastigata* stand planted on an improved pasture site at Kapenga near Rotorua in addition to above-ground biomass in a 30-year-old stand planted in a Nelder trial in Kaingaroa forest near Murupara. Both stands are growing on pumice soils formed on ash showers from various volcanic centres.

The primary objective of this work was to gather new biomass and wood density data for carbon model development of *E. fastigata* stands which will improve predictions of above- and below-ground carbon stocks for hardwood species in New Zealand plantation forests.

Materials and Methods

SITE DESCRIPTION

Kapenga

The study site is located on a uniform slope with a slight easterly aspect about 8 km to the southwest of Rotorua (Latitude 38° 13' S, Longitude 176° 13' E) at an elevation of 370 m on the eastern edge of an 8-year-old *E. fastigata/E. nitens* plantation owned by Hardwood Management Ltd.

Climate at Kapenga is cool and generally sunny. Rotorua airport (16 km to the north east of Kapenga and 287 m elevation) has mean annual rainfall, temperature and sunshine of 1491 mm, 12.7° C, and 2151 hrs respectively (NZ Meteorological service 1983, 1984, 1984a). Ground frosts are reasonably common in winter and occur on average 57 days per year (NZ Meteorological service 1983a).

Topography of the Kapenga *E. fastigata* block is rolling with mainly gentle slopes. The area is mapped as a combination of Haparangi hill soils plus Ngakuru hill soils (S-map; www.landcareresearch.co.nz/databases/smap.asp) which are well drained soils, formed from volcanic ash showers and described in the New Zealand soil classification system as Vitric Orthic Allophanic and Typic Orthic Allophanic Soils respectively (Hewitt 1998).

Kaingaroa Nelder

The study site is part of a 30-year-old *E. fastigata* Nelder trial located about 4 km west of Murupara in Kaingaroa forest (Latitude 38° 27.6' S, Longitude 176° 39.9' E) (Google Earth 2009, confirmed with Garmin GPS60CSX) at an elevation of 280 m. Topography of this area is a lower altitude slope of the Kaingaroa plateau with a slight easterly aspect. Although the complete Nelder trial is a circular plot encompassing a slight gulley running to the north-east the average slope in an east-west direction across the study area is close to zero.

Climate of the Nelder trial area is probably slightly cooler and cloudier than Kapenga. At Murupara with 198 m elevation, mean annual temperature, rainfall and days of frost are 12.7°, 1338 mm and 75 respectively (NZ Meteorological service 1983, 1983a, 1984).

Soils at the trial site are mapped as Pekepeke sand (S-map), a well drained strongly leached yellow-brown pumice soil (Rijske 1988), described in the New Zealand soil classification system as an Immature Orthic Pumice Soil (Hewitt 1998).

STAND AND PLOT DESCRIPTIONS

Kapenga

The *E. fastigata* block containing the biomass stand was planted in 2001 on low cultivated mounds in improved pasture with bare rooted seedlings at nominally 1100 stems/ha with distance between and along rows approximately 4.5 m and 2 m respectively. Land preparation included aerial desiccation and roller crushing of weeds with a combination of spot and ripper mounding followed by pre- and post-plant weed control and fertiliser application (72 kg/ha urea in year 1 and 108 kg/ha of DAP in year 2 (Osbourne 2003).

Grazing by sheep has controlled grass growth but patches of gorse, low ferns and other weeds are present.

In May 2009 a 20 m by 18.9 m plot was established in a uniform area with 1° slope (NZMG coordinates E2792264, N6326389) and an area selected for biomass sampling about 50 m away, where trees were due to be felled for power line maintenance (Appendix 1 - Photograph).

Kaingaroa Nelder

The *E. fastigata* Nelder trial was planted in 1979 and comprised 15 arcs with 45 radial spokes of increasing tree spacing from centre outwards spanning stocking rates from 4444 stems/ha to 91 stems/ha. Biomass measurements were focused on arc 8 which had an initial stocking of 634 stems/ha (Appendix 2 - Photograph) but no plot was installed specifically for biomass sampling. An understorey of tree ferns and hardwood shrubs including mingimingi (*Cyathodes* spp.) and *Coprosma* spp. 4-6 m in height has developed under the eucalypts with patches of exotic weeds such as blackberry and gorse also present.

PLOT TREE MEASUREMENTS

Kapenga

Stems of all trees in the plot, live and dead, were measured for diameter at breast height (dbh) and total height (with a Vertex). Measurement of dbh of each stem of forked trees was summed as the quadratic mean to produce one stem diameter. Plot area was slope corrected and tree basal area and stocking were expressed on a horizontal area basis.

Kaingaroa Nelder

Measurements of heights and dbh had been previously made of all live and recent dead standing trees, in March 2009 ahead of a scheduled clear felling which was later postponed. In August 2009, dbh and total height (with a Vertex), of all live trees in arc 8 were remeasured to check whether this stand had grown since March and to confirm basal area at time of biomass measurement. Plot area was taken from the Scion Permanent Sample Plot (PSP) database.

ABOVE-GROUND BIOMASS PROCEDURES

Kapenga

In May 2009, eight trees were selected for biomass sampling in the area between the measured plot and the lane containing the power poles. The selected trees were representative of the diameter range in the plot and all had at least two immediate neighbours so were not influenced by the edge effect of the unplanted lane.

Biomass trees were felled at approximately 10 cm stump height and sampled by similar procedures to those outlined in Oliver et al. (2009) for biomass of Douglas-fir. Total height and over bark stem diameters at base (0.15 m), 0.7 m, 1.4 m, (dbh), and at 2 m intervals to the tip of the stem were measured for volume calculations, dividing the tree into 2 m zones.

Two representative live branches for estimating crown dry weight were taken from each zone, cut into short sections, weighed fresh, prior to oven-drying and further processing in the laboratory (Appendix 3 – photograph). One dead branch was collected from each zone where present and bulked (including any loose dead bark from branches and stem) to make one dead sample per tree for dry matter determination. The remaining crown was then removed, weighed fresh by separate zone (live) and all zones (dead) and discarded.

A 2.5 cm thick disc was then cut from the base and a 5 cm thick disc cut from each 2 m measurement point, for dry matter determination and bark to wood ratio. A 5 cm disc was also cut at 1.4 m height for basic density determination.

Kaingaroa Nelder

Biomass sampling in arc 8 was restricted to trees in spokes 17 to 37 (from a possible 45 trees) because half the Nelder may be retained for long term study.

Four biomass trees were selected from arc 8 spanning the live tree diameter range with the only restriction being that as far as possible there were neighbouring trees immediately adjacent to a biomass sample tree.

All trees were felled and sampled in August 2009 following the same procedures as for Kapenga trees except zone length was increased to 3 m to cater for the older and larger trees in the Nelder (Appendix 4 – Photograph).

BELOW-GROUND BIOMASS PROCEDURES AT KAPENGA

Of the eight above-ground biomass trees, five root systems were selected to study below-ground biomass. These included the trees of largest and smallest dbh and three of intermediate diameter. All five stumps were extracted in May 2009, with a three tonne excavator with bucket/digger attachment.

The soil structure at the Kapenga site meant that intact root systems could not be simply lifted free of the soil by loosening of major roots as might be expected in a pure sandy soil (Beets et al. 2007a).

The procedure for retrieving *E. fastigata* stumps and roots at Kapenga was based on the hypothesis that for any one biomass tree root out-growth may not equal root in-growth from immediate neighbours because of differing tree size. At Kapenga this applies more to trees along each row than across rows because of the relatively large inter-row distance. This means that extracting roots based on an equal soil volume for all trees is inaccurate for estimation of an individual tree root/shoot (R/S) ratio or implies a prohibitive amount of work to estimate a plot (area) based R/S ratio even by sampling a smaller sub-plot.

The extraction method employed was to dig out all visible eucalypt roots down to about 1.5 m depth around each stump until the excavator could lift the stump with remaining attached roots, free of the ground (Appendix 5 – Photograph). Although many roots were broken within a metre of the stump there were several more or less complete attached roots covering a range of root base diameters which tapered down to a small diameter (typically 1 cm) at the root break. These attached roots were later used as a guide to root structure and length when assembling sets of roots for biomass estimation. All visible broken roots were retrieved from the excavated soil around each stump including fine root pieces down to about 1 mm diameter.

Excavation of soil and roots of any one stump was limited to an area covering about half the distance to each neighbouring tree along rows and extended about 2-3 m on either side of the stump between rows.

Stumps were trimmed to ground level and root systems then transported to the laboratory for washing and assembly of root samples for further processing (Appendix 6 – Photograph).

OUTER WOOD BASIC DENSITY SURVEY

In the Kapenga plot 32 dominant or co-dominant live standing trees were sampled with one bark to pith wood density core taken from each at 1.4 m height.

In Arc 8 of the Kaingaroa Nelder eight 27 dominant or co-dominant live trees from the full 45 spokes, excluding those selected for biomass, were sampled at 1.4 m height with one bark to pith density core taken from each tree.

Cores from both plots were transported to the laboratory and refrigerated until basic density of the outer 5 cm was determined on each core using the maximum moisture content method (Smith, 1954).

SOIL SAMPLING

At Kapenga thirty 0 – 5 cm mineral soil cores were collected systematically over the whole plot with a Hoffer tube sampler from midway between each mounded row in apparently "undisturbed ground" and bulked to give one surface soil sample for C and N analysis.
At Kaingaroa twenty seven 0 – 5 cm mineral soil cores were collected systematically over the whole Nelder with a Hoffer tube sampler between approximately every 5th arc and every 5th spoke (Dean Meason pers. comm.) and bulked to give one surface soil sample for C and N analysis.

LABORATORY PROCEDURES

Above-ground biomass

Biomass crown samples from both sites were transported to the laboratory and placed in forced ventilation ovens at a temperature of 70° C until constant dry weight had been attained whereupon dead branch samples were weighed. All live leaf bearing branches were separated into leaves and live branch, redried and weighed.

Stem biomass discs were measured for diameter over bark (dob), diameter inside bark (dib) after bark removal, and length at 4 to 8 equidistant points around the disc perimeter, for calculation of disc volume. Disc wood and bark was then oven dried and weighed separately.

Basic density

A standard parallel sided radial strip was cut from bark to bark across each 1.4 m disc and basic density of the outer 5 cm and every successive 5 cm block towards the centre on each radius was determined by the water displacement and oven drying method (Clifton, 1994).

Further basic density determinations may be carried out on biomass discs which involves rehydrating and removal of a wedge which would be split into 5 cm blocks numbered from the outside and analysed as for the 1.4 m discs. This information would be combined with sheath volumes to calculate sheath dry matter increments. The alternative of measuring ring widths and density on plot increment cores by X-ray densitometric analysis was considered but detection of growth rings by densitometer analyses is known to be difficult in *E. fastigata*.

Below ground biomass

Extracted root systems from Kapenga were brushed clean of obvious soil contamination, washed and drained, photographed and weighed fresh. A complete census of attached roots was made for each system by numbering, measuring diameter at base (point of attachment to root stock or bole), and recording type as either tap or lateral prior to removal. Those roots which were more or less complete were stored for later study and oven drying while short broken roots were discarded. The root stock (free of any lateral or tap roots) was then reweighed fresh and cut into 2 pieces prior to oven drying to constant weight at 70 °C.

The fresh root pieces collected from the excavation of each root system were then used to assemble a set of representative sample roots for each tree based on the observed structure including taper and length of more or less complete tap roots and lateral roots that had been removed from each root stock (Appendix 7 – Photograph).

Each sample set of roots was then subdivided into diameter size classes of < 1cm, 1-5 cm, 5-10 cm and > 10 cm and washed free of any remaining soil prior to oven drying to constant weight at 70 °C. Six or 7 sample roots were assembled per tree (usually 5-6 lateral roots and 1 or 2 Tap roots).

Soil

The fine earth fraction (< 2 mm) of air-dried 0 – 5 cm soil samples was analysed for C and N with the LECO CNS 2000 thermal combustion furnace (Blakemore et al. 1987).

INDIVIDUAL TREE AND STAND DRY MATTER CALCULATION

Above-ground biomass

All biomass data were entered into spreadsheets which undertake data checks and calculate individual tree weights and stand dry matter by component using ratio methods. Individual stem dry weights were estimated by the standard method outlined in Oliver et al. (2009) and summarised below:

For each tree, the mean disc (wood plus bark) oven dry density was multiplied by total stem over bark volume to scale up to the total stem over bark (ob) dry weight. A similar calculation done with total stem inside bark (ib) volume and disc wood density gave total stem wood dry weight.

For each tree, crown component dry weights per zone were calculated from sample dry weight/fresh weight ratios multiplied by the zone total fresh weight. Zone dry weights of each component were summed to obtain tree crown component weights.

Stand component weights at each site were calculated by the basal area ratio method (Madgwick, 1981) by multiplying the sum of biomass component weight by the ratio of plot basal area/sum of biomass tree basal areas. Stand weight of stemwood at each site was adjusted by the ratio of survey tree/biomass tree breast height outerwood densities.

Below-ground biomass

Kapenga root stock oven dry weights were added to lateral and tap root dry weights estimated for each tree to obtain total root system dry weight per tree by the following method.

Assembled root biomass samples were oven dried and weighed by size class and summed to obtain total root dry weight. Multiple regression and ANOVA analysis was then used to test the relationship of individual assembled root dry weight to root base diameter and found the best predictor for both tap root and lateral root dry weight to be root base diameter squared.

Ratios of mean root dry weight/root base diameter squared for both tap roots and lateral roots were then derived for individual trees and applied to the census of base diameters of all roots on each sampled root system to predict total root dry weight by root type (tap or lateral) and % dry weight by size class for each tree.

A stand estimate of below-ground biomass was obtained by the basal area ratio method by multiplying sum of root dry weights for each size class by the ratio of plot basal area/sum of sample tree basal area.

ABOVE- AND BELOW-GROUND CARBON

Carbon was assumed to be 50% of dry weight and above- and below-ground stand dry matter was multiplied by 0.5 to obtain stand carbon values on a per hectare basis.

Results and Discussion

TREE GROWTH

Kapenga

Stocking of all live stems at 1.4 m and at ground level (GL) was 1270 and 820 stems/ha respectively, indicating about 50% of trees were multi-stems below breast height (Table 1). There were 79 dead stems/ha representing 6% of total stems and 2.5% of total basal area. Total live stem volume inside bark (ib) estimated from biomass tree data was 204 m^3/ha giving a mean annual volume increment (ib) of 25.5 m^3/ha. This was similar to an 8-year-old *E. saligna* stand with 820 stems/ha growing at Taheke in the Bay of Plenty (Frederick et al. 1985).

Table 1: Stand Characteristics of 8-year-old *E fastigata* at Kapenga.

		Live	Dead
Stocking (at 1.4 m)	stems/ha	1270	79
Stocking (at GL)	stems/ha	820	53
Basal area	m^2/ha	33.6	0.85
Mean dbh	cm	18.4	
Mean height	m	18.5	
Mean top height	m	20.4	
Ht to live crown*	m	11.4	
Volume (ib)*	m^3/ha	204	
Volume (ob)*	m^3/ha	249	
Whole stem wood density*	kg/m^3	425	
Outerwood BH Basic density	kg/m^3	430	

* data from biomass trees.

Mean annual increment (MAI) of diameter and height over 8 years was about 2.3 cm and 2.3 m respectively.

An 8-year-old *E. regnans* stand on volcanic soils near Mangakino, in the central North Island was similar in height but outgrew the Kapenga *E. fastigata* in basal area (39.1 m^2/ha) and volume (ib) (307 m^3/ha) due to the high stocking of 2150 stems/ha (Frederick et al. 1985b).

Kaingaroa Nelder

There were some large trees in Arc 8 of the Nelder which has a mean top height and mean dbh of 40 m and 37.6 cm respectively (Table 2). However the live stocking of 480 stems/ha is probably too high for many individuals to achieve 75 cm dbh in under 40 years (the target tree size in Haslett (1988).

Table 2: Stand Characteristics of 30-year-old *E. fastigata* in arc 8 of the Kaingaroa Nelder (data from Scion PSP database March 09 unless otherwise stated).

Live stocking (at 1.4 m)	stems/ha	480
Basal area	m2/ha	53.4
Mean dbh	cm	37.6
Mean height	m	35.3
Mean top height	m	40.0
Ht to live crown*	m	20.3
Volume (ib)*	m3/ha	352
Volume (ob)*	m3/ha	515
Whole stem wood density*	kg/m3	486
Outerwood BH Basic density	kg/m3	491

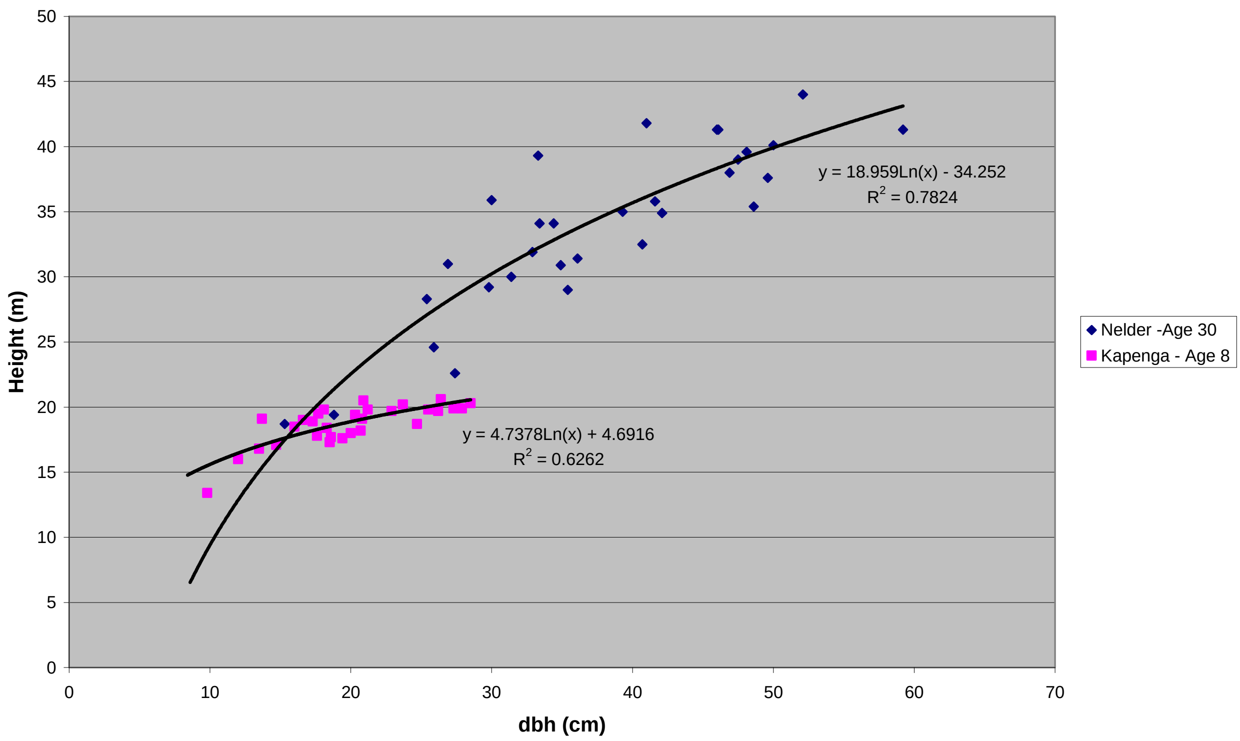
* data from biomass trees.

Total stem volume (ib) of the 30-year-old *E. fastigata* was 352 m^3/ha based on biomass tree measurements giving a MAI of 11.7 m^3/ha; about half the MAI of the young Kapenga stand.

The height–diameter relationship of both *E. fastigata* plots are shown in Figure 1. It appears that at Kapenga tree height varies little with dbh presumably because up to 8 years, the lack of competition from a low stocking of 820 planted stems/ha has resulted in minimal separation in height of small diameter stems from larger stems in spite of the multitude of stem forking.

Height-diameter data for arc 8 of the relatively mature Nelder at less than 500 stems/ha shows that height varies strongly with dbh.

Figure 1: Height–Diameter relationships for *E. fastigata* in the central North Island



ABOVE-GROUND BIOMASS

Kapenga

Individual tree above-ground dry weights are listed in Appendix 8 (calculated by tree component) and ranged from 65 to 265 kg/tree. The heaviest tree was forked at ground level but was considered to be representative of many trees in the stand.

Stand above-ground dry matter totalled 126.7 t/ha (Table 3) with 73 % of the total found in stemwood plus bark (92.6 t/ha), slightly less on both counts than for 8-year-old *E. saligna* at Taheke with a similar stocking (Frederick et al. 1985). Live and dead branch weighed 27.9 t/ha, and comprised 22% of total above-ground dry matter. Bark comprised 12% of total stem weight. Foliage weight of 6.2 t/ha was only 5% of total above-ground weight and is slightly more than found in 8 year-old *E. saligna* (Frederick et al. 1985).

Table 3: Stand above-ground biomass and partitioning into tree components in 8-year-old *E. fastigata* at Kapenga.

Component	OD Wt (tonnes/ha)	% Distribution
Foliage	6.2	5
Live Br	15.9	13
Dead Br	12.0	9
Stemwood[a]	81.5	64
Stembark	11.1	9
AG tree	126.7	100

[a] Adjusted by ratio of survey tree to biomass tree outerwood BH basic density.

Kaingaroa Nelder

Above-ground dry weights of individual trees in the Nelder varied from 140 to 461 kg (Appendix 9). Stand weight of foliage (Table 4) was 2.2 t/ha and comprised only 1% of total above-ground dry matter. The ratio of the Nelder foliage weight to foliage weight at Kapenga was closely aligned with live stocking at both sites. A very high proportion (93%) of the Nelder stand weight was found in stemwood plus bark, and crown components were therefore of minor importance. Bark comprised 16% of total stem weight, more than twice the proportion of bark weight on stems of 17 year-old *E. regnans* growing in Kinleith forest (Frederick et al. 1985a) reflecting the observed greater bark thickness on *E. fastigata* stems.

E. fastigata stemwood weights were only two thirds of 42-year-old *P. radiata* of similar height and diameter from Woodhill forest (Beets et al. 2007a) which is accounted for mainly by higher individual tree volume, but also slightly higher stemwood density in the *P. radiata*, the latter being attributed to the warm northern location of the pine stand.

Total above-ground dry matter of *E. fastigata* in the Nelder comprised less than half of the stand weight (460 t/ha) in the fast growing 17 year-old *E. regnans* stand due to the high stemwood volume (854 m^3/ha) and stocking (1250 stems/ha) in the *E. regnans* stand (Frederick et al. 1985a).

Table 4: Stand above-ground biomass and partitioning of 30-year-old *E. fastigata* in the Nelder at Kaingaroa.

Component	OD Wt (tonnes/ha)	% Distribution
Foliage	2.2	1
Live Br	8.1	4
Dead Br	3.4	2
Stemwood *	170.9	78
Stembark	33.5	15
AG tree	218.1	100

* Adjusted by ratio of survey tree to biomass tree outerwood BH basic density.

BELOW-GROUND BIOMASS AT KAPENGA

Individual root weight

The census of individual root base diameters, sample root weights and predicted oven-dry weights are shown for each stump in Appendix 10 along with the ratio estimators based on root base diameter squared. There were no significant differences in ratio estimators between trees or root type (tap - lateral) however individual ratios (Appendix 10) were applied to keep each tree independent.

Individual tree below-ground

Individual tree below-ground biomass by root size class are shown in Appendix 11. The estimated total below-ground biomass for individual trees varied from just under 10 kg to above 38 kg with 39-60% of total weight found in root stock.

The actual distribution between size classes up to 10 cm diameter will obviously reflect the method adopted to assemble sets of sample roots for biomass based on the observed structure (including taper and length) of attached roots remaining on extracted stumps. Although subjective observation is therefore inherent in the estimates of total root weight based on root diameters, the consistency of root/shoot ratios (Appendix 12) gives confidence in the method used to estimate below-ground biomass.

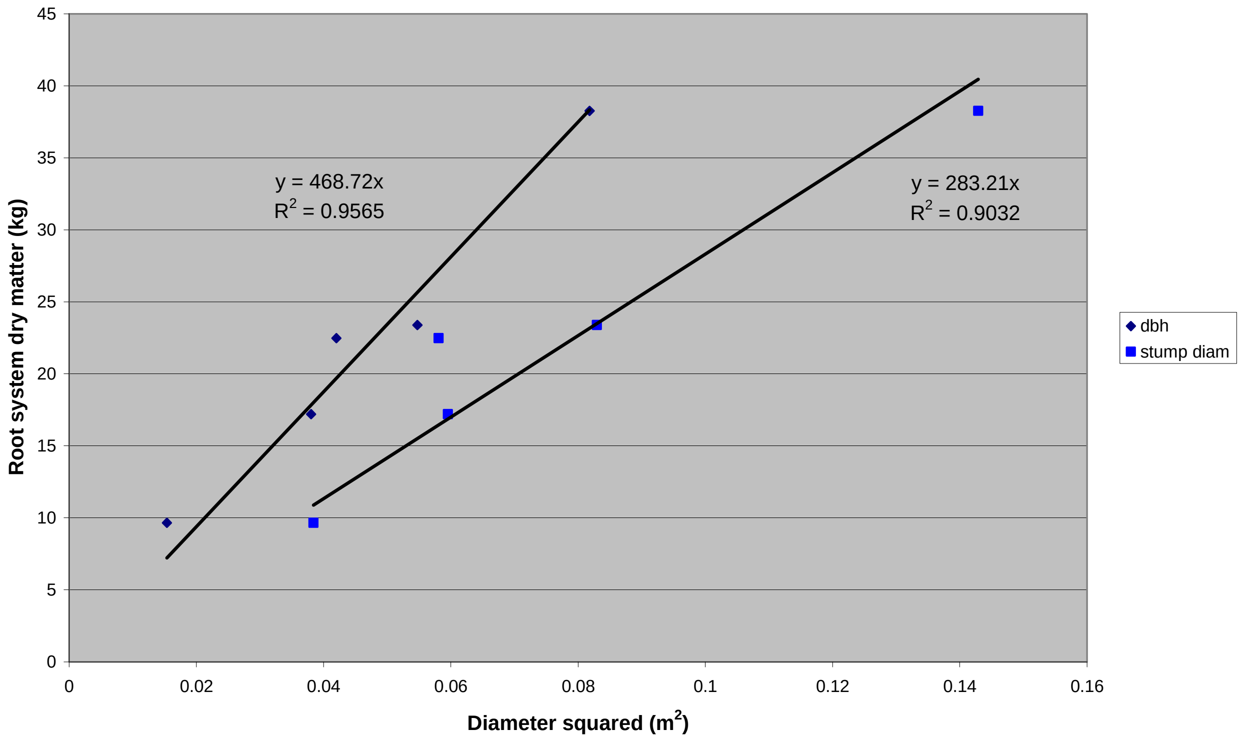
Root stock dry weight was obtained by direct weighing.

Below-ground stand weight

To estimate below-ground stand weight by the basal area ratio method (Madgwick 1981) a comparison was first made with individual stump below ground biomass regressed against both square of dbh and square of stump diameter (Figure 2). The coefficent of determination (R2 = 0.96) using dbh2 as the independent variable was superior to that using stump diameter2 presumably because of the error induced from basal flaring/irregularities at stump height (0.15 m). Both relationships were significant (P=0.01).

Interestingly the stump diameter which showed the most variance from the regression line was not from the large double stem biomass tree but was from a single stem with very little basal swelling, below which a substantial root system was retrieved.

Figure 2: Relationship of root system dry matter at Kapenga with tree dbh2 and stump diameter2 (regressions forced through zero).



On a stand basis, below-ground biomass totalled 20.5 t/ha (Table 5) with over 60% of dry matter found in roots above 10 cm diameter including the root stock. This is comparable to mean root biomass of 14.6 t/ha in Australian eucalypt plantations (average age 8-years) described in Snowden et al. (2000).

Table 5: Kapenga *E fastigata* below ground dry matter and partitioning.

Root Diameter class (cm)	<1	1-5	5-10	>10	Root stock	BG
DM (t/ha)	1.2	4.1	2.8	2.3	10.1	20.5
% distribution	5.9	20.1	13.5	11.2	49.3	100

Roots less than 1 cm diameter comprised less than 6% of the total below ground although this size class was likely to have been slightly underestimated because of the difficulty of retrieving fine roots without intensive sieving of large soil volumes. This is much less than the 16% root mass of the same fine size class Beets et al. (2007a) found below 5 year-old *P. radiata* growing in sand which also had a high proportion (64 %) of root biomass in root stock.

KAPENGA ROOT/SHOOT RATIO

Individual tree root/shoot ratio was quite consistent across the 5 measured trees (Appendix 12) with a range from 0.14 to 0.16.

Shoot weight explained over 98 % of the variation in root weight (regression not shown but significant at P=0.01), slightly better than the correlation for 5 year-old *P. radiata* (96 %) in the Whakarewarewa effluent trial (Beets et al. 2007a).

On a stand area basis the overall root/shoot ratio was 0.16 (Table 6) which appears to be similar to *Eucalyptus* plantation data (up to age 20 years) in Snowden et al. (2000) and slightly lower than the mean value of 0.19 for *P. radiata* over a range of New Zealand studies (Beets et al. 2007).

Table 6: Kapenga stand above- and below-ground carbon and root/shoot ratio.

Component	Carbon (t/ha)	% distribution
Above-ground	63.4	86
Below-ground	10.2	14
Stand AG+BG	73.6	100
Root/Shoot	0.16	

Carbon calculated as 50 % of dry weight.

CARBON ACCUMULATION AT KAPENGA AND KAINGAROA NELDER

Above-ground carbon in the 8-year-old *E. fastigata* at Kapenga was 63.4 t/ha (Table 6) giving a mean rate of carbon accumulation of 7.9 t/ha/year, more than twice the mean rate of above-ground carbon accumulation (3.6 t/ha/year) in 30-year-old *E. fastigata* in the Kaingaroa Nelder trial (Table 4), assuming carbon is 50% of dry weight.

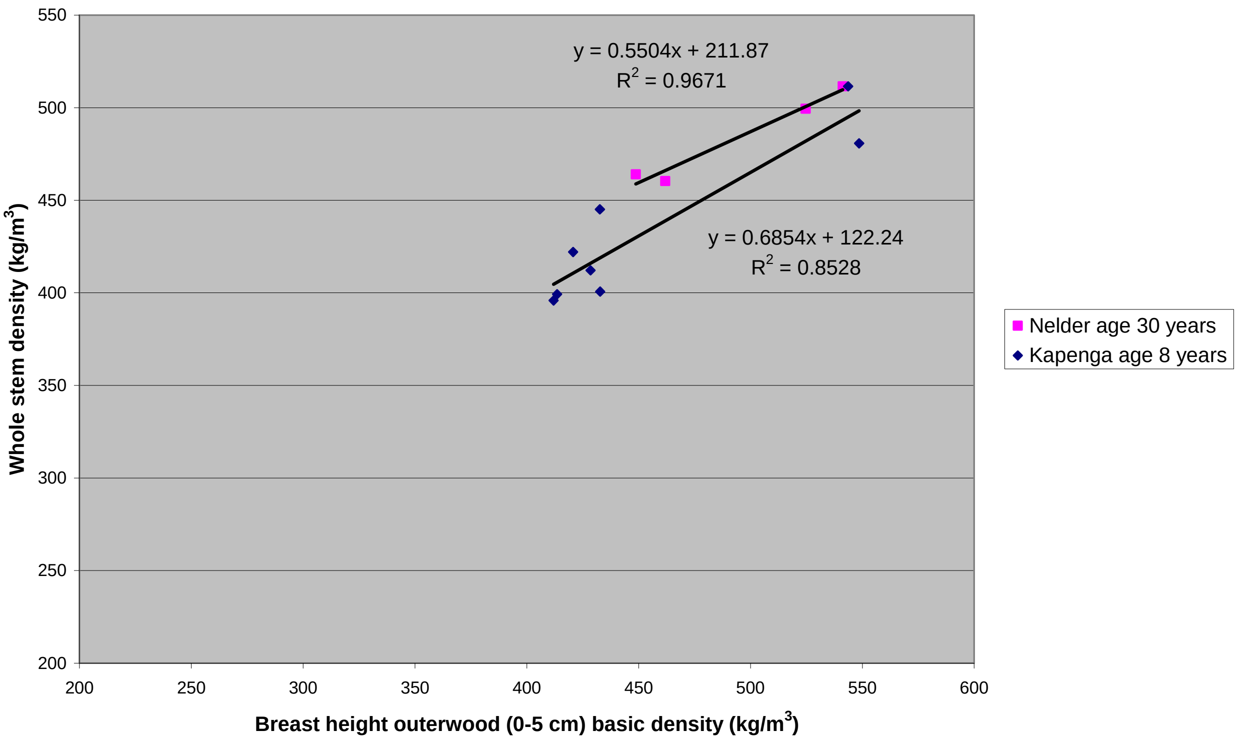
Total above and below-ground carbon at Kapenga amounted to 73.6 t/ha equating to an MAI of 9.2 t C/ha for complete trees (above and below ground).

STEMWOOD DENSITY

The relationship of whole stem density with breast height outerwood basic density for both *E. fastigata* sites are significant (P= 0.01) (Figure 3 shown with regressions and intercepts).

Mean basic density of outerwood in the Nelder trees of 491 kg/m^3 (Table 2) is about 14% higher than mean basic density of the young Kapenga trees and this difference is reflected in the whole stem densities (Table 1, Table 2). The extent to which outerwood density is affected by topsoil fertility differences between the 2 sites and tree age is unknown at this stage however a parallel study of integral analyses of soil and outerwood samples from a range of sites across New Zealand to develop a *fastigata* biomass model may provide this information.

Figure 3: Relationship of whole stem density with breast height outerwood basic density for 30-year-old *E. fastigata* in the Kaingaroa Nelder and 8-year-old *E. fastigata* at Kapenga.



If both regressions are forced through zero the ratio of whole stem density to outerwood basic density for *E. fastigata* in the Nelder and Kapenga is 0.98 and 0.95 respectively although the Nelder regression is a poor fit because of the small number of sample trees. The Kapenga ratio indicates that specific density (ob tape volume and OD weight at 70°C) of the whole stem of *E. fastigata* is less than outerwood basic density at breast height although individual disc data (not shown) shows the mid-top discs often have the highest density which is similar to the trend of basic density data of Frederick et al. (1982) for young *E. regnans* up to three quarters of stem height.

SOIL ANALYSIS

Analysis of C and N concentrations of the top 5 cm of soil at Kapenga is listed with C/N ratios for both sites (Table 7), with Kapenga C/N ratios adjusted and unadjusted for a base nitrogen fertility level of 0.014%.

Table 7: Carbon/nitrogen ratios of surface soil under *E. fastigata* stands at Kapenga and Kaingaroa.

Forest	Site	% C	% N	C/N	C/N (adjusted)
Kapenga	Plot	12.56	1.01	12.4	12.6
Kaingaroa	Nelder Arc 8			25.7	

C/N adj. = C/(N-0.014).

The Kapenga total N concentration and C/N ratios reflect the high fertility of an improved site converted from farmland to forest whereas the Kaingaroa Nelder C/N ratio is similar to the lower fertility of a *P.radiata* unimproved forest site (Beets et al. 2007).

Results

A first rotation *E. fastigata* plantation at Kapenga on an improved ex-pasture site accumulated 127 and 20.5 t/ha of above- and below-ground dry matter respectively over 8 years with stemwood plus bark comprising 73 % of the above-ground total.

A 30-year-old *E. fastigata* Nelder trial at Kaingaroa accumulated 218 t/ha of above-ground biomass with 93 % found in stemwood plus bark and only 1 % in foliage.

Rate of above-ground carbon accumulation in the vigorous young stand at Kapenga averaged 7.9 t/ha/yr, more than twice the mean rate (3.6 t/ha/yr) of carbon accumulation of above-ground trees in the Kaingaroa Nelder.

Above- and below-ground carbon accumulation at Kapenga totalled 73.6 t/ha.

Root/shoot ratio in the young *E. fastigata* at Kapenga was estimated to be 0.16 on a stand area basis and was consistent across individual trees, ranging from 0.14 to 0.16. Shoot weight of *E. fastigata* at Kapenga explained 98% of the variation in root weight.

Outerwood basic density at Kapenga and the Kaingaroa Nelder was 430 kg/m^3 and 491 kg/m^3 respectively.

The ratio of basic density to whole stem density of biomass trees at both sites averaged 0.96 indicating that whole stem wood density is less than breast height outerwood density of *E. fastigata*, similar to *P. radiata.*
Soil C/N ratios reflect the difference in nitrogen fertility status of an improved ex-farm at Kapenga compared to the low fertility of a forest site in the Kaingaroa Nelder.

Conclusions

- The above- and below-ground biomass partitioning data collected here is the most robust information currently available for *E. fastigata* in New Zealand.
- The below- and above-ground biomass accumulation results have been used to parameterise a new carbon web tool for *E. fastigata* in New Zealand, enabling robust carbon sequestration rates to be estimated.
- Carbon sequestration rate information will be able to be utilised by MAF and by investment companies to assess the relative potential of this species for carbon farming on a range of sites.
- Biomass accumulation measured in this study of *E. fastigata* was below the published rates for *E. regnans* and similar to *E. saligna* in the central North Island. Further refinement of the *E. fastigata* carbon model would require more data for the mid-rotation age ranges similar to published data for *E. regnans*

Acknowledgements

The Ministry of Agriculture and Forestry are acknowledged for providing funding for this research. The assistance of Ian Nicholas and the goodwill of Hardwood Management staff, for permitting us to measure the above- and below-ground biomass and excavate stumps in the Kapenga stand is appreciated. We thank Pat Hodgkiss for wood basic density measurements and the Veritec laboratory for soil analyses. The experience of Keith Mott with expertise on the excavator and the assistance of Kane Fleet with biomass work at Kapenga are also appreciated. We are grateful to Dean Meason for advice during the drafting of this report.

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Appendices

Appendix 1. Kapenga measurement plot showing ground vegetation and tree form.

Appendix 2. Kaingaroa Nelder arc 8 showing dominant tree and shrub understorey.

Appendix 3. Biomass sampling of *E. fastigata* live crown at Kapenga.

Appendix 4. Sampling *E. fastigata* stem discs (note thick bark) in the Kaingaroa Nelder.

Appendix 5. Lifting *E. fastigata* stump/root system free after excavation.

Appendix 6. *E. fastigata* extracted root system cleaned ready for weighing and measuring.

Appendix 7. Assembling sets of sample roots based on observed length and taper of roots attached to excavated root system.

Appendix 8. Kapenga 8-year-old *E. fastigata* biomass tree measurements and above-ground dry weights.

Appendix 9. Kaingaroa Nelder 30-year-old *E. fastigata* biomass tree measurements and above-ground dry weights.

Appendix 10. Root base diameters and predicted oven-dry weights with ratio estimators.

Appendix 11. Kapenga *E. fastigata* 8-year-old biomass tree below-ground dry weights.

Appendix 12. Kapenga *E. fastigata* above- and below-ground biomass (kg/tree) and root/shoot ratio.

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Appendix 8. Kapenga 8-year-old *E. fastigata* biomass tree measurements and above-ground dry weights.

	(cm)	(m)	(kg)					
tree no.	dbh	height	Stm wd	Stm bk	Dead br	Live br	Foliage	AG total
1	12.4	15.4	37.171	4.745	7.524	13.233	1.953	64.627
2	28.6	18.4	167.460	21.920	23.508	38.011	14.521	265.420
3	20.8	18.6	104.503	11.605	15.528	18.657	8.033	158.326
4	23.4	19.1	100.045	13.312	13.277	14.247	5.132	146.014
5	20.5	20.2	99.830	10.551	7.194	16.402	6.677	140.654
6	20.8	17.9	80.929	11.947	8.358	12.325	5.010	118.570
7	19.5	18.2	71.853	9.051	11.127	11.607	5.715	109.353
8	19.7	17.0	62.300	9.607	13.443	8.471	5.058	98.879

Appendix 9. Kaingaroa Nelder 30-year-old *E. fastigata* biomass tree measurements and above-ground dry weights.

Arc 8	(cm)	(m)	(kg)					
tree no.	dbh	height	Stm wd	Stm bk	Dead br	Live br	Foliage	AG total
20	25.9	24.2	102.104	26.595	3.874	5.705	1.564	139.842
26	35.9	31.3	353.232	59.333	3.849	19.833	4.505	440.751
30	29.4	28.8	208.789	45.405	1.546	5.121	1.756	262.617
31	35.1	32.3	358.351	68.639	11.102	17.630	5.435	461.157

Appendix 10. Kapenga *E. fastigata* root base diameters and predicted oven-dry weights with ratio estimators.

Tree	Root_type	Census of Base diam. (mm)	DM/D^2_ratio	Actual OD roots (g)	Predicted OD roots (g)
1	Lateral	50	0.1441		360.3
1	Lateral	10	0.1441		14.4
1	Lateral	8	0.1441	35.9	9.2
1	Lateral	16	0.1441		36.9
1	Lateral	7	0.1441		7.1
1	Lateral	8	0.1441		9.2
1	Lateral	17	0.1441		41.7
1	Lateral	5	0.1441		3.6
1	Lateral	10	0.1441		14.4
1	Lateral	15	0.1441		32.4
1	Lateral	17	0.1441		41.7
1	Lateral	18	0.1441		46.7
1	Lateral	66	0.1441	795.2	627.8
1	Lateral	29	0.1441	131.9	121.2
1	Lateral	82	0.1441	764.3	969.1
1	Tap	34	0.1328		153.5
1	Tap	39	0.1328		202.0
1	Tap	72	0.1328	664.9	688.4
1	Tap	57	0.1328	455	431.5
2	Lateral	46	0.1847		390.9
2	Lateral	25	0.1847		115.4
2	Lateral	45	0.1847		374.0
2	Lateral	23	0.1847		97.7
2	Lateral	58	0.1847		621.4
2	Lateral	44	0.1847		357.6
2	Lateral	76	0.1847		1066.9
2	Lateral	168	0.1847	5071.2	5213.4
2	Lateral	72	0.1847	1463.6	957.6
2	Lateral	26	0.1847	191.9	124.9
2	Lateral	78	0.1847	833.9	1123.8
2	Lateral	47	0.1847	267	408.0
2	Tap	90	0.1675		1356.6
2	Tap	99	0.1675		1641.4
2	Tap	167	0.1675	4498.5	4670.7
2	Tap	115	0.1675	2387.1	2214.9

Appendix 10. Cont**.**

Tree	Root_type	Census of Base diam. (mm)	DM/D^2_ratio	Actual OD roots (g)	Predicted OD roots (g)
4	Lateral	93	0.1354		1170.9
4	Lateral	70	0.1354		663.3
4	Lateral	39	0.1354		205.9
4	Lateral	140	0.1354		2653.4
4	Lateral	38	0.1354		195.5
4	Lateral	109	0.1354	1571	1608.4
4	Lateral	100	0.1354	1271	1353.8
4	Lateral	49	0.1354	408	325.0
4	Lateral	9	0.1354	23.4	11.0
4	Lateral	12	0.1354	26.7	19.5
4	Tap	128	0.1142	1871.3	1871.3
5	Lateral	37	0.1605		219.7
5	Lateral	156	0.1605		3905.0
5	Lateral	30	0.1605		144.4
5	Lateral	9	0.1605		13.0
5	Lateral	117	0.1605		2196.6
5	Lateral	101	0.1605		1636.9
5	Lateral	29	0.1605	97.1	134.9
5	Lateral	33	0.1605	283.3	174.7
5	Lateral	70	0.1605	954.6	786.3
5	Lateral	108	0.1605	1825.3	1871.6
5	Tap	83	0.1045	831.9	719.8
5	Tap	135	0.1045	1792.1	1904.2
7	Lateral	122	0.1233		1835.6
7	Lateral	80	0.1233		789.3
7	Lateral	50	0.1233		308.3
7	Lateral	65	0.1233	852.1	521.0
7	Lateral	102	0.1233	1055.8	1283.1
7	Lateral	60	0.1233	330.3	444.0
7	Lateral	29	0.1233	144.3	103.7
7	Lateral	57	0.1233	370	400.7
7	Tap	46	0.1272		269.1
7	Tap	19	0.1272		45.9
7	Tap	107	0.1272	1576.2	1455.9
7	Tap	64	0.1272	400.6	520.9

Appendix 11. Kapenga *E. fastigata* 8-year-old biomass tree below-ground dry weights.

Tree no.	Stump diameter at 0.15 m ht	Root diameter class (includes lateral and tap roots)					
		< 1 cm	1-5 cm	5-10 cm	> 10 cm	Root stock	BG total
	(cm)	(kg)					
1	19.6	0.445	1.484	1.011	0.871	5.841	9.652
2	37.8	2.415	7.865	5.479	4.976	17.530	38.265
4	28.8	1.182	4.154	2.696	2.046	13.315	23.393
5	24.1	1.607	5.642	3.665	2.793	8.767	22.474
7	24.4	0.933	3.197	2.125	1.723	9.220	17.197

Appendix 12. Kapenga *E. fastigata* above- and below-ground biomass (kg/tree) and root/shoot ratio.

Tree no.	Above-ground	Below-ground	Root/Shoot
1	64.627	9.652	0.149
2	265.420	38.265	0.144
4	146.014	23.393	0.160
5	140.654	22.474	0.160
7	109.353	17.197	0.157