SCION

New Zealand Journal of Forestry Science

42 (2012) 29-38

www.scionresearch.com/nzjfs

published on-line:
08/02/2012

Estimating carbon stocks in stands of *Podocarpus cunninghamii* in the eastern South Island high country of New Zealand

Alwyn Williams*,† and David A. Norton

Rural Ecology Research Group, School of Forestry, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand

†*Current address: Centre for Environmental and Climate Research, Lund University, Lund 223-50, Sweden*

(Received for publication 4 February 2011; accepted in revised form 19 January 2012)

*corresponding author: alwyn_williams@hotmail.co.uk

Abstract

The Land-Use, Land-Use Change and Forestry (LULUCF) sector of the Kyoto Protocol requires New Zealand to monitor changes in the country's carbon stocks, including those within indigenous forests. *Podocarpus cunninghamii* Colenso was, in pre-human times, a dominant tree species within the forests of the South Island high country. Anthropogenic disturbance, primarily fire, has converted most of these forests to grassland. Despite this mass deforestation, remnant stands of *Podocarpus cunninghamii* still exist, and may represent important point sinks of carbon. This study provides first estimates of existing above- and below-ground carbon stocks in high country stands of *Podocarpus cunninghamii* and presents a preliminary model of *Podocarpus cunninghamii* carbon sequestration rate. Carbon stocks within high country stands of *Podocarpus cunninghamii* range from 7.3 t ha^{-1} in the drylands to 130.1 t ha^{-1} in the wetter areas. Estimates based on tree ring widths indicate a high country-wide *Podocarpus cunninghamii* carbon sequestration rate of 0.1 – 0.5 t ha^{-1} yr^{-1} for 250 – 1000 stems ha^{-1}, respectively.

Keywords: Afforestation; carbon sequestration; carbon stocks; deforestation; high country; indigenous forest; Kyoto Protocol; New Zealand; South Island; totara.

Introduction

As part of the global effort to confront climate change numerous countries have committed to reducing their carbon emissions (United Nations Framework Convention on Climate Change UNFCC, 1998). The Land-Use, Land-Use Change and Forestry (LULUCF) sector of the Kyoto Protocol requires signatory countries, including New Zealand, to monitor changes in their carbon stocks (gains and losses), including both exotic plantation and indigenous forests. As a result, there is increasing interest in the quantity of carbon stored within New Zealand's indigenous forests, encompassing both new (restored and regenerating) and old growth forests (Carswell et al., 2008; Coomes et al., 2002).

Prior to human arrival, the eastern South Island high country was forested (McGlone, 1989; McWethy et al., 2010). Outside of the areas dominated by *Nothofagus*, *Podocarpus cunninghamii* Colenso (mountain or Hall's totara; also known as *Podocarpus hallii* Kirk) forest was the main forest type. Human activity, primarily burning (McWethy et al., 2010), has converted most of the pre-human cover of *Podocarpus cunninghamii* forest to grassland, however remnant forest stands still remain. These remnants provide vital habitat for the high country's indigenous biodiversity and offer valuable insight into the region's pre-human flora (Norton, 2006; Walker et al., 2009).

On a per-hectare basis, living carbon stocks within forests are substantially greater than grasslands

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)

(Tate et al., 1997), consequently remnant high country stands of *Podocarpus cunninghamii* may represent significant point sinks of carbon in comparison to adjacent induced grasslands; however, little is known of their carbon stocks. Collation of such information is necessary not only for inventories of existing carbon stocks, but also to appreciate the potential of restoration of this forest type to increase carbon stocks. However, current estimates are limited, being based on coarse-scale extrapolations (Coomes, et al., 2002; Tate, et al., 1997) or limited to a single stand (Kirschbaum et al., 2009). This paper provides some initial estimates of carbon stocks for *Podocarpus cunninghamii* growing as the dominant species in forest stands in the eastern South Island high country. Estimates were calculated based on living biomass and tree growth rate data for six sites across a west-east rainfall gradient.

Methods

Sites

Six South Island *Podocarpus cunninghamii* sites were included in this study. These sites were chosen because:

(1) they spanned the high country rainfall gradient that exists east of the Main Divide, and therefore provided samples from both very wet and very dry environments; and

(2) *Podocarpus cunninghamii* was the dominant tree species at each site.

A brief description of each site now follows; see Tables 1 and 2 for data on each site's climate and *Podocarpus cunninghamii* stand characteristics, respectively.

Birdwood Station

Part of the Diadem Range, this site lies on Birdwood Station, near Omarama, and overlooks both the Ahuriri River and State Highway 8 (44° 29' S, 169° 47' E). The *Podocarpus cunninghamii* dominated communities occur within shallow but steep rocky gullies. Where *Podocarpus cunninghamii* forms a canopy it is dense and other vascular plant species are rare; however the shrub community can be quite diverse within areas of thin canopy or light gaps. Species such as *Coprosma propinqua* A.Cunn., *Corokia cotoneaster* Raoul, *Aristotelia fruticosa* Hook.f. and the invasive *Rosa rubiginosa* L. are common. Scattered shrubs, often *Discaria toumatou* Raoul, are present in the pasture surrounding the stands and appear to have a positive association with the appearance of *Podocarpus cunninghamii* seedlings. Natural regeneration of *Podocarpus cunninghamii* and other native shrubs is evidence of the gaps between the stands slowly beginning to in-fill. This is in spite of ongoing sheep grazing on these faces.

Mount Ben Ohau

This site is located in Ruataniwha Conservation Park on the west facing slope of Mount Ben Ohau overlooking Lake Ohau (44° 15' S, 169° 53' E). The site is characterised by numerous rock fields, broken only by patches of grassland, shrub land or *Podocarpus cunninghamii* woodland. Despite the patchy nature of the vegetation, this site represents the largest population of *Podocarpus cunninghamii* in the Mackenzie Ecological Region (Espie et al., 1984). Where enough trees are present to form a canopy, *Podocarpus cunninghamii* is the only canopy tree. Canopy forming species such as *Griselinia littoralis* Raoul and *Sophora microphylla* Aiton are only represented by a few scattered individuals. The shrub component is diverse and often extremely dense. Common species include *Discaria toumatou, Coprosma propinqua, Corokia cotoneaster* and *Aristotelia fruticosa*. Given the openness of the vegetation, a diverse community of grassland plants is also present, including the native *Aciphylla aurea* W.R.B.Oliv. and the invasive exotic *Hieracium pilosella* L..

TABLE 1: Environmental data for each site. All figures, excluding rainfall, are annual means extracted from the Land Environments of New Zealand (LENZ) database, (Landcare Research, 2010). Rainfall figures are from Pascoe (1983) for Upper Hapuku and from Ryan (1987) for all other sites.

Site	Annual rainfall (mm)	Soil water deficit (mm)	Vapour pressure deficit (kPa)	Mean temperature (°C)	Minimum temperature (°C)	Solar radiation (MJ m^{-2} d^{-1})
Upper Hapuku	2000	0.00	0.50	8.09	-1.53	14.60
Upper Lawrence	1000 – 1500	0.00	0.44	8.00	-1.95	13.99
Mount Dobson	1000 – 1500	0.00	0.38	8.08	-2.30	13.40
Mount Cook	1500 – 2000	0.00	0.39	8.03	-2.30	13.85
Mount Ben Ohau	800 – 1000	30.13	0.43	8.20	-2.45	13.89
Birdwood Station	<600	98.73	0.43	8.15	-3.07	13.79

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)

TABLE 2: Stand characteristics of *Podocarpus cunninghamii* at the six study sites.

Site	Altitude (m)	Plot size (ha)	Stem density (stems ha^{-1})	Basal area (m^2 ha^{-1})	Average height (m)	Mean stand age (years ± 1 s.e.)
Upper Hapuku	850	0.20	250	35.29	9.90	156 ± 13
Upper Lawrence	850	0.20	250	44.65	12.25	287 ± 28
Mount Cook	800	0.40	125	6.17	6.97	109 ± 14
Mount Dobson	850	0.21	238	14.13	6.05	134 ± 11
Mount Ben Ohau	750	0.12	416	10.02	4.04	59 ± 3
Birdwood Station	700	0.05	1000	6.27	3.68	52 ± 2

Mount Dobson

The site is located approximately 10 km east of Lake Tekapo within the Te Kahui Kaupeka Conservation Park (formerly known as the Mount Dobson Conservation Area) at the southern end of the Two Thumb Range (43° 58' S, 170° 41' E). The stand is present on a steep gully face with rock outcrops at the top of the site. The canopy is dominated by *Podocarpus cunninghamii, Griselinia littoralis* and *Pseudopanax crassifolius* (Sol. ex A.Cunn.) C.Koch, with emerging *Podocarpus cunninghamii* also present. Trees and shrubs such as *Pseudopanax colensoi* var. *ternatus* Wardle*, Coprosma linariifolia* Hook.f. and *Coprosma propinqua* all occur frequently. The site lies within subalpine grassland and scrub, and extensive cutting of wilding conifers has taken place on adjacent land.

Tasman Valley

The site lies on the steep east facing slopes of the Mount Cook Range, at the end of the Tasman Valley Road overlooking Tasman Lake in Mount Cook National Park (43° 41' S, 170° 09' E). It is covered in dense forest grading into thick subalpine scrub at higher altitudes. *Podocarpus cunninghamii* is common within the canopy and as an emergent. The canopy itself is dominated by *Griselinia littoralis, Pseudopanax colensoi* var. *ternatus* and *Phyllocladus alpinus* Hook.f., with *Dracophyllum longifolium* (J.R.Forst et G.Forst.) R.Br. increasing in abundance higher up. Large specimens of *Podocarpus cunninghamii* are present throughout but are far from common. Most *Podocarpus cunninghamii* trees are 5 – 8 m tall.

Upper Lawrence Valley

Located in the Hakatere Conservation Park, on the true right of the Lawrence River approximately 7.5 km upstream of the confluence with the Clyde River, this site represents a relatively extensive area of *Podocarpus cunninghamii* dominated vegetation (43° 24' S, 170° 54' E). Large *Podocarpus cunninghamii* trees (15 – 20 m tall) form an emergent layer above an angiosperm canopy dominated by *Griselinia littoralis* (3-5 m tall). Other common trees and shrubs are *Phyllocladus alpinus, Pseudopanax crassifolius, Coprosma linariifolia, Coprosma propinqua* and *Myrsine divaricata* A.Cunn.. The sheer size and abundance of *Podocarpus cunninghamii* trees at this site, together with the intact broadleaf canopy, suggests that while the historical forest area has suffered a considerable reduction, the remaining stands are relatively intact and representative of old growth forest.

Upper Hapuku

The site studied is located within a series of steep valleys cloaked in *Podocarpus cunninghamii* dominated forest in the Mount Manakau Scenic Reserve (42° 14' S, 173° 40' E). Extensive stands of large *Podocarpus cunninghamii* trees (15 – 20 m tall) dominate the vegetation. *Griselinia littoralis*, *Pseudopanax crassifolius* and *Coprosma linariifolia* occur frequently, though not in great enough numbers to form a contiguous sub-canopy. Shrubs such as *Coprosma propinqua* and *Hebe traversii* (Hook.f.) Andersen are common; together with the aforementioned species they form a two-tiered under storey. Ungulate damage to all sub-canopy species is clear, with seedlings, saplings and epicormic shoots all showing evidence of browsing.

Data collection

Rectangular plots of 0.05 – 0.4 ha were established within each of the six sites. The area of each plot was dependent on the spacing of *Podocarpus cunninghamii* trees, with the objective being to sample 50 trees with a diameter at breast height (DBH; 1.4 m) ≥5 cm. A single increment core was extracted at 50 – 140 cm above ground level from all trees with a DBH ≥5 cm. The height at which an increment core was extracted was affected by forked stems and the need to avoid bulges, crooks and fused stems. Where trees had multiple stems that originated below 1.4 m, the two stems with the greatest DBH were selected, measured, and an increment core extracted from both to give a tree average. A total of 50 trees were sampled at each site, giving a total of 300 sampled trees. The DBH of all trees ≥5 cm DBH was recorded, and the heights of all trees were estimated using a Suunto clinometer. An individual *Podocarpus cunninghamii* was considered to be a tree if it was >1.4 m in height and had a DBH ≥5 cm.

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)

Cores were stored in plastic straws prior to arrival in the laboratory, where they were left to air dry for two weeks before being mounted onto grooved wooden boards, transverse surface upwards. After 24 hours each core was sanded with a 120-grade belt sander followed by a 280-grade orbital sander. Cores were examined under a binocular dissecting microscope and the number of rings counted (Stokes & Smiley, 1968). Where the chronological centre of the core was missed or the core was rotten it was necessary to estimate the age of the core. This was achieved using the following equation:

$$A = (r - p) / (d / 20) + N \qquad [1]$$

Where A is age, r is the geometric radius, p is the length of the partial core, d is the width of the innermost 20 rings, and N is the number of rings counted from the partial core (Norton et al., 1987). These ages were used to provide an average stand age for each site. It should be noted that the age data does not take into account the time it takes for *Podocarpus cunninghamii* to reach coring age. As a result all age estimates are underestimates of true age; this is a problem further compounded by missing rings (Bell & Bell, 1959; Scott, 1972).

Four soil samples (15 cm depth) were taken from each plot using a 2.5-cm diameter soil borer. Samples were sieved to 2 mm and left to air dry. For each site, the soil samples were bulked to provide a single representative sample of the site. These were then sent to a commercial analytical laboratory (Hill Laboratories Ltd, Hamilton, New Zealand) for analysis of pH, total carbon, total nitrogen and plant-available phosphorous (Olsen P). Table 3 contains the data from these analyses. Soil pH was measured after mixing soil in water (1 : 2 soil : water v/v). Total carbon and nitrogen were measured by Dumas combustion. Plant-available phosphorus was measured by molybdenum blue colorimetry following Olsen extraction.

Estimation of living carbon stocks

The procedure to estimate carbon stocks followed that of Coomes et al. (2002), Kirschbaum et al. (2009) and Carswell et al. (2009), using an equation developed by Beets (1980) in a mixed beech/podocarp forest. Firstly, aboveground tree biomass (AGB) was estimated using DBH and height data in the following equation:

$$AGB = 0.0000598 \times \rho \times (d^2h)^{0.946} \times (1 - 0.0019d) + 0.03d^{2.33} + 0.0406d^{1.53} \qquad [2]$$

Where d is DBH (cm) and h is tree height (m); ρ is wood density (kg m^{-3}). No published data are available for *Podocarpus cunninghamii* wood density so the average wood density of the closely related *Podocarpus totara* G.Benn. ex D.Don in Northland (446 kg m^{-3}) was used instead (Bergin et al., 2008)[1]. The root biomass of each tree was assumed to be 25% of aboveground biomass, and together gave total tree biomass. Total tree carbon stock was then assumed to be 50% of total tree biomass. Individual tree carbon stocks were then summed for each plot, giving a plot carbon stock. Plot carbon stocks were then multiplied by 1/plot size (Table 2), to give a tonnes per hectare (t ha^{-1}) carbon stock for each site. Each per-hectare carbon stock was then divided by the average cosine of the slope of that site. The differences in carbon stocks with LENZ-derived annual soil moisture deficits were analysed by linear regression.

Estimation of carbon sequestration rate

To estimate the carbon sequestration rate, counts of tree rings were undertaken only on cores that reached the pith, allowing as complete a chronology of rings as possible to be analysed. The width (mm) of every block of 10 rings was measured, providing a rate of radius increment for each 10-year period of each tree's life to the present day. This increment was doubled to provide a diameter figure. The mean growth rate for

TABLE 3: Soil properties for each site.

Site	pH	Total Carbon (%)	Total Nitrogen (%)	Carbon : Nitrogen ratio	Olsen Phosphorus (mg L^{-1})
Upper Hapuku	5.8	6.9	0.45	15.3	15
Upper Lawrence	5.3	9.3	0.59	15.8	13
Mount Dobson	5.3	7.5	0.50	15.0	16
Mount Cook	4.6	8.3	0.46	18.0	8
Mount Ben Ohau	6.3	6.6	0.51	12.9	16
Birdwood Station	5.7	4.9	0.36	13.6	22

[1] *Given the much slower growth rate of* Podocarpus cunninghamii *compared with* Podocarpus totara*, using Northland* Podocarpus totara *wood density is likely to underestimate high country* Podocarpus cunninghamii *wood density.*

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)

each 10-year period was then calculated for all cores. All data over 120 years of age was excluded due to the paucity of samples. Periodic mean diameter annual increment (PMAI) was then modelled using the following equation (where *a* is age in years):

$$PMAI = 0.000000655a^3 - 0.000237a^2 + 0.0173a + 1.16 \quad [3]$$

The PMAI values were then summed to give a cumulative PMAI, which was used to estimate *Podocarpus cunninghamii* diameter increment with age. The relationship between *Podocarpus cunninghamii* DBH and height was modelled using a log-log linear regression. This relationship was then used to predict *Podocarpus cunninghamii* height at the respective diameters in the cumulative PMAI model. These predicted diameters and heights were then used in the process described above for estimating carbon stocks, along with two example stocking densities (250 stems ha^{-1} and 1000 stems ha^{-1}), to estimate per hectare carbon stocks over a 100-year period. Both per hectare carbon stocks were divided by the average cosine of the slopes of all sites. All modelling, statistical analysis and graphing were done using R version 2.10.1 (R Development Core Team, 2009).

Results

Estimation of living carbon stocks

Per-hectare estimates of above- and below-ground carbon within *Podocarpus cunninghamii* at the six study sites are shown in Table 4. Per-hectare carbon stocks are highest at sites with the greatest basal area. Thus, the greatest unit quantities of carbon are stored at Upper Lawrence and Upper Hapuku, while the lowest are at the driest site, Birdwood Station. The mean carbon stock for sites with no annual soil moisture deficit (wet sites) was 71.5 ± 26.4 t ha^{-1} (± 1 s.e.; n = 4), while the mean carbon stock for the sites with annual soil moisture deficit (dry sites) was 12.8 ± 5.45 t ha^{-1} (n = 2). Per hectare carbon stocks showed a significant negative relationship with annual soil moisture deficit ($t_{1,3}$ = -3.21, p = 0.049).

TABLE 4: Carbon stocks of *Podocarpus cunninghamii* at the six study sites.

Site	Per hectare carbon stock (t ha^{-1})
Upper Hapuku	100.5
Upper Lawrence	130.1
Mount Cook	17.3
Mount Dobson	38.0
Mount Ben Ohau	18.2
Birdwood Station	7.3

Estimation of carbon sequestration rate

Of the 300 trees sampled, only 47 cores reached the pith and were therefore used to model PMAI (Figure 1A). The data was heavily biased towards trees aged 10 – 50 years (mean n per 10-year age class = 44), with less data available for trees 60 – 100 years (mean n per 10 year age class = 16); only a few trees

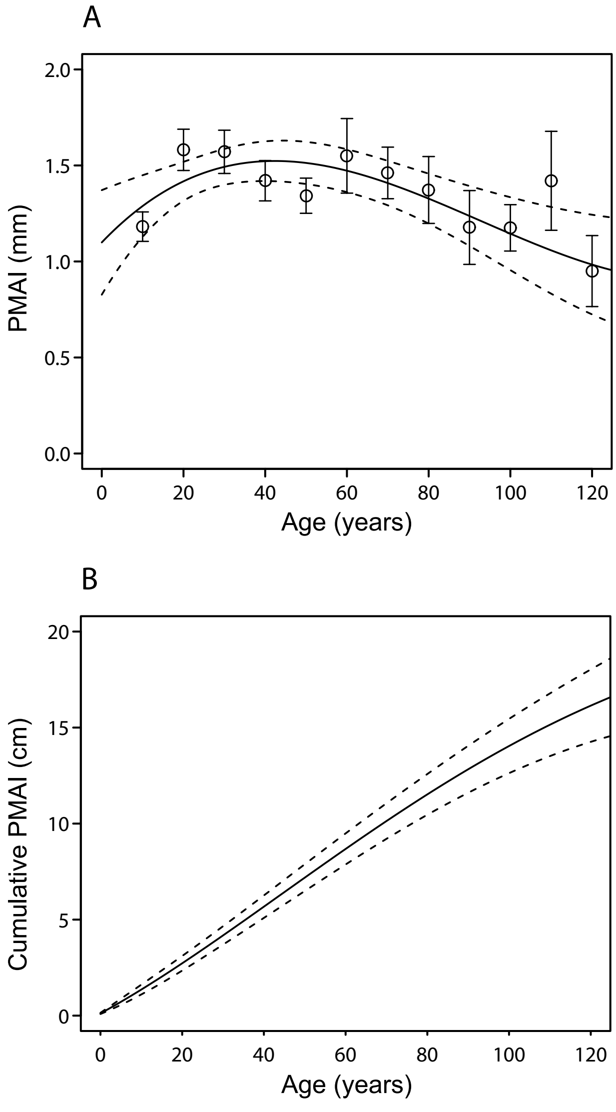

FIGURE 1: A: Periodic mean annual increment (PMAI) of high country *Podocarpus cunninghamii* (solid line). The points show mean annual increment for each 10-year age class ± 1 s.e.; B: Cumulative PMAI. The dotted lines on both Figures show the 95% confidence interval.

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)

provided data for 110 – 160 years (mean n per 10-year age class = 2). In addition, the data is heavily biased towards sites with colder and drier growing conditions; of the 47 trees sampled, 25 come from the dryland sites Birdwood Station and Mount Ben Ohau; 11 come from Mount Cook National Park, which like Birdwood Station and Mount Ben Ohau has significantly lower winter minimum temperatures compared with Upper Lawrence and Upper Hapuku (Table 1). Periodic mean diameter annual increment shows a trend of increasing diameter increment to a maximum of 1.5 mm after 50 years, before steadily declining to 1.2 mm at 100 years. Cumulative PMAI is shown in Figure 1B; the expected DBH of a tree after 100 years is 14.3 ± 1.4 cm (± 95% Confidence Interval). The relationship between DBH and height, based on the full dataset (n = 300), is shown in Figure 2. The predicted height of *Podocarpus cunninghamii* after 100 years is 5.2 ± 0.2 m (± 95% Confidence Interval) (based on DBH of 14.3 cm).

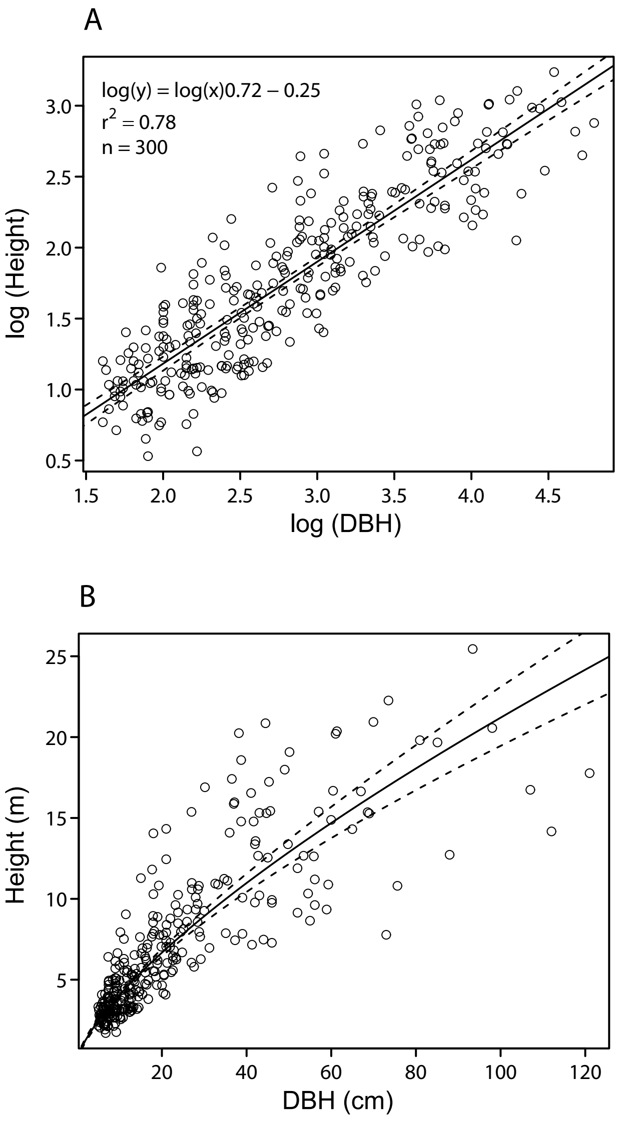

FIGURE 2: A: log-log relationship of DBH and height; B: unlogged relationship of DBH and height.
The dotted lines on both graphs show the 95% confidence interval.

The estimated carbon stock of a single *Podocarpus cunninghamii* tree after 100 years (14.3 cm DBH and 5.2 m height) is 22.55 kg m^{-3}. The annual carbon sequestration rate and 100 year carbon stock of a stand of *Podocarpus cunninghamii* at 250 stems ha^{-1} is predicted to be 0.1 ± 0.03 t ha^{-1} yr^{-1} and 11.3 ± 2.4 t ha^{-1}, respectively. For a stand of 1 000 stems ha^{-1} the annual sequestration rate is predicted at 0.5 ± 0.1 t ha^{-1} yr^{-1}, with a carbon stock of 45.0 ± 9.5 t ha^{-1} after 100 years. These predictions are based on mean increment rates without taking into account the effects of competition within stands. The increment rate of more densely stocked stands would be expected to be lower as a result of increased competition.

Discussion

Estimation of living carbon stocks

The results here provide a first estimate of live above- and below-ground carbon stocks within high country stands of *Podocarpus cunninghamii*. The mean carbon stock values of 71.5 ± 26.4 t ha^{-1} and 12.8 ± 5.5 t ha^{-1} for wet and dry sites, respectively, are much lower than those previously published for New Zealand indigenous forests comparable to those studied here; Tate et al. (1997) estimated 274.5 t ha^{-1} and Coomes et al. (2002) estimated 174 t ha^{-1}. However, Tate et al. (1997) assessed a range of different highland podocarp-broadleaved forest types, while the Coomes et al. (2002) study included biomass values of all tree species within plots and also sampled West Coast stands with much greater biomass than those studied here. The only figure available relating specifically to *Podocarpus cunninghamii* comes from *Podocarpus cunninghamii–Nothofagus solandri–Phyllocladus alpinus* forest at Twizel, where live carbon stocks were estimated at 160 t ha^{-1} (Kirschbaum et al., 2009), based on forest biomass models (Hall & Hollinger, 2000). However, this figure includes the biomass of all tree species present within the sampled plot, while the present study only measured the biomass of *Podocarpus cunninghamii*.

The high country climate varies widely; areas close to the Main Divide receive high levels of annual rainfall (>2 000 mm) while further east annual rainfall declines to <600 mm. The eastern drylands, which were particularly susceptible to historical fire-driven forest loss (McWethy et al., 2010), have been heavily deforested and surviving stands are highly degraded. In contrast, areas close to the Main Divide still support extensive stands of relatively intact *Podocarpus cunninghamii* forest (Wardle, 1991). Stocks of carbon are lower within degraded versus intact forest (Gibbs et al., 2007), and as such per hectare

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)

stocks of carbon within remnants closer to the Main Divide would, in general, be expected to be greater than stocks further east. It is likely that the figures given for the relatively intact stands of *Podocarpus cunninghamii* in the wetter parts of the high country are likely to more closely resemble published figures of indigenous forest carbon stocks. On the other hand, the degraded stands in the drylands are likely to more closely resemble published figures of indigenous shrubland carbon stocks. This certainly appears to be the case; Upper Lawrence and Upper Hapuku, which are both closed canopy stands, have estimated carbon stocks of 130.1 and 100.5 t ha^{-1}, respectively. *Podocarpus cunninghamii* is by far the largest species in these forests, and the majority of standing biomass is probably held within them. As such, these estimates can be seen as conservative minimum estimates of live carbon within these wet and relatively mild forests. In addition, these estimates ignore soil carbon pools, which can represent a substantial amount of additional carbon, although less than the standing pool (Carswell et al., 2008; Kirschbaum et al., 2009). With regard to the dryland sites, the estimated carbon stocks of Mount Ben Ohau and Birdwood Station are 18.2 and 7.3 t ha^{-1}, respectively, which are similar to the 26.7 t ha^{-1} published for indigenous eastern shrublands, of which 5.9 t ha^{-1} was contributed by trees (Coomes et al., 2002). Again, the figures derived in the present study only include the contribution of *Podocarpus cunninghamii*, thus ignoring the actual shrubland component; although it is considered that the shrubland component would be relatively minor.

Despite the estimates of carbon stocks in the dryland stands appearing low relative to the wetter stands, they are still far greater than carbon stocks estimated for improved and unimproved pasture (2.1 – 2.9 t ha^{-1} (Tate et al., 1997)). The figure for Mount Ben Ohau carbon stocks, which has a fractured canopy (c. 46% cover) is comparable to that estimated for short-tussock grasslands (10.8 – 27.2 t ha^{-1} (Tate et al., 1997)), which is typically the adjacent vegetation cover in the high country. This result is somewhat puzzling given the obvious differences in standing biomass between woodland and grassland. However, the Tate et al. (1997) grassland figures were not based on any empirical data and therefore may have overestimated grassland carbon stocks (Carswell et al., 2008). Age and size class distributions of Birdwood Station and Mount Ben Ohau (data not shown) indicate that the majority of trees in both stands are relatively young (<100 years old). These are post-human disturbance stands and will thus continue to increase in biomass. As such, the figures given here are considered to underestimate the potential carbon stocks of these sites, as it is expected they will develop larger carbon stocks over time.

Carbon stocks within *Podocarpus cunninghamii* stands cannot be estimated solely on annual soil moisture deficit. Stands at both Mount Cook National Park and Mount Dobson, just like Upper Lawrence and Upper Hapuku, have no annual soil moisture deficits. However, the estimated carbon stocks of Mount Cook National Park and Mount Dobson are approximately five times lower. *Podocarpus cunninghamii* basal area and stocking density are also smaller at both these sites compared with Upper Lawrence and Upper Hapuku. The reasons for this are unclear, but the frequency and extent of large scale disturbance (e.g. snow avalanches), as well as mean annual and winter minimum temperatures may play an important role. For example, the Mount Dobson and Upper Lawrence site are floristically very similar, but the age and size class distributions of *Podocarpus cunninghamii* show that Mount Dobson has far fewer individuals in the larger size classes (data not shown). Mount Dobson is also populated by younger trees, indicating more recent disturbance and stand recovery.

The estimated living carbon stocks within stands of *Podocarpus cunninghamii* do represent significant pools of carbon when compared with the grasslands that they typically occur within. Less disturbed forest stands contain higher quantities of carbon (e.g. Upper Lawrence > Mount Dobson > Birdwood Station). The rehabilitation of disturbed stands should therefore lead to the storage of even greater quantities of carbon.

Estimation of carbon sequestration rate

A preliminary model of annual *Podocarpus cunninghamii* diameter increment and carbon sequestration rates over a 100-year period in the high country has been developed. The model has several limitations and consequently the results should be interpreted with caution. The age data does not take into account the time it takes for *Podocarpus cunninghamii* to reach coring age. As a result all age estimates are underestimates of true age; this is a problem further compounded by missing rings (Bell & Bell, 1959; Scott, 1972). Tree ring counts are also heavily skewed to younger age classes (<60 years) due to rotten centres of larger trees and a paucity of larger trees in general. Given that the dryland sites had greater numbers of smaller trees, the data behind the model is biased towards dryland samples. As a result, the model is likely to underestimate growth in the wetter parts of the high country. The growth data is also based on measurements of tree rings, which come from a single radius of each tree. Ideally, mean growth rate estimates should be based on repeated measurements over time (Kirschbaum, et al., 2009). The rate of diameter growth also ignores density dependent effects arising from different stocking rates. Finally, an allometric equation specific to *Podocarpus cunninghamii* would improve biomass and carbon stock estimates. The allometric equation used here was taken from Coomes et al. (2002), which was based on data collected from a single, mixed beech/podocarp forest (Beets, 1980).

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)

The range of PMAIs predicted by the model is within that recorded for the New Zealand Podocarpaceae (0.8 – 3 mm yr^{-1}) (Hall & Hollinger, 2000). The estimated annual carbon sequestration rates (0.1 and 0.4 t ha^{-1} yr^{-1} for 250 and 1000 stems ha^{-1}, respectively) are lower than the estimated mean national indigenous forest sequestration rate of 1.4 t ha^{-1} yr^{-1} (Kirschbaum et al., 2009). However, the mean national rate includes areas of forest in mild and wet lowland environments more favourable for tree growth, includes faster growing tree species, and does not limit the number of potential species within indigenous forest to just one (Hall & Hollinger, 2000). As such, it is not surprising that predicted *Podocarpus cunninghamii* sequestration rates are lower than the national mean.

Conclusions

In the last few decades increasing areas of grazing grassland have been retired and placed within the New Zealand government's public conservation estate (Department of Conservation, 2010). As a result there are now extensive grassland areas with the potential to restore pre-human forest flora (Walker et al., 2009). In addition to the Crown Estate, private land also has the potential for indigenous restoration through the afforestation of unproductive and erosion-prone marginal lands (Kirschbaum et al., 2009). The area of erosion-prone hill country on the South Island suitable for afforestion has been estimated at between 222 611 and 400 105 ha, of which the majority is described as low-producing or depleted grasslands (Davis et al., 2009). While not every hectare of this hill country is suitable for *Podocarpus cunninghamii*, for example *Nothofagus* may be more suited in some sites, the area available for *Podocarpus cunninghamii* restoration is still significant. Furthermore, the predicted 100-year carbon stock of a 1,000 stems ha^{-1} *Podocarpus cunninghamii* stand (45 t ha^{-1}) exceeds the estimated range of carbon stock values for short tussock grassland. As such, afforestation of Kyoto-compliant high country grasslands with *Podocarpus cunninghamii* forest has the potential to increase New Zealand's carbon stocks, and thereby assist it achieve its Kyoto commitments in the medium to long term (Carswell et al., 2008; Kirschbaum et al., 2009).

In the short term, the estimated carbon sequestration rate of *Podocarpus cunninghamii* is much lower than that calculated for radiata pine (*Pinus radiata* D.Don) (Davis et al., 2009). However, in the long term, indigenous forests have the potential to develop greater carbon stocks than conventionally managed exotic conifer forests due to slower growth rates producing denser wood with slow turnover times (Carswell et al., 2008; Chazdon, 2008). As such, indigenous afforestation could contribute significantly to the government's Kyoto carbon reduction commitments (Kirschbaum et al., 2009). Such restoration would have additional benefits in terms of soil erosion control, enhancement of indigenous biodiversity, as well as provide a potential income source to landowners through the Permanent Forest Sink Initiative (Ministry of Agriculture and Forestry, 2007). When combined with the estimated area of marginal land available for afforestation, these considerations augur favourably for the restoration of *Podocarpus cunninghamii* vegetation communities to the high country.

In closing, this study provides useful initial estimates of carbon sequestration rates of *Podocarpus cunninghamii* that can assist decision makers decide which species to regenerate or plant. These estimates could be refined by using separate annual increments for wet and dry sites, larger sample sizes and empirical wood density.

Acknowledgements

Many thanks go to Max Hübner, Frisco Nobilly, and Justine and Robert Carson-Iles for field assistance. We would also like to thank the reviewers and editors, whose comments have improved this manuscript. This work was supported financially by The Brian Mason Scientific & Technical Trust and the School of Forestry, University of Canterbury.

References

Beets, P. N. (1980). Amount and distribution of dry matter in a mature beech/podocarp community. *New Zealand Journal of Forestry Science, 10*, 395-418.

Bell, V., & Bell, R. E. (1959). Dendrochronological studies in New Zealand. *Tree-ring Bulletin, 22*, 7-11.

Bergin, D. O., Kimberley, M. O., & Low, C. B. (2008). Provenance variation in *Podocarpus totara* (D. Don): Growth, tree form and wood density on a coastal site in the north of the natural range, New Zealand. *Forest Ecology and Management, 255*, 1367-1378.

Carswell, F. E., Burrows, L. E., & Mason, N. W. H. (2009). *Above-ground carbon sequestration by early-succesional woody vegetation. A preliminary analysis*. Wellington, New Zealand: Department of Conservation.

Carswell, F. E., Mason, N. W. H., Davis, M. R., Briggs, C. M., Clinton, P. W., Green, W., Standish, R. J., Allen, R. B., & Burrows, L. E. (2008). *Synthesis of carbon stock information regarding conservation land*. Lincoln, New Zealand: Landcare Research.

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)

Chazdon, R. L. (2008). Beyond deforestation: restoring forests and ecosystem services on degraded lands. *Science, 320*, 1458-1460.

Coomes, D. A., Allen, R. B., Scott, N. A., Goulding, C., & Beets, P. (2002). Designing systems to monitor carbon stocks in forests and shrublands. *Forest Ecology and Management, 164*, 89-108.

Davis, M., Douglas, G., Ledgard, N., Palmer, D., Dhakal, B., Paul, T., Bergin, D., Hock, B., & Barton, I. (2009). *Establishing indigenous forest on erosion-prone grassland: land areas, establishment methods, costs and carbon benefits*. Rotorua, New Zealand: Scion.

Department of Conservation. (2010). *History of tenure review.* Wellington, New Zealand: Department of Conservation. Retrieved 13 September, 2010, from http://www.doc.govt.nz/conservation/land-and-freshwater/land/south-island-high-country/tenure-review/history/

Espie, P. R., Hunt, J. E., Butts, C. A., Cooper, P. J., & Harrington, W. M. A. (1984). *Mackenzie Ecological Region - New Zealand Protected Natural Area Programme*. Wellington, New Zealand: Department of Lands and Survey.

Gibbs, H. K., Brown, S., Niles, J. O., & Foley, J. A. (2007). Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environmental Research Letters, 2*, 1-13.

Hall, G. M. J., & Hollinger, D. Y. (2000). Simulating New Zealand forest dynamics with a generalized temperate forest gap model. *Ecological Applications, 10*, 115-130.

Kirschbaum, M., Trotter, C., Wakelin, S., Braisden, T., Curton, D., Dymond, J., Ghani, A., Jones, H., Deurer, M., Arnold, G., Beets, P., Davis, M., Hedley, C., Peltzer, D., Ross, C., Schipper, L., Sutherland, A., Wang, H., Beare, M., Clothier, B., Mason, N., & Ward, M. (2009). *Carbon Stocks and Changes in New Zealand's Soils and Forests, and Implications of Post-2012 Accounting Options for Land-Based Emissions Offsets and Mitigation Opportunities - Including Appendices*. Lincoln, New Zealand: Landcare Research.

Landcare Research (2010). Retrieved March 2010 from http://www.landcareresearch.co.nz/databases/lenz/

Ministry of Agriculture and Forestry. (2007). *Forestry in a New Zealand Emissions Trading Scheme. Engagement Document*. Wellington, New Zealand: Ministry of Agriculture and Forestry.

McGlone, M. S. (1989). The Polynesian settlement of New Zealand in relation to environmental and biotic changes. *New Zealand Journal of Ecology, 12*, 115-129.

McWethy, D. B., Whitlock, C., Wilmshurst, J. M., McGlone, M. S., Fromont, M., Li, X., Dieffenbacher-Krall, A., Hobbs, W. O., Fritz, S. C., & Cook, E. R. (2010). Rapid landscape transformation in South Island, New Zealand, following initial Polynesian settlement. *Proceedings of the National Academy of Sciences USA, 107*, 21343-21348.

Norton, D. A. (2006). Managing high country landscapes into the future. In R. S. Lough (Ed.), *High Country Landscape Management Forum 2005 Proceedings* (pp. 97-103). Dunedin, New Zealand: Otago Regional Council.

Norton, D. A., Palmer, J. G., & Ogden, J. (1987). Dendroecological studies in New Zealand 1. An evaluation of tree age estimates based on increment cores. *New Zealand Journal of Botany, 25*, 373-383.

Pascoe, R. M. (1983). *The climate and weather of Marlborough*. Wellington: New Zealand Meteorological Service.

R Development Core Team. (2009). *R: A language and environment for statistical computing.* Vienna, Austria: R Foundation for Statistical Computing. http://www.R-project.org

Ryan, A. P. (1987). *The climate and weather of Canterbury, including Aorangi*. Wellington, New Zealand: New Zealand Meteorological Service.

Scott, D. (1972). Correlation between tree-ring width and climate in two areas in New Zealand. *Journal of The Royal Society of New Zealand, 2*, 545-560.

Stokes, M. A., & Smiley, T. L. (1968). *An Introduction to Tree-Ring Dating*. Chicago, USA: The University of Chicago Press.

Tate, K. R., Giltrap, D. J., Claydon, J. J., Newsome, P. F., Atkinson, I. A. E., Taylor, M. D., & Lee, R. (1997). Organic carbon stocks in New Zealand's terrestrial ecosystems. *Journal of The Royal Society of New Zealand, 27*, 315-335.

United Nations Framework Convention on Climate Change. (1998). *Kyoto Protocol to the United*

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)

Nations Framework Convention on Climate Change: United Nations.

Walker, S., Cieraad, E., Monks, A., Burrows, L., Wood, J., Price, R., Rogers, G., & Lee, W. (2009). Long-term dynamics and rehabilitation of woody ecosystems in dryland South Island, New Zealand. In R. J. Hobbs & K. N. Suding (Eds.), *New Models for Ecosystem Dynamics and Restoration* (pp. 99-111). Washington DC, USA: Island Press.

Wardle, P. (1991). *Vegetation of New Zealand*. Cambridge, UK: Cambridge University Press.

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)