Marden et al. *New Zealand Journal of Forestry Science* (2025) 55:3
https://doi.org/10.33494/nzjfs552025x387x
E-ISSN: 1179-5395
published on-line: 26/02/2025

RESEARCH ARTICLE **Open Access**

New Zealand Journal of Forestry Science

Total plant biomass, carbon stock, and species- and age-specific allometry for 12 of New Zealand's early-colonising indigenous shrub and tree species to 5 years of age

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(Received for publication 28 April 2024; accepted in revised form 20 January 2025)
Editor: Eckehard Brockerhoff

Abstract

Background: Changes in biomass and carbon stocks of open-spaced plantings are important considerations in the restoration of biodiversity and ecological function of New Zealand's degraded (non-forested) landscapes and streamside margins. Species- and age-specific allometric relationships of biomass and carbon stocks were developed for a diverse range of indigenous seral shrub and tree species during their juvenile growth period.

Methods: Whole plants of *Coprosma robusta* Raoul (karamu), *Plagianthus regius (*Poit.) Hochr. (lowland ribbonwood), *Sophora tetraptera* J.S.Muell. (eastern kōwhai), *Pittosporum eugenoides* (Cunn.) (lemonwood), *Pittosporum tenuifolium* (Gaertner) (kōhūhū), *Hoheria populnea* A.Cunn. (North Island lacebark), *Myrsine australis* (A.Rich) Allan (māpou), *Pseudopanax arboreus* (Murray) Philipson (fivefinger), *Cordyline australis* (G. Forst.) Endl. (cabbage tree), *Knightia excelsa* (R.Br.) (rewarewa), *Leptospermum scoparium* (J.R.Forst. & G.Forst (mānuka), and *Coriaria arborea* (Linds) (tree tutu) were planted as 2-year-old nursery-raised seedlings in a plot-based field trial. Plants of each species were destructively sampled annually over 5 consecutive years and species-specific allometric equations developed for foliage, branch, stem, total above-ground biomass (AGB), total below-ground biomass (BGB), and whole plant biomass to calculate carbon stocks.

Results: In each year and for each of the 12 test species, root-collar diameter over bark (RCD) gave the best fit for plant height, foliage, branch, stem, total AGB, total BGB, and whole plant biomass. At age 5 years, *Coriaria arborea* and *Cordyline australis* accumulated significantly more AGB (P = 0.05) than the remaining species, none of which were not significantly different from one another and each species had allocated more than 20% of their total biomass to BGB, with BGB:AGB ratios of between 0.24 and 0.44. Species-specific mean tree biomass values at this age ranged from 0.5 to 14.0 kg per plant. The planting of equal numbers of the seven best-performing species as 2-year-old seedlings could potentially amass a carbon stock of 13.1 t CO_2 1000 stems ha^{-1} within 3 years after establishment as open-spaced plantings.

Conclusions: RCD proved to be a reliable predictor of plant height, foliage biomass, branch biomass, stem biomass, total ABG, total BGB, and whole plant biomass. Optimisation of the carbon potential amassed by mixed plantings of indigenous seral plants will require the development of allometric equations for a wider range of species best suited to restoring ecological integrity to degraded landscapes and to improve the accuracy of existing biomass and carbon stock inventories.

Keywords: Above- and below-ground biomass; carbon sequestration; degraded landscapes; destructive sampling; native plants; restoration.

Introduction

In the global carbon cycle, rapid and measurable gains can be made through afforestation /reforestation of non-forested land (Knapp et al. 2008; Pinno & Wilson 2011). Following New Zealand's ratification of the Kyoto Protocol (Intergovernmental Panel on Climate Change 2000; New Zealand Climate Change Office 2003), afforestation grant schemes (Ministry for Primary Industries 2015) were introduced, primarily to encourage the establishment of new forest to reduce greenhouse gas emissions and as an erosion control strategy (Ministry for Primary Industries 2016; Marden et al. 2020). Together with the One Billion Trees Fund (Ministry for Primary Industries 2018), these schemes aimed to target c. 1.45 million ha of land considered marginal for long-term agriculture and/or short-rotation exotic plantation forest and better suited to transitioning to permanent indigenous shrubland or forest, which also provides an opportunity to earn carbon credits (Trotter et al. 2005).

New Zealand-based studies have attempted to quantify the biomass of indigenous forest stands, mostly for live tree carbon sequestration (Scott et al. 2000; Trotter et al. 2005; Carswell et al. 2012; Dale 2013; Beets et al. 2014; Schwendenmann & Mitchell 2014). Where these forests included seral vegetation, allometric functions were largely based on figures derived from well-established individual kānuka (*Kunzea ericoides* var. *ericoides* (A.Rich.) J.Thompson), a widespread and early coloniser of abandoned pastoral and eroding hill country. Similar functions have been derived for a limited number of later successional species, mostly of unknown age (Beets et al. 2008; Russo et al. 2010) and from a subset of New Zealand forest classes at a limited number of sites (Beets 1980; Allen et al. 1998; Beets et al. 2008; Peltzer & Payton[2]). As a result, where species-specific and/or regional values are not available, co-generic values or the mean of all published values were used (Beets et al. 2008). By continuing to use non-age-specific co-generic values, it is impossible to assess the accuracy of potential bias in the national carbon budget calculations (Scott et al. 2000).

While carbon stocks have been recorded in single-species indigenous forest stands following natural disturbance (Davis et al. 2003; Litton et al. 2003), in naturally reverting seral stands of *Leptospermum scoparium* (Trotter et al. 2005), and in areas planted in mānuka specifically for honey production (Marden et al. 2020), carbon is not expected to accumulate linearly in natural vegetation successions to a permanent indigenous cover (Peet 1981). Since the pattern and growth performance of many of New Zealand's early colonising shrub and tree species when established as open-spaced plantings remain elusive, particularly during their juvenile period, the amount of biomass and carbon stocks likely to be sequestered is largely unknown (Carswell et al. 2012).

The patterns and distribution of AGB (above-ground biomass) and carbon stocks are reasonably well understood, however, knowledge of the BGB (below-ground biomass) and its distribution is limited (McNaughton et al. 1998). Cairns et al. (1997) presented an allometric equation through which the root biomass of a forest can be predicted from the shoot biomass and applied to individual plants, and to stands of vegetation at varying scales from local, to landscape, regions or biome, of 20% for BGB. Mokany et al. (2006) concluded that allometric equations for specific species provided a more accurate means for estimating root biomass and fundamental to improving our understanding of carbon allocation and storage in terrestrial ecosystems.

As little is known about biomass allocation to root systems, some allometric relationships are more difficult to quantify than others. This disparity in knowledge is because of difficulties in measuring root biomass (Vogt et al. 1996; Titlyanova et al. 1999). The use of non-invasive techniques (such as ground-penetrating radar) is limited to coarse root systems (Hruska et al. 1999); and in studies where coarse roots are the focus, the biomass of the root bole was not included (Will 1966; Heth & Donald 1978; Watson & O'Loughlin 1990). Although the precision of root biomass estimates tends to be low, they have nonetheless been used in estimations of BGB in the absence of better species-specific and age-specific data (Hall et al.[1]).

While Cairns et al. (1997) suggested a value of 20% for BGB, there are errors associated with applying allometric relationships derived from adult tree functions to juvenile trees. Although these errors may be small (Peltzer & Payton[2]), allometric relationships relating tree diameter and height to biomass for a greater range of the most common seral shrub and tree species are required. A recent study in which juvenile saplings of eight of New Zealand's dominant conifer and broadleaved forest species were destructively sampled, showed that the proportion of total plant biomass allocated to their respective root systems (inclusive of the stump) was species-specific. Furthermore, it varied between 21% and 42% and decreased with increasing tree age (Marden et al. 2018b). The assumption, therefore, that all plant species within forest and shrubland communities at different stages of seral development or in different environments allocate 20% of their biomass to roots is questionable.

In an earlier paper, the root attributes (depth, spread, and architecture) of 12 of New Zealand's most common early colonising indigenous seral shrub and tree species were measured to assess their potential effectiveness and/or limitation to improve stream bank stability (Marden et al. 2005). For these same species, allometric equations were later derived to establish relationships between root collar diameter (RCD; measured over

[1] Hall, G., Wiser, S., Allen, R., Moore, T., Beets, P., & Goulding, C. (1998). *Estimate of the carbon stored in New Zealand's indigenous forest and scrub vegetation for 1990.* [Landcare Research Contract Report JNT9798/147], 36 p. Wellington, New Zealand: Ministry for the Environment.

[2] Peltzer, D.A., & Payton, I.J. (2006). *Analysis of carbon monitoring system data for indigenous forests and shrub lands collected in 2002/03.* [Landcare Research Contract Report LC0506/099], 55 p. Lincoln, New Zealand: Landcare Research.

bark) and total root biomass, root length, root diameter size classes, root bole and total BGB annually for plants between 1- and 5-years-old (Marden et al. 2018b). These species are common to many of New Zealand's degraded (non-forested) landscapes and streamside margins that encompass a diverse range of environmental conditions. To transition these areas to a permanent indigenous shrubland or forest will likely require the re-establishment of open-spaced, mixed-species plantings of early colonising indigenous seral shrub and tree species with the potential to sequester carbon.

In this paper, we present species and age-specific allometric equations relating RCD to foliage, branch and stem biomass, to total AGB, to total BGB, and to whole plant biomass during each of their first 5 years of growth. Information on the potential for different combinations of open-spaced plantings of indigenous seral shrub and tree species to accumulate biomass and carbon stocks is essential to the refining of current annual estimates for this age range.

Methods

Study location

The trial site was established on a low-lying, sheltered, flat alluvial terrace beside the Taruheru River in Gisborne (Figure 1). This site had previously been used to measure the plant growth performance of different clones of poplar (*Populus* spp.) and willow (*Salix* spp.) (Phillips et al. 2014), a range of exotic forest tree species (Phillips et al. 2015), eight of New Zealand's more common indigenous conifer and broadleaved tree species (Marden et al. 2018a), the 12 shrub and tree species documented in Marden et al. (2005) and Marden et al. (2018b), and in this paper. Average temperatures over summer are 23 °C, and 12 °C during winter. Mean annual rainfall is c. 1,000 mm and mean evapotranspiration is 985 mm, with moderate soil moisture deficits from November to February (National Institute of Water and Atmospheric Research High Intensity Rainfall Design System (HIRDS). https://niwa.co.nz/information-services/hirds). Other

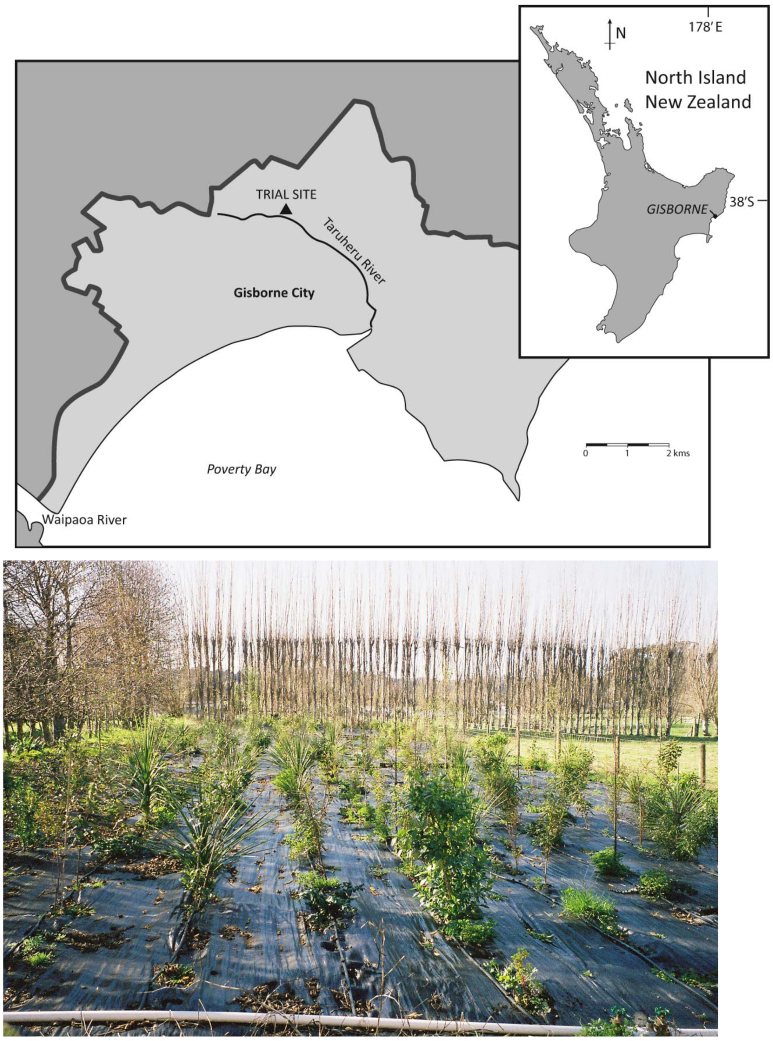

FIGURE 1: Location map with photograph of 3-year-old plants at the trial site, Gisborne City, North Island, New Zealand. Reproduced from Marden et al. 2018b.

than a water table that fluctuates between >1.5 m depth to within c. 0.2 m of the surface for short and infrequent periods following prolonged, heavy rainfall (Phillips et al. 2014), the Typic Sandy Brown Soil (Hewitt 2010) is free draining and has no physical or chemical impediments to root development to about 1.2 m depth.

Trial design

We considered it was neither practical nor environmentally acceptable to source plants directly from their natural environment, so containerised plants were purchased from a local plant nursery. Seeds were collected from wild populations of trees and shrubs within the Turanga Ecological District (Clarkson & Clarkson 1991) and are therefore endemic to the East Coast region.

Seeds were sown in seed trays until they were approximately 5 cm tall with roots 1 to 5 cm long. and considered sufficiently robust before transplanting into 80 mm tall x 50 mm x 50 mm wide polythene tubes for ~1-year to allow for further root development. Plants on-grown for planting as 2-year-old seedlings were re-potted into larger 1.2 litre polythene bags (120 mm deep × 110 mm diameter) filled with a 50:50 mix of bark and pumice and remained in these planter bags until they developed a strong root system and robust top growth, then planted at the trial site. Plant age was designated as zero years at the date each species was transplanted from the seed tray to a tube. To minimise root disturbance, seedlings were planted with the soil attached. Root binding was minimal and tap root length did not exceed the depth of the planting bag, so no root pruning before planting was required.

In preparation for planting, the trial site (measuring 50 m × 20 m) was tilled and weed mat was laid down. The site was subdivided into three blocks and planted in a day in early autumn (March 1999) once soil moisture levels had recovered from a summer deficit. A computer-based block design was used to minimise the adjacency of plants of the same species. Equal numbers of each species were planted in each block. To optimise plant growth, blocks 1 and 2 (where plants were to be extracted 1 and 2 years after planting, i.e. at age 3 and 4 years, respectively) were planted at 1 m spacing. Block 3 (where plants were to be extracted 3 years after planting, i.e., at age 5 years) was planted at 1.5–2.0 m spacing. The purpose of the increased spacing in block 3 was to reduce the effects of competition and potential suppression of the slower growing species, particularly during the latter stages of the trial, and to facilitate the excavation of root systems of individual plants without damaging the roots of adjacent plants.

Species selection

Species selection was undertaken using published information from the Allan Herbarium (2000) and included some of the more common indigenous seral species associated with natural successions on abandoned pastoral hill country, the conversion of exotic plantation forest to a permanent indigenous cover across a wide range of landscapes and particularly in the restoration of streamside (i.e., riparian) margins of degraded waterways. All 12 of the listed species are evergreen, each with the potential to reach a height >5 m (Salmon 1998) and for a stand of mixed species to provide canopy cover of 30% of each hectare to be eligible for inclusion in the Emission Trading Scheme (ETS) (https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/ets/). They include *Coprosma robusta*, *Plagianthus regius* (lowland ribbonwood), *Sophora tetraptera* (eastern kōwhai), *Pittosporum eugenoides* (lemonwood), *Pittosporum tenuifolium* (kōhūhū), *Hoheria populnea* (North Island lacebark), *Myrsine australis* (māpou), *Pseudopanax arboreus* (fivefinger), *Cordyline australis* (cabbage tree), *Knightia excelsa* (rewarewa), *Leptospermum scoparium* (mānuka), and *Coriaria arborea* (tree tutu) (Table 1).

TABLE 1: Plant species and number of sample trees extracted annually from a field trial in Gisborne, New Zealand.

Botanical name	**Common name**	**Number of plants extracted/species/year**					**Species total**
		Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	
Coriaria arborea	tutu	10	10	10	8	5	43
Myrsine australis	māpou	10	10	10	10	10	50
Pseudopanax arboreus	fivefinger	10	10	10	8	8	46
Sophora tetraptera	kōwhai	10	8	8	8	10	44
Cordyline australis	cabbage tree	10	10	10	10	10	50
Hoheria populnea	lacebark	10	10	10	10	8	48
Knightia excelsa	rewarewa	10	10	10	10	9	49
Pittosporum tenuifolium	kōhūhū	10	10	10	9	10	49
Pittosporum eugenoides	lemonwood	10	10	10	10	10	50
Coprosma robusta	karamu	10	10	7	8	10	45
Plagianthus regius	ribbonwood	10	10	10	10	10	50
Leptospermum scoparium	mānuka	10	10	5	0	5	30
Annual totals		**120**	**118**	**110**	**101**	**105**	**554**

Seedling propagation and trial design

Containerised 1- and 2-year-old seedlings were partitioned into their above- and below-ground components. For the field component of the trial, 2-year-old containerised plants were established at the trial site and on-grown for 3 more years. The aim was to sample 10 plants per species per year. Frost, insect attack, and wind-throw accounted for the shortfall in sample size for some of the species in years 3 to 5. Only five *Leptospermum scoparium* plants survived to year 4 so these were left to on-grow through to the end of the trial. Over the duration of this trial 554 individual plants were sampled destructively (Table 1).

Annual measurements of tree height, stem diameter at breast height (DBH, measured at 1.4 m above ground level), and RCD were measured at ground level before removing the plants from the trial site (Table 2). The above-ground components were separated into branches, foliage, and stem then oven dried and weighed (Appendix 1) before converting biomass to carbon. Root system extraction and measurement methods followed well-established procedures (e.g. Watson et al. 1999; Marden et al. 2005; Phillips et al. 2014, 2015).

Compressed air (240 kPa) (kilopascals) delivered through an air lance was used to excavate 3-, 4-, and 5-year-old bare-rooted plants. This process removed the soil from the root systems without damage or significant loss of the fibrous root mass. Once removed from the ground, the roots were washed to remove adhering soil matter, photographed, then divided into root bole (stump) and roots. Detailed measurements of mean annual increments in root depth, root spread, distribution of roots (length, diameter size class, and mass) from the root bole, and allometric relationships between RCD and root mass and root bole mass, have been presented in Marden et al. (2005) and Marden et al. (2018b).

All above- and below-ground plant components were oven dried at 100 °C for 24 h or until no further weight loss was detectable, then weighed to the nearest 0.1 g. Component biomass, AGB and BGB were calculated as a percentage of total plant biomass using dry mass. Dry weight was converted to carbon using 0.5 as a multiplier (Coomes et al. 2002). A conversion factor of biomass × 1.65 (Williams 1978) was used to calculate carbon stocks (t CO_2). Carbon stock values do not include woody debris or fine litter.

Statistical analyses

An ANOVA was used to determine the effects of year and species on above- and below-ground parameters. The Student–Newman–Keuls *post hoc* analysis was used to determine differences among the species within a year, and among years when all species were averaged within each year. The normality of each analysis was determined by visual assessment of residual plots. Where data exhibited non-normality, they were transformed using the equation $\log_e(x + c)$, where x is the parameter and c = 1. All ANOVA analyses were conducted using Genstat 12 (VSN International, Hemel Hempstead, UK) and were considered significant if $P < 0.05$. All data are presented as a mean with standard errors.

RCD was used instead of DBH in the analysis of tree allometry because at the time of planting, and except for *Coriaria arborea*, the remaining species were single stemmed, many of which were not expected to reach DBH height (1.4 m) for some years after establishment of the trial. More importantly, RCD may serve as a better predictor of both AGB and BGB quantities because the root collar is measured at the intersection of above- and below-ground parameters and stem taper in seedlings is minimal (Wagner & Ter-Mikaelian 1999).

Allometric regressions were performed in R (R Development Core Team 2022) (Appendices 2–8). Because of apparent non-linearity in the relationship between RCD and height for some species, models for each species were selected through comparison of linear (y = mx) and natural log-linear (y = mln(x)) models in ordinary least squares regression. No intercept was fitted, because all values for other variables are zero when RCD is zero. Linear least-squares regressions were performed using the glm() function. Model comparisons were made using the Akaike information criterion (AIC; Burnham & Anderson 2002). The log-linear model was selected if AIC (y = mln(x)) –AIC(y = mx) ≤ –2 (Burnham & Anderson 2002). The significance of regressions was assessed using a t-test of the linear regression co-efficient. Standard errors of predicted values in ordinary least squares regressions were obtained using the predict() function.

Relationships between RCD and stem, branch, foliage, total AGB, total BGB and whole-plant biomass were analysed using the non-linear regression function nls(), which uses an iterative algorithm to fit regression coefficients that minimise the sum of squared errors between observed and predicted values. Biomass variables generally increase exponentially with increasing RCD, but for different species (e.g. *Coriaria arborea)* biomass variables can be linear (e.g. in this current paper). Therefore, models for each species were selected through comparison of linear (y = mx) and exponential ($y = a_e(bx)$) models. Model comparisons were again made using AIC. The exponential model was selected if AIC ($y = a_e(bx)$) – AIC(y = mx) ≤ –2 (Burnham & Anderson 2002). Pseudo R-squared values were estimated as the complement of the error sum of squared deviance between observed and predicted value (SSerror), divided by the total sum of squares of the observed data (SStotal), giving r-square = 1-SSerror/SStotal (Koenker & Machado 1999).

The significance of exponential regressions was assessed using an F-test of the ratio of model to error mean-squared deviance (with model squared deviance = SStotal-SSerror, model degrees of freedom = 1, and error degrees of freedom = n–2). Ninety-five percent confidence bounds of fitted values in exponential models were obtained using the predictNLS() function in the *propagate* package(Koenker & Machado 1999) with the 2.5th and 97.5th percentiles derived from 10,000 simulations per model.

TABLE 2: Above-ground plant attributes of 12 early colonising indigenous species in Gisborne, New Zealand. (DBH – diameter at breast height).

Species/Age	Height (m)	DBH (mm)	Root collar diameter (mm)
Year 1			
Coriaria arborea	0.44 (0.01)^{b}	-	3.7 (0.3)^{b}
Myrsine australis	0.54 (0.01)^{c}	-	7.0 (0.4)^{cd}
Pseudopanax arboreus	0.66 (0.03)^{e}	0.7 (0.03)	9.0 (0.5)^{ef}
Sophora tetraptera	0.76 (0.02)^{fg}	-	8.2 (0.4)^{de}
Cordyline australis	0.70 (0.02)^{ef}	-	13.0 (0.5)^{h}
Hoheria populnea	0.79 (0.03)^{g}	-	9.8 (0.4)^{fg}
Knightia excelsa	0.13 (0.004)^{a}	-	2.6 (0.2)^{a}
Pittosporum tenuifolium	0.42 (0.01)^{b}	-	7.2 (0.4)^{cd}
Pittosporum eugenoides	0.57 (0.02)^{cd}	-	7.5 (0.4)^{cd}
Coprosma robusta	0.62 (0.03)^{cde}	-	8.2 (0.4)^{de}
Plagianthus regius	0.90 (0.04)^{h}	-	10.4 (0.4)^{g}
Leptospermum scoparium	0.64 (0.03)^{de}	-	6.4 (0.3)^{c}
Year 2			
Coriaria arborea	0.33 (0.04)^{a}	-	22.1 (3.3)^{e}
Myrsine australis	0.53 (0.01)^{b}	-	8.5 (0.3)^{ab}
Pseudopanax arboreus	0.96 (0.03)^{ef}	1.0 (0.03)^{a}	11.3 (0.4)^{bc}
Sophora tetraptera	0.57 (0.05)^{bcd}	-	8.2 (0.5)^{ab}
Cordyline australis	0.57 (0.02)^{bc}	-	24.1 (1.3)^{e}
Hoheria populnea	1.01 (0.02)^{ef}	-	9.5 (0.2)^{abc}
Knightia excelsa	0.78 (0.03)^{cde}	-	11.1 (0.4)^{bc}
Pittosporum tenuifolium	0.83 (0.03)^{e}	-	6.1 (0.4)^{a}
Pittosporum eugenoides	0.70 (0.04)^{ce}	-	8.1 (0.4)^{ab}
Coprosma robusta	1.16 (0.08)^{f}	0.4 (0.4)^{a}	12.7 (0.7)^{c}
Plagianthus regius	1.74 (0.17)^{g}	5.5 (1.1)^{b}	17.4 (0.4)^{d}
Leptospermum scoparium	0.79 (0.04)^{cde}	-	6.6 (0.3)^{a}
Year 3			
Coriaria arborea	1.64 (0.09)^{cd}	36.3 (10.8)^{b}	78.7 (4.0)^{h}
Myrsine australis	0.79 (0.03)^{a}	-	10.2 (0.4)^{a}
Pseudopanax arboreus	1.04 (0.05)^{b}	1.0 (0.1)^{a}	20.5 (1.7)^{bcd}
Sophora tetraptera	1.50 (0.12)^{c}	11.4 (2.5)^{b}	22.9 (2.9)^{def}
Cordyline australis	1.24 (0.13)^{b}	14.5 (6.0)^{ab}	46.5 (4.9)^{g}
Hoheria populnea	1.09 (0.08)^{b}	4.0 (4.0)^{a}	17.0 (0.9)^{abc}
Knightia excelsa	1.17 (0.08)^{b}	0.6 (0.6)^{a}	21.1 (1.3)^{bcd}
Pittosporum tenuifolium	1.11 (0.03)^{b}	-	19.4 (0.8)^{bc}
Pittosporum eugenoides	1.12 (0.03)^{b}	-	24.4 (1.4)^{cde}
Coprosma robusta	1.27 (0.03)^{b}	-	33.1 (3.2)^{f}
Plagianthus regius	1.80 (0.07)^{d}	11.5 (1.1)^{b}	29.8 (1.4)^{ef}
Leptospermum scoparium	1.16 (0.05)^{b}	-	12.0 (0.7)^{ab}
Year 4			
Coriaria arborea	2.20 (0.10)^{cd}	90.2 (15.9)^{g}	126.0 (10.4)^{f}
Myrsine australis	1.06 (0.05)^{a}	-	18.2 (0.8)^{a}
Pseudopanax arboreus	2.16 (0.15)^{cd}	12.4 (2.6)^{cd}	45.3 (3.4)^{bc}
Sophora tetraptera	1.97 (0.07)^{bcd}	19.0 (2.1)^{de}	40.1 (7.8)^{bc}
Cordyline australis	2.30 (0.10)^{cd}	48.3 (2.8)^{f}	96.5 (4.5)^{e}
Hoheria populnea	2.48 (0.19)^{d}	24.1 (2.8)^{de}	37.0 (2.1)^{bc}
Knightia excelsa	1.59 (0.08)^{b}	3.9 (0.8)^{a}	28.7 (3.6)^{ab}
Pittosporum tenuifolium	2.00 (0.11)^{bcd}	14.9 (2.6)^{cd}	40.6 (3.8)^{bc}
Pittosporum eugenoides	1.84 (0.17)^{bc}	8.1 (1.8)^{ab}	33.9 (2.4)^{bc}
Coprosma robusta	1.84 (0.13)^{bc}	9.8 (3.3)^{bc}	50.7 (3.4)^{c}
Plagianthus regius	3.05 (0.20)^{c}	38.4 (5.2)^{ef}	69.0 (4.9)^{d}
Leptospermum scoparium	-	-	-
Year 5			
Coriaria arborea	2.44 (0.28)^{bc}	147.4 (48.0)^{e}	292.8 (71.4)^{d}
Myrsine australis	1.31 (0.10)^{a}	1.0 (0.6)^{a}	28.1 (2.6)^{a}
Pseudopanax arboreus	2.09 (0.16)^{b}	41.3 (17.2)^{b}	51.9 (6.4)^{ab}
Sophora tetraptera	2.51 (0.19)^{bc}	37.6 (9.8)^{bcd}	44.6 (4.4)^{ab}
Cordyline australis	3.10 (0.12)^{de}	69.4 (3.8)^{d}	121.3 (8.1)^{c}
Hoheria populnea	3.43 (0.12)^{e}	63.0 (12.4)^{cd}	60.7 (8.4)^{ab}
Knightia excelsa	2.31 (0.12)^{bc}	19.9 (3.1)^{b}	43.9 (4.2)^{ab}
Pittosporum tenuifolium	2.80 (0.16)^{bc}	44.3 (6.8)^{bcd}	55.7 (2.2)^{ab}
Pittosporum eugenoides	2.97 (0.09)^{de}	26.7 (2.7)^{bc}	61.0 (2.5)^{ab}
Coprosma robusta	2.19 (0.17)^{b}	52.8 (13.8)^{bcd}	72.4 (6.9)^{ab}
Plagianthus regius	3.19 (0.15)^{de}	66.2 (10.1)^{d}	85.2 (6.8)^{b}
Leptospermum scoparium	2.46 (0.09)^{bc}	20.6 (2.6)^{b}	34.4 (3.0)^{ab}

Note: Values in brackets represent the standard error of the mean. Values with different letters within each parameter and year were significantly different. (Student–Newman–Keuls ($P < 0.05$).

Results

Plant attributes

Growth trends between the species varied depending on the plant attribute assessed. For example, *Knightia excelsa* rapidly and significantly increased in both height and RCD but not DBH whereas the height of *Coprosma robusta* did not increase significantly over the study period, RCD plateaued at age 3 years and DBH did not increase until age 5 years (Table 2).

Seedling height, when all species were combined, was significantly less between ages 1 and 2 years (but not different between these ages) than between ages 3 and 5 years (but not different between these ages) (P < 0.001) (Table 2). When individual species were assessed separately, *Pittosporum tenuifolium* and *Knightia excelsa* were the only species to significantly increase in height in each year (P < 0.001), in contrast to *Coprosma robusta* which did not increase in height over the course of the study (P = 0.146). The height of *Cordyline australis*, *Sophora tetraptera, Pittosporum eugenoides,* and *Myrsine australis* increased annually from age 2 years onwards while the remaining species increased in height every second or third year (P < 0.001).

At age 5 years, the four tallest species (*Hoheria populnea*, *Plagianthus regius*, *Cordyline australis*, and *Pittosporum eugenoides*) were of similar height (c. 3 m), and significantly taller than the remaining species (Table 2). *Myrsine australis* (1.3 m) was significantly shorter than all the other species.

In each year of the trial there were significant differences in RCD among species (Table 2). *Knightia excelsa* was the only species to show a significant increase in RCD in each year of the study, *Cordyline australis*, *Pittosporum tenuifolium* and *Plagianthus regius* increased significantly in RCD each year from age 2 years and *Myrsine australis, Pittosporum eugenoides* and *Hoheria populnea* from age 3 years (P < 0.001). In contrast, the RCD values for *Coprosma robusta* plateaued at age 3 years, and the other remaining species increased in RCD every second or third year (P < 0.001).

At age 5 years, the RCD of the multi-stemmed *Coriaria arborea* (293 mm) and of the single-stemmed *Cordyline australis* (121 mm) was significantly greater than for the remaining species, and *Myrsine australis* (28.1 mm) a significantly smaller RCD than *Plagianthus regius* (85.2 mm).

Cordyline australis had significant increases in DBH in each year from age 2 years, and *Pittosporum tenuifolium*, *Hoheria populnea, Pittosporum eugenoides, Plagianthus regius, Leptospermum scoparium,* and *Coriaria arborea* from age 3 years (P < 0.001). The remaining species showed delayed DBH accrual and did not show significant increases in this parameter until 4 or 5 years old – except for *Myrsine australis* which showed no significant increases in DBH over the study period.

At age 5 years, there were significant differences between species with respect to DBH (Table 2). The DBH of *Myrsine australis* (1 mm) was significantly smaller than for all the other species, while that of *Coriaria arborea* (147 mm) was significantly larger. While the DBH for *Cordyline australis* and *Plagianthus regius* (69 and 66 mm, respectively) was significantly greater than for *Pseudopanax arboreus* (41 mm), there were few differences among the remaining species.

Allometric relationships

Height

Allometric relationships between RCD and height were highly significant (P < 0.001), with r^2 values ranging from to 0.90 (*Coriaria arborea*) to 0.97 (*Cordyline australis*) (Table 3, Appendix 2).

Biomass

Total and component above-ground biomass

The goodness of fit of relationships between RCD and total AGB varied with r^2 values (percentage of variance explained) ranging between 0.79 (*Coriaria arborea*) and 0.94 (*Leptospermum scoparium*, *Pseudopanax arboreus*) (Table 3, Appendix 3). For each of the test species, AGB made up between 70% and 81% of the total biomass of individual plants (Table 4). At age 5 years, *Cordyline australis* and *Coriaria arborea* accumulated significantly more AGB (P < 0.05) than did the remaining species. *Myrsine australis* had significantly less ABG than most of the other species except for *Pseudopanax arboreus*, *Leptospermum scoparium, Sophora tetraptera* and *Knightia excelsa* (Table 4).

Allometric relationship values between RCD and stem biomass ranged between r^2 values of 0.66 (*Coriaria arborea*) and 0.96 (*Pseudopanax arboreus*, *Leptospermum scoparium*) (Table 5 and Appendix 4). Stem biomass, as a proportion of total biomass, exceeded that of the other AGB components for *Coriaria arborea* (53.1%), *Pseudopanax arboreus* (52.1%), *Cordyline australis* (51%), *Hoheria populnea* (50.9%), *Plagianthus regius* (50.8%), *Knightia excelsa* (45.4%), *Sophora tetraptera* (35.5%), and *Coprosma robusta* (34.9%) (Table 4).

The r^2 of allometric relationships between RCD and branch biomass ranged between 0.45 (*Pseudopanax arboreus*) and 0.90 (*Leptospermum scoparium*) (Table 5 and Appendix 5). Branch biomass was the dominant component for three species: *Myrsine australis* (42.1%), *Pittosporum eugenoides* (40.5%), and *Pittosporum tenuifolium* (38.5%) (Table 4).

The r^2 of allometric relationships between RCD and foliage biomass ranged between 0.7 (*Coriaria arborea*) and 0.96 (*Pseudopanax arboreus*) (Table 5 and Appendix 6). At age 5 years, *Cordyline australis* had the greatest foliage biomass of all the test species (P < 0.05) (Table 4). *Coriaria arborea* also had significantly more foliage than most of the other species except for *Pittosporum eugenoides*, and *Coprosma robusta*. For *Cordyline australis,* foliage (49%) and stem (51%) biomass were apportioned equally; the foliage biomass of *Pseudopanax arboreus* and *Knightia excelsa* exceeded branch biomass; and for *Coriaria arborea, Hoheria*

TABLE 3: Allometric equations for 12 space-planted, early colonising indigenous shrub and tree species relating RCD to height, total above-ground biomass (AGB), and total below-ground biomass (BGB) at age 5 years, Gisborne, New Zealand.

Species	**Height**			**Total above-ground biomass**			**Total below-ground biomass**		
	r^2	***P***	**Equation**	r^2	***P***	**Equation**	r^2	***P***	**Equation**
Coriaria arborea	0.901	<0.001	y = 0.38ln(x)	0.789	<0.001	y = 29.4x	0.861	<0.001	y = 332e0.00615x
Myrsine australis	0.957	<0.001	y = 0.348ln(x)	0.861	<0.001	y = 26e0.0823x	0.818	<0.001	y = 12.9e0.075x
Pseudopanax arboreus	0.94	<0.001	y = 0.0444x	0.943	<0.001	y = 103e0.047x	0.897	<0.001	y = 41e0.0421x
Sophora tetraptera	0.921	<0.001	y = 0.529ln(x)	0.8	<0.001	y = 127e0.0464x	0.757	<0.001	y = 25.6e0.0572x
Cordyline australis	0.965	<0.001	y = 0.0247x	0.877	<0.001	y = 650e0.0212x	0.912	<0.001	y = 99.4e0.0253x
Hoheria populnea	0.904	<0.001	y = 0.0571x	0.858	<0.001	y = 322e0.0348x	0.796	<0.001	y = 110e0.0333x
Knightia excelsa	0.936	<0.001	y = 0.0513x	0.799	<0.001	y = 63.7e0.0526x	0.758	<0.001	y = 21.3e0.05x
Pittosporum tenuifolium	0.944	<0.001	y = 0.05x	0.845	<0.001	y = 137e0.0546x	0.845	<0.001	y = 29.8e0.0613x
Pittosporum eugenoides	0.968	<0.001	y = 0.0499x	0.897	<0.001	y = 221e0.0455x	0.931	<0.001	y = 53.9e0.0522x
Coprosma robusta	0.945	<0.001	y = 0.453ln(x)	0.89	<0.001	y = 407e0.0298x	0.947	<0.001	y = 85.7e0.0333x
Plagianthus regius	0.947	<0.001	y = 0.646ln(x)	0.869	<0.001	y = 551e0.0227x	0.941	<0.001	y = 161e0.0256x
Leptospermum scoparium	0.936	<0.001	y = 0.0762x	0.949	<0.001	y = 52.7e0.0871x	0.949	<0.001	y = 14.1e0.0852x

TABLE 4: Mean total biomass (kg) and mean component biomass as a percentage of above-ground biomass (AGB) and below-ground biomass (BGB); and AGB and BGB as a percentage of total plant biomass for 12 space-planted, early colonising indigenous shrub and tree species, at age 5 years, Gisborne, New Zealand.

Species	**Total biomass of AGB plus BGB (kg)**	**Percentage component biomass of AGB (%)**			**AGB as percentage of total plant biomass (%)**	**Percentage component biomass of BGB (%)**		**BGB as percentage of total plant biomass (%)**
		Foliage	**Branches**	**Stem**		**Root bole**	**Roots**	
Coriaria arborea	12.2	18.8	27.2	53.0	76.0	34.7	65.3	24.0
Myrsine australis	0.5	34.2	42.1	23.7	71.7	13.3	86.7	28.3
Pseudopanax arboreus	2.1	39.9	8.0	52.1	77.3	25.5	74.5	22.7
Sophora tetraptera	2.9	29.5	35.0	35.5	70.0	27.9	72.1	30.0
Cordyline australis	14.0	49.0	-	51.0	80.7	85.2	14.8	19.3
Hoheria populnea	5.6	18.6	30.5	50.9	76.2	29.9	70.1	23.8
Knightia excelsa	1.3	35.5	19.1	45.4	76.2	32.3	67.7	23.8
Pittosporum tenuifolium	5.1	25.8	38.5	35.7	76.0	31.0	69.0	24.0
Pittosporum eugenoides	5.8	29.3	40.5	30.2	73.4	22.6	77.4	26.6
Coprosma robusta	6.1	32.0	33.1	34.9	78.5	29.5	70.5	21.5
Plagianthus regius	6.9	8.9	40.3	50.8	73.5	36.3	63.7	26.5
Leptospermum scoparium	1.6	35.6	31.1	33.3	80.5	40.6	59.4	19.5

TABLE 5: Allometric equations relating root collar diameter (RCD) to foliage, branch, and stem biomass for 12 space-planted, early colonising indigenous shrub and tree species, at age 5 years, Gisborne, New Zealand.

Species	**Foliage**			**Branch**			**Stem**		
	r^2	***P***	**Equation**	r^2	***P***	**Equation**	r^2	***P***	**Equation**
Coriaria arborea	0.698	<0.001	y = 6.39x	0.849	<0.001	y = 7.75x	0.656	<0.001	y = 15.2x
Myrsine australis	0.85	<0.001	y = 9.7e0.0787x	0.805	<0.001	y = 10.2e0.0831x	0.881	<0.001	y = 6.18e0.0856x
Pseudopanax arboreus	0.961	<0.001	y = 36.6e0.0483x	0.453	<0.001	y = 4.35x	0.964	<0.001	y = 33.3e0.0529x
Sophora tetraptera	0.784	<0.001	y = 25.1e0.0524x	0.761	<0.001	y = 49.6e0.0462x	0.71	<0.001	y = 53.3e0.0422x
Cordyline australis	0.855	<0.001	y = 35.3x				0.87	<0.001	y = 186e0.0258x
Hoheria populnea	0.867	<0.001	y = 65.1e0.0341x	0.768	<0.001	y = 118e0.032x	0.88	<0.001	y = 140e0.037x
Knightia excelsa	0.793	<0.001	y = 26.6e0.0499x	0.78	<0.001	y = 8.97e0.0586x	0.793	<0.001	y = 28.4e0.0525x
Pittosporum tenuifolium	0.793	<0.001	y = 51.2e0.0478x	0.812	<0.001	y = 31e0.0642x	0.794	<0.001	y = 58e0.0513x
Pittosporum eugenoides	0.896	<0.001	y = 80.7e0.0421x	0.842	<0.001	y = 86.1e0.0458x	0.899	<0.001	y = 54.6e0.049x
Coprosma robusta	0.819	<0.001	y = 18.2x	0.872	<0.001	y = 20x	0.848	<0.001	y = 59.6e0.0399x
Plagianthus regius	0.774	<0.001	y = 45.7e0.0247x	0.858	<0.001	y = 220e0.0227x	0.858	<0.001	y = 286e0.0224x
Leptospermum scoparium	0.885	<0.001	y = 24.4e0.0788x	0.901	<0.001	y = 12.5e0.0951x	0.956	<0.001	y = 15.3e0.0912x

populnea, and Plagianthus regius, foliage comprised the least of their three AGB components (Table 4).

Total and component below-ground biomass

The relationship between RCD and total BGB ranged between an r^2 of 0.76 (*Knightia excelsa*, *Sophora tetraptera*) and 0.95 (*Leptospermum scoparium*, *Plagianthus regius*, *Coprosma robusta)* (Table 3 and Appendix 7). At age 5 years, *Coriaria arborea* and *Cordyline australis* had accumulated significantly more total BGB than had the remaining species; however, differences in BGB between each of the remaining species were not significant ($P < 0.05$) (Table 4). Whereas the tap-rooted species *Cordyline australis* (the deepest-rooted of the test species) allocated 85% of its total BGB to the root bole, the remaining species allocated a smaller proportion of between 13% (*Myrsine australis*) and 40% (*Leptospermum scoparium)*, and this difference was significant ($P = 0.05$). Apart from *Cordyline australis*, the biomass allocation to roots of the remaining species ranged between 59% (*Leptospermum scoparium)* and 87% (*Myrsine australis*), exceeding that of the root bole.

BGB to AGB ratio

Across all years, BGB as percentage of total plant biomass for all species was highly variable. Four species showed an increase in BGB at age 5 years (*Myrsine australis, Sophora tetraptera, Coriaria arborea and Pittosporum tenuifolium*), while the remainder of species showed a decrease in BGB as percentage of total plant biomass. At age 5 years, BGB for *Sophora tetraptera* (30%) was significantly greater ($P = 0.05$) than for *Cordyline australis* and *Leptospermum scoparium* (19%) (Table 4).

Total plant biomass

The relationship between RCD and whole-plant biomass ranged from an r^2 of 0.79 (*Knightia excelsa, Sophora tetraptera*) to 0.95 (*Leptospermum scoparium)* (Table 6 and Appendix 8).

Biomass accumulation by individual plants of each species increased significantly with age. At a rate of 0.1 kg/yr, *Myrsine australis* accumulated the least biomass at age 5 years (0.5 kg plant^{-1}), but not significantly different to that amassed by *Pseudopanax arboreus*, *Knightia excelsa*, *Leptospermum scoparium*, or *Sophora tetraptera.* Conversely, over 5 years, *Cordyline australis* accumulated on average 14 kg of plant biomass (2.8 kg plant^{-1} yr^{-1}) and *Coriaria arborea* 12 kg (2.4 kg plant^{-1} yr^{-1}), significantly greater than any of the other species (Table 7). The remainder of the species, including *Hoheria populnea*, *Pittosporum tenuifolium*, *Pittosporum eugenoides*, *Plagianthus regius*, and *Coprosma robusta*, each accumulated a mean total plant biomass at age 5 years (i.e. 3 years after planting at the trial site) of between 5 kg and 7 kg plant^{-1} (Table 7).

Carbon content

The mean total carbon content accumulated by individual plants was significantly higher for *Cordyline australis*

TABLE 6: Allometric equations relating root collar diameter (RCD) to whole-plant biomass for 12 space-planted, early colonising indigenous shrub and tree species, at age 5 years, Gisborne, New Zealand.

Species	**Total biomass**		
	r^2	***P***	**Equation**
Coriaria arborea	0.82	<0.001	y = 39.4x
Myrsine australis	0.85	<0.001	y = 38.8e0.0801x
Pseudopanax arboreus	0.94	<0.001	y = 144e0.0458x
Sophora tetraptera	0.79	<0.001	y = 154e0.0488x
Cordyline australis	0.90	<0.001	y = 750e0.0219x
Hoheria populnea	0.85	<0.001	y = 433e0.0344x
Knightia excelsa	0.79	<0.001	y = 84.9e0.052x
Pittosporum tenuifolium	0.85	<0.001	y = 167e0.056x
Pittosporum eugenoides	0.91	<0.001	y = 274e0.0471x
Coprosma robusta	0.92	<0.001	y = 491e0.0306x
Plagianthus regius	0.90	<0.001	y = 711e0.0235x
Leptospermum scoparium	0.95	<0.001	y = 66.7e0.0868x

(7 kg) and *Coriaria arborea* (6.1 kg) than for the remaining species, including *Hoheria populnea*, *Pittosporum tenuifolium*, *Pittosporum eugenoides*, *Plagianthus regius*, and *Coprosma robusta*, which accumulated between 1 and 3 kg carbon per plant over 5 years. *Knightia excelsa*, *Myrsine australis*, and *Leptospermum scoparium* each accumulated <1 kg of carbon per plant over 5 years (Table 7).

At age 5 years, the carbon accumulation by *Sophora tetraptera*, *Pittosporum eugenoides*, *Coprosma robusta*, and *Leptospermum scoparium* was relatively evenly distributed between foliage, branches, and stem (Table 8). For the remaining species, including *Plagianthus regius*, *Pittosporum tenuifolium*, *Hoheria populnea*, and *Coriaria arborea*, both stem and branch carbon exceeded foliage carbon, and for *Knightia excelsa* and *Pseudopanax arboreus,* branches accumulated the least carbon. For *Cordyline australis*, carbon accumulation was evenly distributed between stem and foliage. Stem carbon exceeded branch and foliage carbon combined for *Coriaria arborea*, *Pseudopanax arboreus, Cordyline australis*, *Hoheria populnea*, and *Plagianthus regius.* Apart from the tap-rooted *Cordyline australis*, root carbon exceeded root bole carbon (Table 8).

Carbon stocks

For many species there were no significant differences between the carbon content of the AGB components (foliage, branch and stem). The BGB components (root bole and roots) were also usually smaller than ABG components for many species. For *Coriaria arborea* and *Sophora tetraptera* there were no significant differences between any of the components (Table 8).

At a planting density of 1000 stems ha^{-1} consisting of equal numbers (~83 of each of the 12 test species) would amass a forest carbon stock of 8.8 t CO_2

TABLE 7: Mean 5-year-old tree biomass (dry weight), biomass accumulation, carbon content, and carbon stock for 12 space-planted, early colonising indigenous shrub and tree species, at age 5 years, Gisborne, New Zealand.

Botanical name	**Mean tree biomass (kg)**	**Biomass accumulation (kg yr^{-1})**	**Carbon content (kg)**	**Carbon stock (t CO_2. 1,000 stems ha^{-1})**
Coriaria arborea	12.2 (4.5)^{d}	2.4 (0.9)^{f}	6.1 (2.3)^{d}	20.13
Myrsine australis	0.5 (0.1)^{a}	0.1 (0.02)^{a}	0.3 (0.05)^{a}	0.83
Pseudopanax arboreus	2.1 (0.7)^{abc}	0.4 (0.1)^{abcd}	1.1 (0.4)^{abc}	3.47
Sophora tetraptera	2.9 (0.8)^{abc}	0.6 (0.2)^{abcde}	1.4 (0.4)^{abc}	4.79
Cordyline australis	14.0 (1.3)^{d}	2.8 (0.3)^{f}	7.0 (0.6)^{d}	23.10
Hoheria populnea	5.6 (1.5)^{bc}	1.1 (0.3)^{cde}	2.8 (0.7)^{bc}	9.24
Knightia excelsa	1.3 (0.3)^{ab}	0.3 (0.1^{ab}	0.7 (0.1)^{ab}	2.15
Pittosporum tenuifolium	5.1 (0.5)^{abc}	(0.1)^{bcde}	2.5 (0.3)^{abc}	8.42
Pittosporum eugenoides	5.8 (0.4)^{bc}	1.2 (0.1)^{cde}	2.9 (0.2)^{bc}	9.57
Coprosma robusta	6.1 (1.1)^{bc}	1.2 (0.2)^{de}	3.0 (0.5)^{bc}	10.07
Plagianthus regius	6.9 (1.1)^{c}	1.4 (0.2)^{e}	3.4 (0.5)^{c}	11.39
Leptospermum scoparium	1.6 (0.3)^{ab}	0.3 (0.1)^{abc}	0.8 (0.1)^{ab}	2.64

Values in brackets represent the standard error of the mean. Values with different letters within each parameter were significantly different (Student–Newman–Keuls *P* = 0.05). The carbon stock values do not include woody debris or fine litter.

TABLE 8: Mean above- and below-ground component carbon (kg), total carbon (kg), and component carbon as a percentage of total carbon for 12 space-planted, early colonising indigenous shrub and tree species, at age 5 years, Gisborne, New Zealand.

Species	**Component carbon (kg)**						**Total carbon (kg)**	**Percentage of total carbon**				
	Foliage	**Branches**	**Stem**	**Root bole**	**Roots**	***P* value**		**Foliage**	**Branches**	**Stem**	**Root bole**	**Roots**
Coriaria arborea	0.87	1.27	2.47	0.51	0.96	0.078	6.1 (2.3)	14.31	20.88	40.62	8.39	15.79
Myrsine australis	0.07^{b}	0.08^{b}	0.05^{b}	0.01^{a}	0.07^{b}	<0.001	0.3 (0.05)	25.00	28.57	17.86	3.57	25.00
Pseudopanax arboreus	0.33^{b}	0.07^{b}	0.43^{b}	0.06^{a}	0.18^{b}	<0.001	1.1 (0.4)	30.84	6.54	40.19	5.61	16.82
Sophora tetraptera	0.30	0.35	0.36	0.12	0.31	0.298	1.4 (0.4)	20.83	24.31	25.00	8.33	21.53
Cordyline australis	2.77^{c}	-	2.88^{c}	1.15^{b}	0.20^{a}	<0.001	7.0 (0.6)	39.6	-	41.1	16.4	2.9
Hoheria populnea	0.40^{a}	0.66^{ab}	1.10^{b}	0.20^{a}	0.47^{a}	0.004	2.8 (0.7)	14.13	23.32	38.87	7.07	16.61
Knightia excelsa	0.18^{ab}	0.10^{ab}	0.23^{c}	0.04^{a}	0.11^{ab}	<0.001	0.7 (0.1)	27.27	15.15	34.85	6.06	16.67
Pittosporum tenuifolium	0.49^{bc}	0.74^{c}	0.68^{c}	0.18^{a}	0.43^{b}	<0.001	2.5 (0.3)	19.44	29.37	26.98	7.14	17.06
Pittosporum eugenoides	0.63^{b}	0.87^{b}	0.65^{b}	0.19^{a}	0.60^{b}	<0.001	2.9 (0.2)	21.43	29.59	22.11	6.46	20.41
Coprosma robusta	0.76^{b}	0.79^{b}	0.84^{b}	0.19^{a}	0.47^{ab}	0.006	3.0 (0.5)	24.92	25.90	27.54	6.23	15.41
Plagianthus regius	0.23^{a}	1.02^{b}	1.29^{b}	0.34^{a}	0.58^{a}	<0.001	3.4 (0.5)	6.65	29.48	37.28	9.83	16.76
Leptospermum scoparium	0.23^{b}	0.20^{b}	0.20^{b}	0.06^{a}	0.09^{a}	<0.001	0.8 (0.1)	29.49	25.64	25.64	7.69	11.54

Values in brackets represent the standard error of the mean. Values with different letters within each parameter were significantly different (Student–Newman–Keuls $P = 0.05$).

1000 stems ha^{-1} at age 5 years.

Maximum gains in carbon stock could be achieved by mixed plantings of equal numbers (~143) of the seven best-performing of the test species including *Cordyline australis*, *Coriaria arborea*, *Plagianthus regius, Coprosma robusta*, *Pittosporum eugenoides*, *Hoheria populnea and Pittosporum tenuifolium* with a potential to amass a carbon stock of 13.1 t CO_2 1000 stems ha^{-1}, an additional 4.3 t CO_2 1000 stems ha^{-1}.

Discussion

As the range of geographical sites being considered for protection in New Zealand encompass a wide range of environmental conditions across different open (non-forested) landscapes increases, the potential influence of local and micro site factors on overall plant survival and growth performance becomes greater (Marden et al. 2020). In the current study, site factors appear to have had a significant influence on the growth performance of *Leptospermum scoparium* and *Myrsine australis*, with significantly slower growth on fertile soils than has previously been measured for similar-aged plants established on harsher and less fertile sites more typical of their natural occurrence. Other influences, including susceptibility to frost (e.g. *Coriaria arborea*), attack by scale insects (e.g. *Leptospermum scoparium*), leaf rust (e.g. *Knightia excelsa* and *Coprosma robusta*), and windthrow (e.g. *Coprosma robusta*, *Coriaria arborea*, and *Cordyline australis*) have had an influence on AGB performance and therefore overall plant biomass productivity and carbon stock values. While the openness/exposure of sites is likely to affect the early growth performance of shade-tolerant species, including *Pittosporum eugenoides* and *Pseudopanax arboreus*, they have proven – once established – to be sufficiently hardy to tolerate a wide range of environmental conditions (Marden et al. 2005, 2020; Marden & Lambie 2016).

Although the physiological age of all the species tested and documented in this paper was similar at the time of planting, there were initial and significant differences in their above-ground metrics. However, once established, and although interspecific differences in year-on-year growth remained variable between ages 1 and 3 years, by age 4 years Cordyline australis*, Coriaria arborea, Plagianthus regius, Coprosma robusta, Pittosporum eugenoides, Hoheria populnea, Pittosporum tenuifolium, and Sophora tetraptera* were the better performers in terms of their growth and this trend continued into the last year of the trial. In each year of the trial, and for each of the 12 species trialled, RCD was found to be a good fit for estimating foliage, branch and stem biomass, total AGB, total BGM, and whole plant biomass. We also found that the allocation of biomass between these components is species specific and age dependent. Furthermore, while species such as *Leptospermum scoparium*, *Plagianthus regius*, *Coprosma robusta*, *Hoheria populnea*, *Pseudopanax arboreus*, *Knightia excelsa* and *Cordyline australis* initially invested more of their total plant biomass into developing a robust root system, this investment decreased with increasing age. This finding is consistent with international literature showing that a decrease in the root: shoot ratio is related to an increase in plant height/size (Cao & Ohkubo 1998; Ovington 1957; Litton et al. 2003). For the remainder of species, annual increments in the BGB of *Coriaria arborea*, *Myrsine australis*, *Sophora tetraptera*, *Pittosporum tenuifolium*, and *Pittosporum eugenoides*, though small, were steady. Local site conditions also influence the allocation of biomass between the below-ground and above-ground plant components. For example, following the planting of *Leptospermum scoparium* on steep hill country severely impacted by storm-initiated slope failures, the apportionment of biomass between the below- and above-ground plant components occurred earliest, and remained constant with increasing age in plantings established on interfluves and colluvial slopes least affected by erosion (Marden et al. 2020). Here, deep, well-aerated and naturally fertile allophanic soils are more likely to retain large soil moisture and nutrient reserves for longer periods (Scholten et al. 2017; Yost et al. 2018). Conversely, *Leptospermum scoparium* established on slopes severely affected by erosion, developed a compact root system dominated by a dense and shallow network of fibrous roots, likely in response to the harsher site conditions and shallow skeletal soils (Marden et al. 2020). This may indicate that where soils are thin and soil moisture levels are low during lengthy dry spells, the allocation of a higher proportion of biomass towards early root development is an attempt to improve accessibility to limited resources (Lloreet et al. 1999) and reflects the influence of harsher edaphic factors on root development (Ketterings et al. 2001). Typically, at many such sites, although the presence of impenetrable bedrock at shallow depths further restricts root development, particularly of the vertical anchoring roots, the BGB of *Leptospermum scoparium* excavated from harsh landslide-prone sites 6 years after planting approximated 24% while that for plants established on the deeper and more fertile sites was just 16% (Marden et al. 2020).

Thus, differences in the availability of nutrients and water, together with contrasting site factors (e.g. altitude, location in the landscape, susceptibility to erosion, sheltered versus exposed sites, soil depth and bulk density, barriers to root penetration) probably explain much of the variation in *Leptospermum scoparium* biomass productivity and carbon stocks across these different landforms (Marden et al. 2020).

For the 12 early-colonising indigenous forest and shrub species documented in this paper, their total BGB (including the stump) at age 5 years ranged between 24% and 44% of total tree biomass, which is similar to values reported for 8 of New Zealand's dominant conifer and broadleaved forest speciesof between 21% and 42% at the same age (Marden et al. 2018a). Both studies indicate that for these indigenous shrub and tree species that typically comprise a significant component of New Zealand's early seral forest associations, each has the potential to allocate more than the internationally and locally accepted figure of 20% of their total biomass to BGB at age 5-years.

The variability in the proportion of BGB allocated to the root bole versus the roots of different root system types (e.g. tap-rooted versus heart–rooted) has been less well documented. For example, the tap-rooted species *Cordyline australis* (the deepest-rooted of the test species) allocated 85% of its total BGB to the root bole, significantly more than each of the heart-rooted species (where root bole allocation as a percentage of total BGB ranged between 13% and 39% Marden et al. 2018b). The allocation of total BGB to the root boles of the eight most common indigenous conifer and broadleaved forest species at the same age ranged between 16% and 30%. For *Leptospermum scoparium* established across naturally fertile interfluve and colluvial slopes, 30% of the total BGB was allocated to the root bole, whereas on landslide-affected slopes it was allocated equally between roots and the root bole, which was a significant difference (Marden et al. 2020). This is consistent with findings that there are interspecific differences in biomass allocation to root systems, with each species allocating differing proportions of their total biomass to different root components at different stages of growth (Korner 1998).

Interspecific differences in root distribution have implications for the planting densities required to provide full, near-surface root occupancy of the soil and/or to maximise the root density to the depth requirement at specific sites. The tap-rooted *Cordyline australis* will probably provide a higher level of soil reinforcement directly under the stand and to a greater depth than for heart-rooted species but reinforcement levels quickly taper off laterally as root density decreases away from the stand edge. In contrast, the remaining 11 test species will probably provide a higher level of near-surface soil reinforcement and to a greater distance from the stem, but the level of reinforcement will rapidly decline at a relatively shallow depth.

In New Zealand, regenerating indigenous shrublands dominated by *Leptospermum scoparium* and *Kunzea* spp. are a widespread first stage in the succession to an indigenous forest and account for about 70% of the national area of regenerating indigenous vegetation (Ministry for Primary Industries 2017) with considerable potential to amass carbon stocks. For these areas the value of carbon stocks pre-calculated 5 years after the commencement of reversion is estimated at 7.8 t CO_2 ha^{-1}, which includes carbon stock values for woody debris and fine litter (Ministry for Primary Industries 2017). Conversely, while the growth performance of other individual species or the collective growth of different mixes of many of New Zealand's other indigenous shrub and tree species that also commonly make up early successional stages of reversions to tall forest have not been measured, their potential to amass carbon stocks remains unknown (Carswell et al. 2012).

The results of recent studies on the growth performance of a selection of New Zealand's indigenous and shrub species present during the early stages of natural reversion provide insights into their potential as individual or different mixes to amass carbon stocks. For example, the same amount of carbon stock could be achieved within 3-years of planting 74 of each of the 12 trialled indigenous shrub and tree species as 2-year-old seedlings at a density of c. 888 stems ha^{-1}.

Alternatively, by planting a mix of equal numbers of the seven best-performing of these same species as 2-year-old seedlings, at a density more typical of an exotic forest regime, could potentially amass a carbon stock of 13.1 t CO_2 1000 stems ha^{-1} within 3 years, almost double the carbon stocks calculated by the Ministry for Primary Industries for naturally regenerating indigenous shrublands at age 5 years.

A further option for transitioning degraded landscapes to a permanent indigenous vegetation cover is through the planting of successional indigenous podocarp/conifer species. However, to achieve a similar level of carbon stock would require the planting of equal numbers of each podocarp and conifer species trialled by Marden et al. (2018b), at a density of c. 4,200 stems ha^{-1}. For monoculture plantings of *Leptospermum scoparium,* c. 2,200 stems ha^{-1} would be required to achieve a similar level of carbon stock amassed by naturally regenerating indigenous shrublands at age 5 years.

A means of increasing species diversity earlier could include the planting of a mix of both early colonising and successional indigenous podocarp/conifer species. Site selection will prove critical in reducing the likelihood of suppression of the generally slower-to-establish successional species by the faster growing early colonising species. To compensate for these differences in growth performance during their early establishment period, the successional species would likely preform best, and survive in larger numbers, if planted on the more fertile sites and if the early colonising species were restricted to the harsher sites to which they are best adapted. The potential to amass carbon stocks will depend on species selection, the ratio of early colonising species versus successional podocarp/conifer species planted, and the overall planting density.

However, irrespective of the species mix and planting regime adopted for new areas of indigenous forest establishment, the potentially achievable forest carbon stock by age 5 years is likely to be an order of magnitude less than the ~91.6 t CO2 ha^{-1} of forest carbon stock recorded for 4-year-old *Pinus radiata* (from Marden & Lambie 2016) and the 77 t CO2 ha^{-1} estimated for 5-year-old post-1989 plantings in the East Coast region (Ministry for Primary Industries 2017). Notwithstanding, the planting of indigenous conifers and broadleaved species on erodible marginal land will ultimately afford a more continuous and permanent forest sink for carbon over an active growth phase that extends from 150 to 500 years (Hall 2001; Hinds & Reid 1957) that is consistent with the prolonged effort likely required to effect significant reductions in atmospheric CO_2 levels.

Of note, while *Coriaria arborea* has the second highest rate of biomass accumulation of the test species (~12 kg per plant at age 5 years), the second highest carbon stock values by age 5 years (~20 t CO_2 1000 stems ha^{-1}), and is one of the earliest and most widespread species to effectively restore slope stability in eroded landscapes (Marden et al. 2018b), it is toxic to browsing animals, and nectar foraged by bees has been found as a contaminant in honey (Beasley et al. 2018).

In the longer term and irrespective of the mixes of species and planting density (as carbon is not expected to accumulate linearly), estimates of the potential carbon stocks likely to be sequestered remain unknown. Although seeds were sourced from wild populations of trees and shrubs endemic to the East Coast region and specifically from within the Turanga Ecological District (Clarkson & Clarkson 1991), the influence of genetics of the parent plants from which seedlings were propagated and of variations in planting density on biomass productivity and carbon stocks also remain unknown.

Consideration of factors that influence plant growth, and matching species to the most appropriate site are both essential to the success of large-scale restoration programmes that involve mixed plantings of indigenous tree and shrub species on open sites and that seek to gain optimal growth and carbon gains (Tāne's Tree Trust 2012).

Guidelines for planting nursery-raised seedlings of early colonising seral species recommend densities between 1,000 (amenity plantings including riparian corridors) and 10,000 stems ha^{-1} for large-scale restoration programmes on erosion-prone marginal land. Planting at the high density is cost prohibitive and often of no enduring benefit. Planting at wider spacings provides room for air circulation and for root networks to develop without undue competition and suppression from adjacent plants. With good aftercare practices, survival rates of 90% are achievable and full root occupancy and canopy closure occur within 4 and 8 years of planting, respectively. Options that promote full soil-root reinforcement and quickest canopy closure are likely to be the most effective in enhancing slope stability (Phillips et al. 2001).

Conclusions and Recommendations

While this study provides detailed information on the allocation of biomass to individual above- and below-ground plant components of 12 of New Zealand's common riparian and early colonising shrub and tree species, the conclusions are drawn from their early growth period at one trial site that included effective weed control. It must be acknowledged that allometric relationships are likely to change with increasing tree age and differing rates of growth in other environments. It is therefore important that further allometric equations relating tree diameter and height to biomass are obtained for a wider range of species comprising New Zealand's dominant seral mixed-plant communities, across a range of sites conditions. It is also important that measurements of root biomass be based on whole-root extraction methods (in preference to applying allometric relationships derived from adult-tree functions).

The excavation and partitioning of entire plant systems into their above- and below-ground components has provided rare and valuable insights into interspecies differences in the allocation of root biomass following the establishment of some of the more common of New

Zealand's indigenous forest and shrubland species. However, we note that the assumption that all plant species allocate 20% of their biomass to roots is unlikely to hold true for forest and shrubland species at different stages of seral development or in different environments.

Whole-root system excavations have also added value in characterising the spatial distribution of root biomass with depth and distance from the root bole over time (Marden et al. 2018b). Such data are integral to the selection of an appropriate species mix and planting density, and as a means of assessing the period (years after planting) before juvenile plantings and/or the transition through natural reversion processes are likely to afford effective mitigation against different forms of erosion (e.g. shallow landslides and small-scale, deeper-seated slope failures), particularly on marginal land better suited to transitioning to a permanent forest cover; and such data will also be integral to selection of species for stabilising different bank styles.

The species-specific allometric equations presented for the early colonising shrubland and forest species documented in this paper, together with those derived in previous studies for *Leptospermum scoparium* and eight successional conifer and broadleaved species has highlighted their strengths and limitations, as individual and/or as mixed plantings, in restoring stability and increasing biodiversity to erodible marginal pastoral land and ecological integrity and functionality to streamside corridors. With the potential to transition a significant c. 1.45 million hectares to a more continuous and permanent forest cover, species-specific allometric equations afford an opportunity to validate current estimates of carbon stocks and report potential carbon stocks, consistent with the prolonged effort required to effect significant reductions in New Zealand's atmospheric carbon dioxide levels.

List of abbreviations

AGB above-ground biomass
BGB below-ground biomass
DBH diameter at breast height
RCD root collar diameter

Competing interests

The authors declare they have no competing interests.

Funding

This research was supported by funding from the Ministry of Business, Innovation and Employment (MBIE), the Sustainable Land Use Research Initiative (SLURI) through Plant & Food Research, in-part through the Manaaki Whenua – Landcare Research Strategic Science Investment Fund and, in part, through the Smarter Targeting of Erosion Control (STEC) programme (Contract C09X1804).

Authors' contributions

MM was the primary author. MM and DR designed and established the trial site, excavated, and measured the plants, and compiled the data. NM and SL provided the statistical analyses. All authors read and approved the manuscript.

Acknowledgements

We acknowledge the support of the Tairawhiti Polytechnic Rural Studies Unit, Gisborne, on whose land the riparian plant trial was located. Graphics were drawn by Norman Mason and Nicolette Faville. Ray Prebble and Helen O'Leary edited the manuscript. Robyn Simcock and Mark Smale reviewed the manuscript and provided valuable comments. Thanks also to the three anonymous external reviewers and to the Editor for their valuable comments.

Availability of data and materials

Please contact the corresponding author for data requests.

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Appendices

APPENDIX 1: Mean foliage, branch, and stem biomass (g), total above-ground (AGB) and below-ground (BGB) biomass, and the BGB:AGB ratio for 12 space-planted, early colonising indigenous shrub and tree species, at age 5 years, Gisborne, New Zealand.

Species/Age	Foliage (g)	Branches (g)	Stem (g)	Total AGB (g)	Total BGB (g)	BGB:AGB ratio
Year 1						
Coriaria arborea	1.1 (0.1)^{ab}	-	0.5 (0.1)^{a}	0.6 (0.2)^{a}	0.3 (0.03)^{a}	0.17 (0.01)^{a}
Myrsine australis	7.8 (0.9)^{g}	5.1 (0.7)^{d}	3.1 (0.1)^{b}	15.9 (1.6)^{ef}	3.6 (0.4)^{bcd}	0.28 (0.01)^{ab}
Pseudopanax arboreus	6.4 (0.8)^{fg}	-	9.0 (1.0)^{e}	15.4 (1.6)^{ef}	6.5 (0.8)^{cd}	0.43 (0.04)^{bc}
Sophora tetraptera	3.8 (0.3)^{de}	1.3 (0.2)^{ab}	5.2 (0.6)^{cd}	10.3 (1.0)^{bcd}	4.0 (0.5)^{bcd}	0.38 (0.03)^{bc}
Cordyline australis	15.2 (0.7)^{h}	-	0.3 (0.1)^{a}	15.6 (0.7)^{ef}	9.0 (0.8)^{e}	0.59 (0.06)^{de}
Hoheria populnea	3.6 (1.0)^{de}	1.1 (0.2)^{ab}	8.8 (0.4)^{e}	13.6 (1.0)^{cde}	9.3 (0.7)^{e}	0.70 (0.06)^{e}
Knightia excelsa	0.5 (0.1)^{a}	-	0.1 (0.01)^{a}	0.7 (0.1)^{a}	0.3 (0.1)^{a}	0.38 (0.05)^{bc}
Pittosporum tenuifolium	2.8(0.4)^{bd}	3.4 (0.6)^{c}	3.5 (0.3)^{bc}	9.7 (1.0)^{bc}	3.9 (0.5)^{bc}	0.40 (0.02)^{bc}
Pittosporum eugenoides	3.8 (0.4)^{de}	2.7 (0.4)^{bc}	6.2 (0.6)^{d}	12.6 (1.0)^{bcde}	3.5 (0.4)^{b}	0.27 (0.02)^{ab}
Coprosma robusta	3.8 (0.4)^{de}	0.2 (0.1)^{a}	4.9 (0.5)^{cd}	8.9 (0.8)^{b}	6.3 (0.5)^{c}	0.73 (0.06)^{e}
Plagianthus regius	1.3 (0.1)^{abc}	7.0 (0.6)^{e}	9.9 (0.7)^{e}	18.2 (1.2)^{f}	9.1 (0.7)^{e}	0.51 (0.03)^{cd}
Leptospermum scoparium	5.3 (0.4)^{ef}	4.2 (0.7)^{cd}	4.0 (0.2)^{bc}	13.5 (1.2)^{de}	9.4 (1.6)^{e}	0.69 (0.09)^{e}
Year 2						
Coriaria arborea	15.6 (4.6)^{bc}	5.7 (1.7)^{ab}	11.1 (3.4)^{abc}	32.4 (9.5)^{ab}	7.5 (1.9)^{ab}	0.27 (0.03)^{a}
Myrsine australis	6.8 (1.1)^{ab}	7.5 (0.4)^{b}	7.3 (0.6)^{ab}	21.4 (1.8)^{ab}	8.5 (0.9)^{ab}	0.40 (0.03)^{ab}
Pseudopanax arboreus	22.7 (1.5)^{c}	0.8 (0.5)^{a}	31.5 (3.2)^{d}	55.0 (4.5)^{c}	12.5 (1.5)^{b}	0.23 (0.03)^{a}
Sophora tetraptera	3.4 (0.7)^{ab}	2.9 (0.9)^{ab}	4.2 (0.9)^{a}	10.6 (2.3)^{a}	6.9 (0.9)^{ab}	0.74 (0.09)^{d}
Cordyline australis	61.9 (7.2)^{d}	-	16.9 (3.0)^{bc}	78.8 (9.5)^{d}	25.5 (3.6)^{c}	0.39 (0.09)^{ab}
Hoheria populnea	2.1 (0.2)^{a}	1.7 (0.2)^{a}	8.2 (0.6)^{ab}	11.9 (1.0)^{a}	7.1 (0.5)^{ab}	0.62 (0.07)^{cd}
Knightia excelsa	11.5 (1.0)^{ab}	3.4 (1.2)^{ab}	11.2 (1.4)^{abc}	26.1 (1.8)^{ab}	6.8 (0.8)^{ab}	0.26 (0.02)^{a}
Pittosporum tenuifolium	5.9 (0.6)^{ab}	5.2 (0.4)^{ab}	6.3 (0.6)^{ab}	17.4 (1.3)^{ab}	4.1 (0.4)^{a}	0.24 (0.02)^{a}
Pittosporum eugenoides	6.7 (0.8)^{ab}	4.9 (0.6)^{ab}	9.3 (0.7)^{ab}	21.2 (1.3)^{ab}	4.2 (0.3)^{a}	0.20 (0.02)^{a}
Coprosma robusta	13.9 (3.2)^{abc}	4.8 (0.9)^{ab}	21.0 (5.0)^{c}	39.7 (8.8)^{bc}	7.9 (1.4)^{ab}	0.21 (0.01)^{a}
Plagianthus regius	7.0 (1.5)^{abc}	21.8 (2.9)^{c}	76.8 (6.5)^{e}	105.5 (9.9)^{e}	39.6 (3.4)^{d}	0.39 (0.03)^{ab}
Leptospermum scoparium	5.9 (0.5)^{ab}	4.8 (0.4)^{ab}	5.6 (0.5)^{ab}	16.4 (1.2)^{ab}	8.5 (1.9)^{ab}	0.53 (0.11)^{bc}

Values in brackets represent the standard error of the mean. Values with different letters within each parameter and year were significantly different. (Student–Newman–Keuls ($P < 0.05$).

APPENDIX 1 *continued*

Year 3						
Coriaria arborea	639.1 (172.7)^{b}	324.6 (42.1)^{d}	429.9 (66.0)^{d}	1393.6 (255.7)^{d}	409.2 (45.1)^{c}	0.33 (0.02)^{a}
Myrsine australis	7.5 (0.7)^{a}	10.0 (1.2)^{a}	8.5 (0.9)^{a}	26.0 (2.1)^{a}	13.2 (1.2)^{a}	0.51 (0.03)^{b}
Pseudopanax arboreus	54.8 (8.6)^{a}	14.6 (3.0)^{a}	47.9 (7.9)^{a}	117.2 (17.2)^{ab}	28.3 (3.9)^{a}	0.25 (0.02)^{a}
Sophora tetraptera	126.5 (25.5)^{a}	136.2 (32.1)^{b}	127.9 (34.5)^{abc}	390.5 (87.8)^{ab}	121.8 (31.5)^{a}	0.31 (0.02)^{a}
Cordyline australis	634.7 (140.0)^{b}	-	232.3 (73.9)^{b}	867.0 (207.3)^{c}	274.8 (71.2)^{b}	0.36 (0.05)^{a}
Hoheria populnea	21.7 (3.1)^{a}	10.0 (2.5)^{a}	27.3 (4.7)^{a}	59.0 (8.8)^{a}	29.8 (4.0)^{a}	0.53 (0.07)^{b}
Knightia excelsa	51.7 (6.9)^{a}	14.4 (3.3)^{a}	49.2 (6.7)^{c}	113.3 (14.0)^{ab}	37.6 (3.2)^{a}	0.36 (0.03)^{a}
Pittosporum tenuifolium	51.1 (4.4)^{a}	551.1 (5.5)^{a}	35.8 (1.1)^{a}	142.1 (10.4)^{ab}	39.2 (3.3)^{a}	0.28 (0.01)^{a}
Pittosporum eugenoides	110.7 (18.7)^{a}	46.9 (10.1)^{a}	52.8 (5.6)^{a}	210.4 (31.9)^{ab}	61.1 (8.2)^{a}	0.30 (0.01)^{a}
Coprosma robusta	212.6 (24.6)^{a}	208.9 (42.1)^{c}	85.6 (17.5)^{a}	507.0 (77.3)^{b}	124.3 (23.1)^{a}	0.25 (0.02)^{a}
Plagianthus regius	17.5 (2.7)^{a}	59.2 (7.0)^{a}	128.3 (14.7)^{ab}	205.0 (21.8)^{ab}	75.6 (12.1)^{a}	0.35 (0.02)^{a}
Leptospermum scoparium	22.0 (2.5)^{a}	9.3 (0.5)^{a}	19.2 (3.1)^{a}	50.5 (3.5)^{ab}	34.5 (3.9)^{a}	0.70 (0.09)^{c}
Year 4						
Coriaria arborea	910.6 (251.0)^{b}	1090.3 (233.6)^{b}	1222.3 (246.1)^{b}	3223.2 (693.2)^{b}	1261.4 (156.9)^{c}	0.47 (0.08)^{b}
Myrsine australis	34.6 (4.9)^{a}	24.5 (3.3)^{a}	32.3 (4.4)^{a}	91.4 (10.1)^{a}	43.1 (5.5)^{a}	0.47 (0.03)^{bc}
Pseudopanax arboreus	412.1 (103.2)^{a}	321.9 (130.0)^{a}	444.6 (86.3)^{a}	1178.7 (297.4)^{a}	392.9 (87.6)^{ab}	0.36 (0.02)^{ab}
Sophora tetraptera	199.7 (52.6)^{a}	342.1 (144.2)^{a}	253.5 (76.0)^{a}	795.2 (262.7)^{a}	247.1 (59.8)^{ab}	0.37 (0.06)^{ab}
Cordyline australis	2756.2 (249.9)^{c}	-	1801.8 (272.1)^{c}	4558.0 (495.4)^{c}	1131.9 (185.5)^{c}	0.25 (0.03)^{a}
Hoheria populnea	228.0 (43.6)^{a}	346.4 (72.7)^{a}	361.2 (59.9)^{a}	935.5 (157.3)^{a}	289.2 (45.0)^{ab}	0.32 (0.02)^{a}
Knightia excelsa	115.9 (20.7)^{a}	48.7 (7.9)^{a}	112.9 (18.3)^{a}	277.4 (45.4)^{a}	71.1 (10.0)^{a}	0.27 (0.01)^{a}
Pittosporum tenuifolium	225.4 (42.0)^{a}	260.3 (52.0)^{a}	282.2 (63.8)^{a}	768.0 (154.7)^{a}	216.4 (36.3)^{ab}	0.28 (0.02)^{a}
Pittosporum eugenoides	334.1 (65.7)^{a}	320.9 (78.2)^{a}	262.7 (51.5)^{a}	917.7 (192.5)^{a}	265.1 (54.2)^{ab}	0.30 (0.01)^{a}
Coprosma robusta	877.7 (107.5)^{b}	1090.6 (154.4)^{b}	429.3 (52.5)^{a}	2397.5 (266.3)^{b}	524.5 (74.4)^{b}	0.23 (0.03)^{a}
Plagianthus regius	289.4 (110.5)^{a}	1126.0 (188.1)^{b}	1433.0 (239.2)^{bc}	2848.5 (511.1)^{b}	1054.4 (188.6)^{c}	0.37 (0.03)^{abc}
Leptospermum scoparium	-	-	-	-	-	-

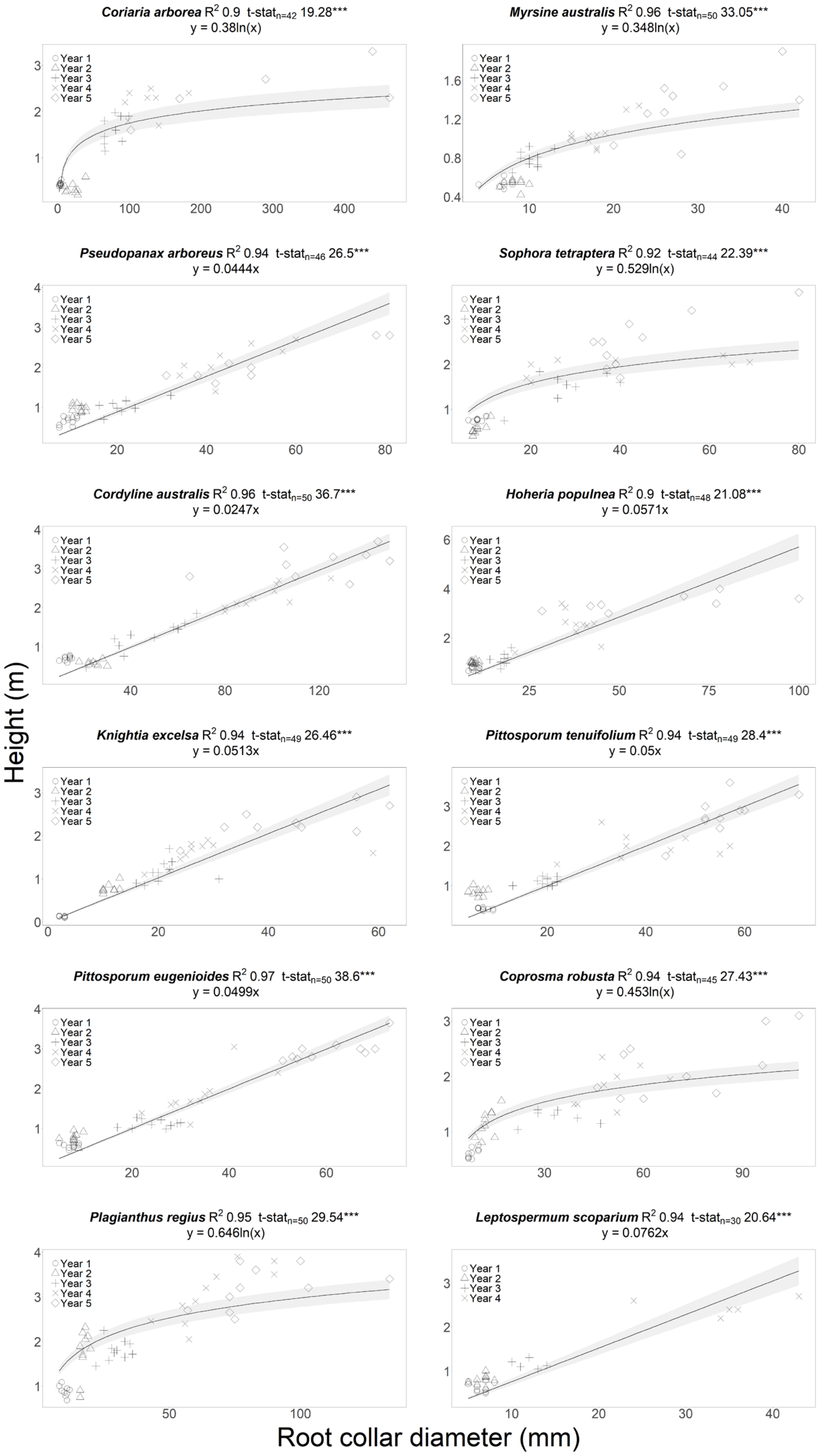
Values in brackets represent the standard error of the mean. Values with different letters within each parameter and year were significantly different. (Student–Newman–Keuls ($P < 0.05$).

APPENDIX 1 *continued*

Year 5						
Coriaria arborea	1745.6 (727.8)^{d}	2537.1 (544.3)^{d}	4949.6 (2429.8)^{c}	9332.2 (3454.3)^{e}	2937.5 (1118.8)^{f}	0.33 (0.05)^{abc}
Myrsine australis	129.6 (23.9)^{a}	164.4 (31.6)^{a}	91.6 (24.0)^{a}	385.7 (77.2)^{a}	156.8 (26.8)^{a}	0.44 (0.04)^{c}
Pseudopanax arboreus	654.6 (220.7)^{ab}	133.2 (36.0)^{a}	853.3 (308.4)^{ab}	1641.1 (561.6)^{abc}	467.8 (143.9)^{abcd}	0.31 (0.02)^{abc}
Sophora tetraptera	587.9 (176.4)^{ab}	700.5 (226.3)^{ab}	714.3 (168.1)^{ab}	2002.7 (530.0)^{abcd}	859.7 (266.6)^{abcde}	0.40 (0.04)^{bc}
Cordyline australis	5535.5 (377.8)^{e}	-	5774.6 (789.4)^{c}	11310.1 (991.0)^{e}	2699.3 (394.6)^{f}	0.24 (0.03)^{a}
Hoheria populnea	802.1 (207.7)^{abc}	1308.0 (339.7)^{bc}	2190.6 (612.8)^{ab}	4300.8 (1133.3)^{bcd}	1343.2 (358.5)^{abcde}	0.32 (0.03)^{abc}
Knightia excelsa	352.2 (75.3)^{ab}	187.6 (45.8)^{a}	452.9 (87.3)^{ab}	992.7 (205.2)^{ab}	311.8 (55.4)^{ab}	0.34 (0.04)^{abc}
Pittosporum tenuifolium	989.7 (95.7)^{abc}	1482.7 (246.4)^{c}	1374.6 (140.6)^{ab}	3847.0 (364.3)^{bcd}	1216.4 (157.5)^{abcde}	0.31 (0.02)^{abc}
Pittosporum eugenoides	1245.0 (59.2)^{bcd}	1726.4 (152.3)^{c}	1289.2 (123.4)^{ab}	4260.6 (257.2)^{bcd}	1545.4 (147.8)^{bde}	0.36 (0.03)^{abc}
Coprosma robusta	1525.1 (241.2)^{cd}	1581.6 (152.3)^{c}	1665.1 (465.5)^{ab}	4771.8 (484.4)^{cd}	1317.8 (263.8)^{abcde}	0.28 (0.03)^{ab}
Plagianthus regius	448.3 (92.2)^{ab}	2038.8 (300.6)^{cd}	2570.7 (387.3)^{b}	5057.8 (751.7)^{d}	1816.5 (352.9)^{e}	0.35 (0.03)^{abc}
Leptospermum scoparium	466.5 (69.3)^{ab}	413.0 (104.8)^{a}	442.7^{ab}	1322.2 (218.0)^{abc}	319.1 (65.3)^{abc}	0.24 (0.01)^{a}

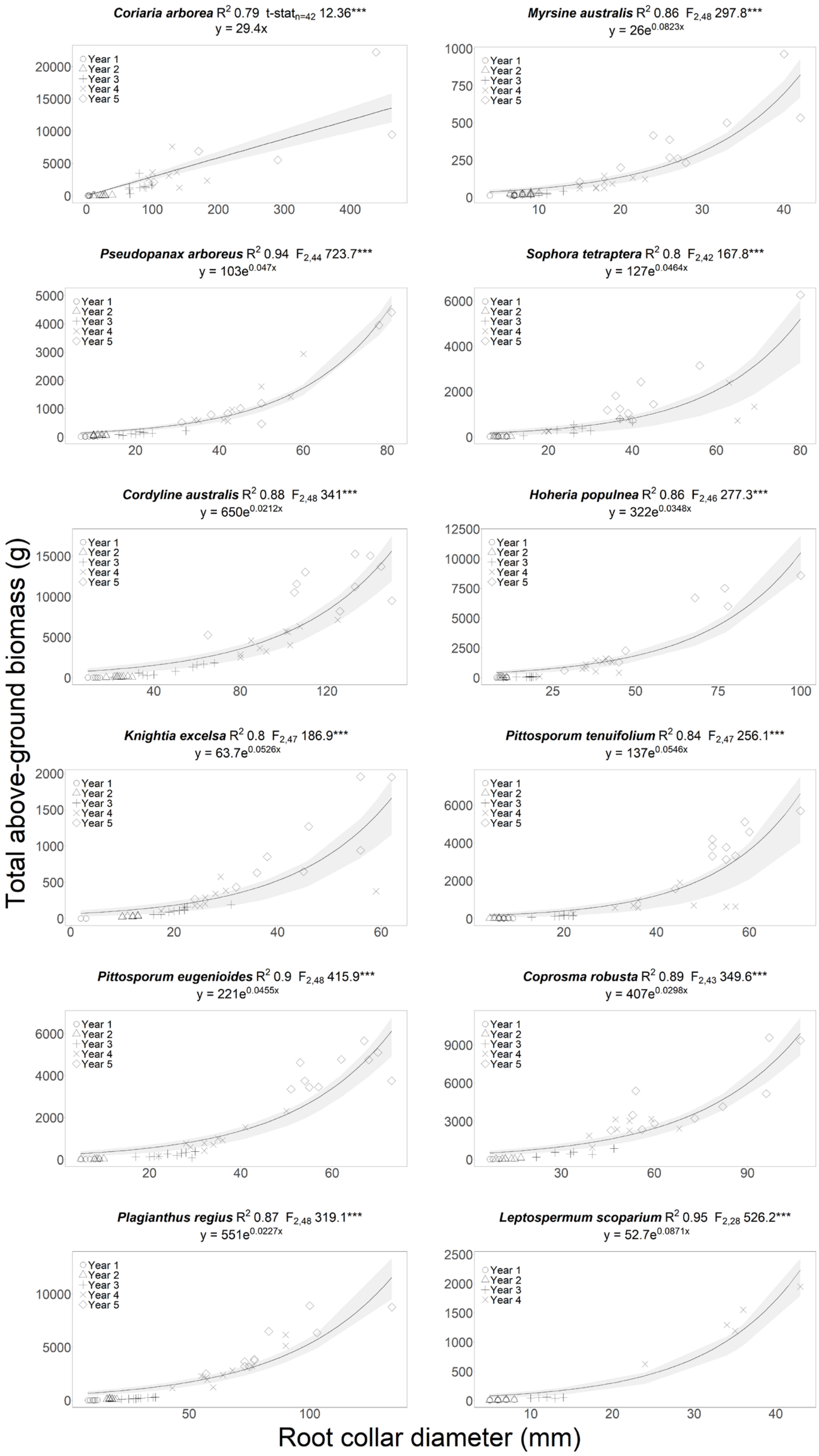
Values in brackets represent the standard error of the mean. Values with different letters within each parameter and year were significantly different. (Student–Newman–Keuls ($P < 0.05$).

APPENDIX 2



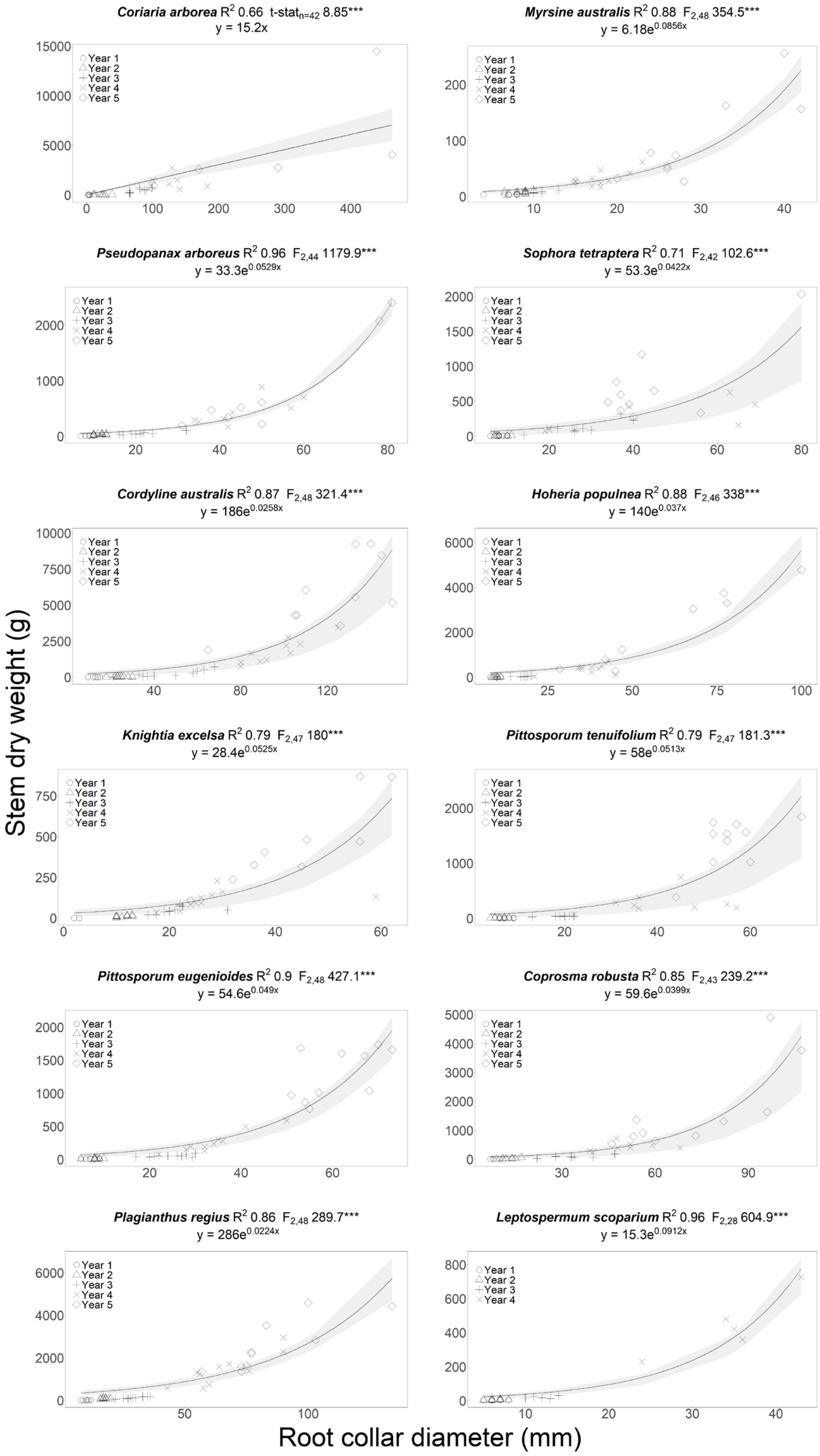
Allometric relationships between root collar diameter (RCD) and height. Sub-figure titles include an *r*-squared value for the overall regression; a *t*-statistic (and number of replicates) for the linear co-efficient; *P* values for the *t*-statistic; and the form of the equation and a linear co-efficient value (rounded to 3 significant figures). Solid lines indicate the fitted regression curve, and shaded areas indicate the standard error of fitted values. Point symbols indicate the year of harvest.

APPENDIX 3



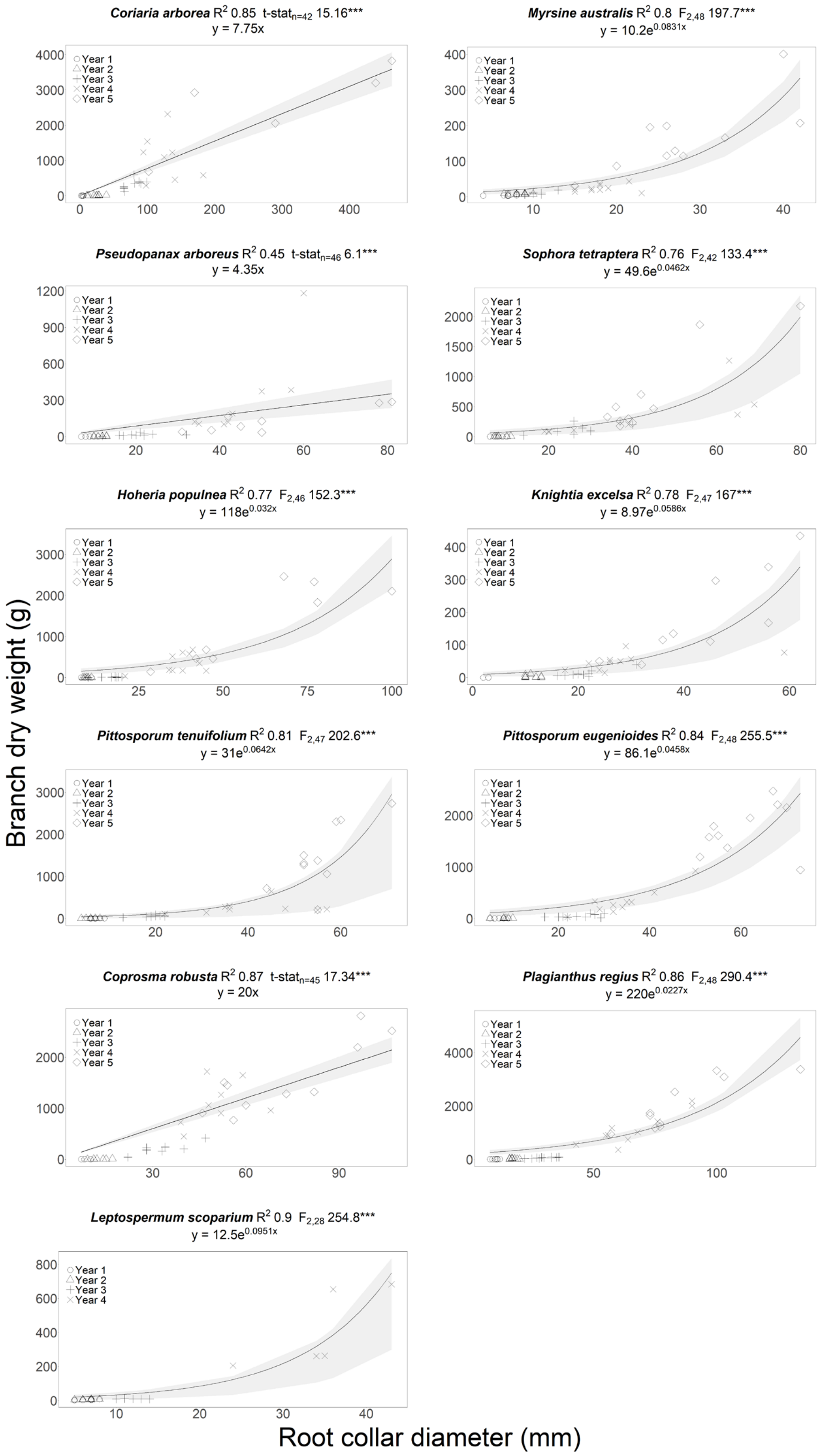
Allometric relationships between root collar diameter (RCD) and total above-ground biomass. Sub-figure titles for linear models include an r-squared value for the overall regression; a t-statistic (and number of replicates) for the linear co-efficient; and P-values for the t-statistic. Sub-figure titles for exponential models include a pseudo r-squared value for the overall regression; an F-statistic (and model and error degrees of freedom) for the overall regression; and P-values for the F-statistic. All sub-figure titles show the form of the equation and fitted regression co-efficient values (rounded to 3 significant figures). Solid lines indicate the fitted regression curve. Shaded areas for linear models indicate the standard error of fitted values. Shaded areas for exponential models indicate the standard error of fitted values. Point symbols indicate the year of harvest.

APPENDIX 4



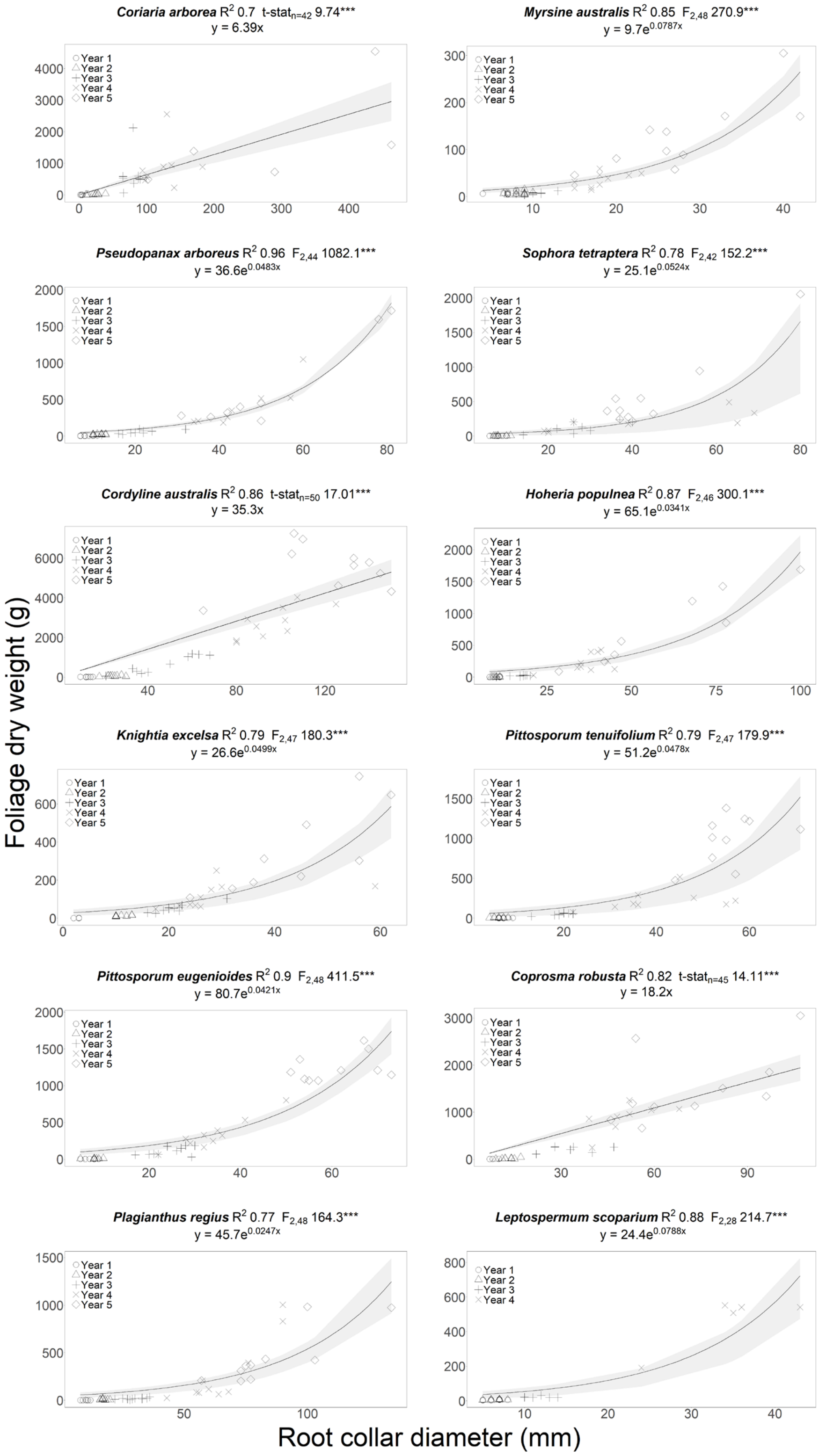
Allometric relationships between root collar diameter (RCD) and stem dry weight. Sub-figure titles for linear models include an r-squared value for the overall regression; a t-statistic (and number of replicates) for the linear co-efficient; and P-values for the t-statistic. Sub-figure titles for exponential models include a pseudo r-squared value for the overall regression; an F-statistic (and model and error degrees of freedom) for the overall regression; and P-values for the F-statistic. All sub-figure titles show the form of the equation and fitted regression co-efficient values (rounded to 3 significant figures). Solid lines indicate the fitted regression curve. Shaded areas for linear models indicate the standard error of fitted values. Shaded areas for exponential models indicate the standard error of fitted values. Point symbols indicate the year of harvest.

APPENDIX 5



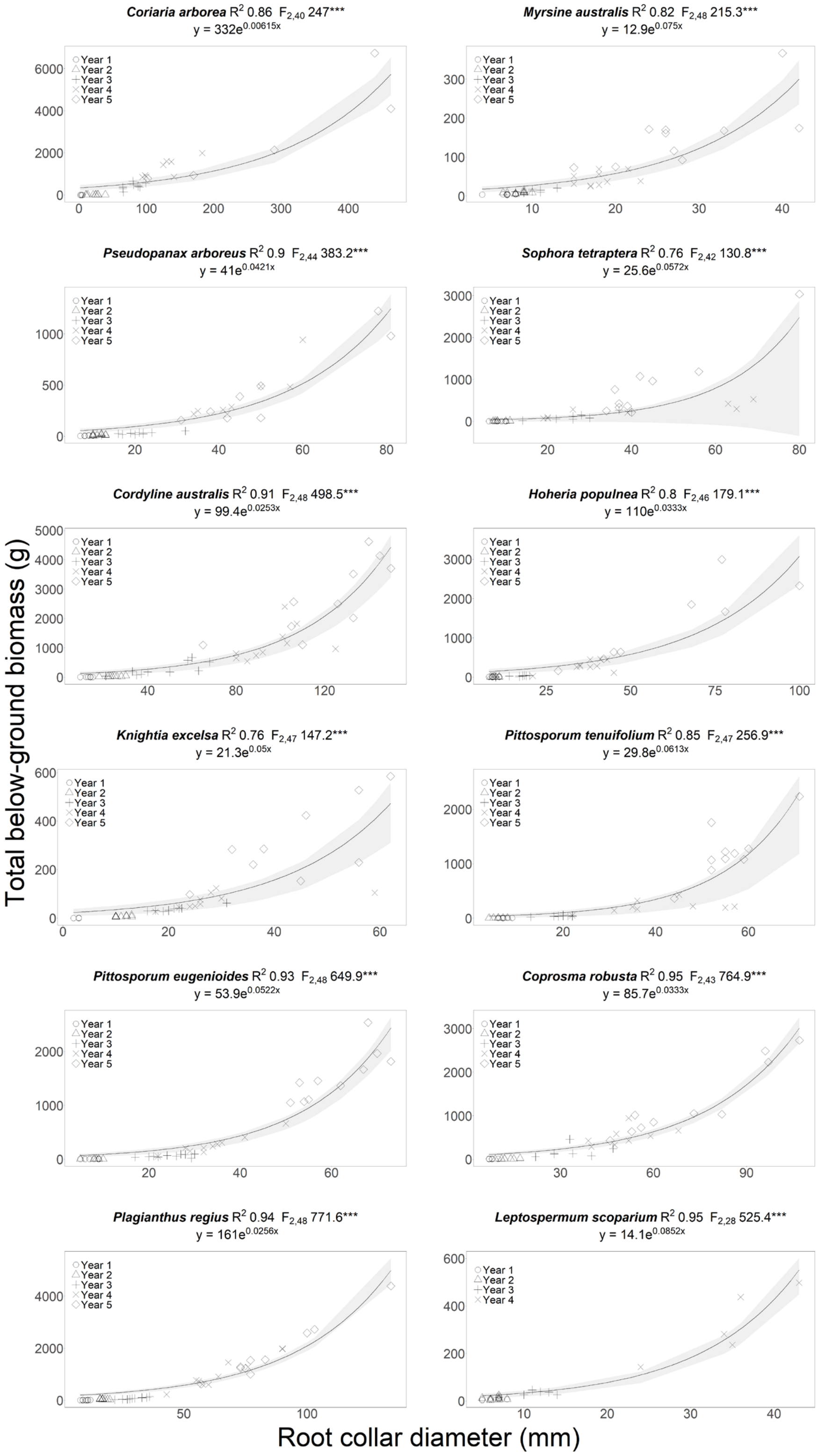
Allometric relationships between root collar diameter (RCD) and branch dry weight. Sub-figure titles for linear models include an r-squared value for the overall regression; a t-statistic (and number of replicates) for the linear co-efficient; and P-values for the t-statistic. Sub-figure titles for exponential models include a pseudo r-squared value for the overall regression; an F-statistic (and model and error degrees of freedom) for the overall regression; and P-values for the F-statistic. All sub-figure titles show the form of the equation and fitted regression co-efficient values (rounded to 3 significant figures). Solid lines indicate the fitted regression curve. Shaded areas for linear models indicate the standard error of fitted values. Shaded areas for exponential models indicate the standard error of fitted values. Point symbols indicate the year of harvest.

APPENDIX 6



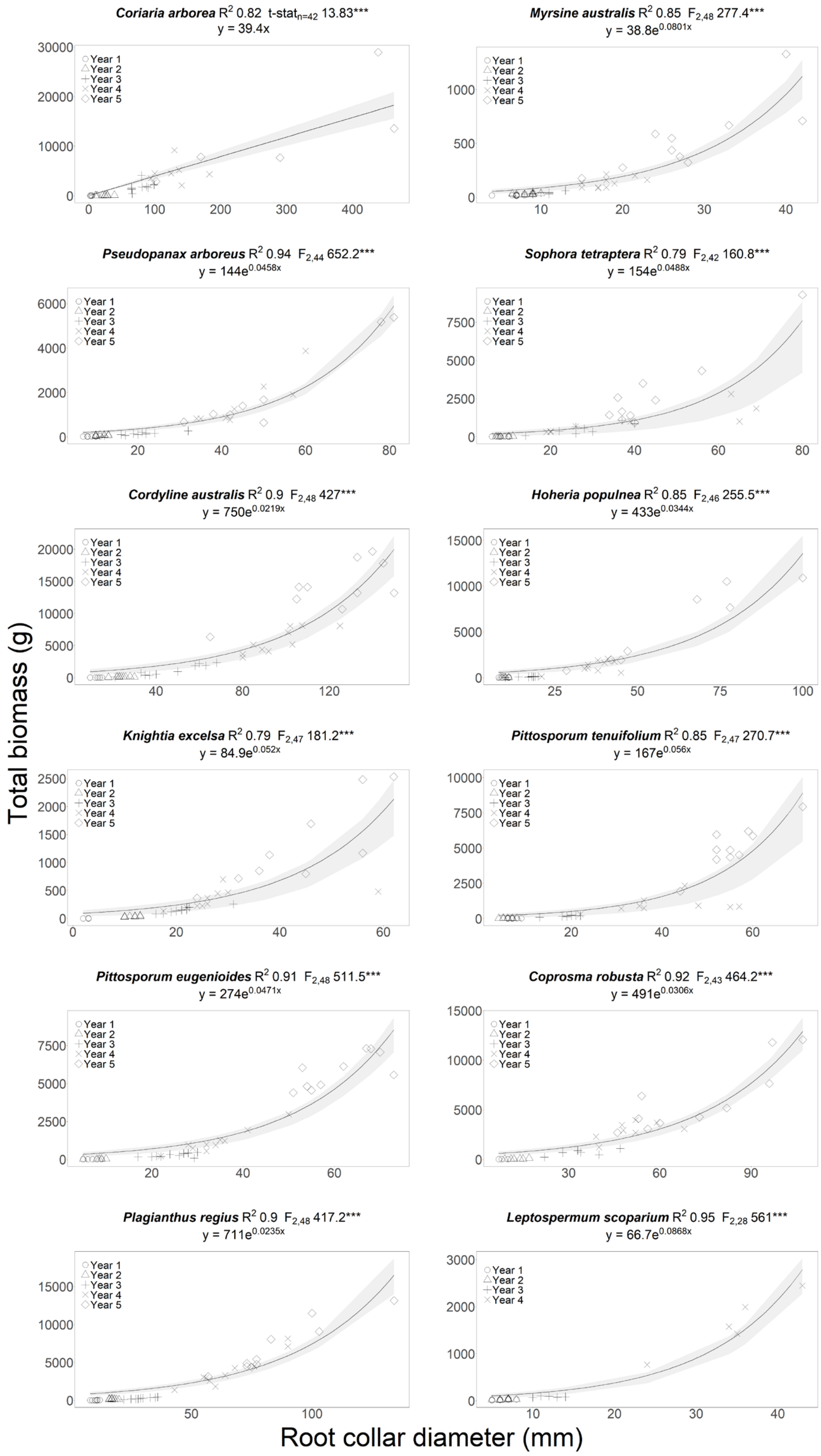
Allometric relationships between root collar diameter (RCD) and foliage dry weight. Sub-figure titles for linear models include an r-squared value for the overall regression; a t-statistic (and number of replicates) for the linear co-efficient; and P-values for the t-statistic. Sub-figure titles for exponential models include a pseudo r-squared value for the overall regression; an F-statistic (and model and error degrees of freedom) for the overall regression; and P-values for the F-statistic. All sub-figure titles show the form of the equation and fitted regression co-efficient values (rounded to 3 significant figures). Solid lines indicate the fitted regression curve. Shaded areas for linear models indicate the standard error of fitted values. Shaded areas for exponential models indicate the standard error of fitted values. Point symbols indicate the year of harvest.

APPENDIX 7



Allometric relationships between root collar diameter (RCD) and total below-ground biomass. Sub-figure titles for linear models include an r-squared value for the overall regression; a t-statistic (and number of replicates) for the linear co-efficient; and P-values for the t-statistic. Sub-figure titles for exponential models include a pseudo r-squared for the overall regression; an F-statistic (and model and error degrees of freedom) for the overall regression; and P-values for the F-statistic. All sub-figure titles show the form of the equation and fitted regression co-efficient values (rounded to 3 significant figures). Solid lines indicate the fitted regression curve. Shaded areas for linear models indicate the standard error of fitted values. Shaded areas for exponential models indicate the standard error of fitted values. Point symbols indicate the year of harvest.

APPENDIX 8



Allometric relationships between root collar diameter (RCD) and total biomass. Sub-figure titles for linear models include an r-squared value for the overall regression; a t-statistic (and number of replicates) for the linear co-efficient; and P-values for the t-statistic. Sub-figure titles for exponential models include a pseudo r-squared for the overall regression; an F-statistic (and model and error degrees of freedom) for the overall regression; and P-values for the F-statistic. All sub-figure titles show the form of the equation and fitted regression co-efficient values (rounded to 3 significant figures). Solid lines indicate the fitted regression curve. Shaded areas for linear models indicate the standard error of fitted values. Shaded areas for exponential models indicate the standard error of fitted values. Point symbols indicate the year of harvest.