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Diameter growth rates of tawa (*Beilschmiedia tawa*) across the middle North Island, New Zealand – implications for sustainable forest management

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Abstract

Background: Tawa (*Beilschmiedia tawa* (A. Cunn.) Kirk) remains a minor but significant hardwood timber in New Zealand, currently sourced from tawa-dominant forest on freehold and Maori land where selective harvesting under sustainable management plans is permitted. Sustainable management plans require reliable tree growth estimates, which are used to calculate annual volume increment and harvest levels. The aims of this study were to model the relationship between diameter growth rate and tree size using existing data, and to determine the influences of within-stand competition, local climate and soil parent material on growth rates.

Methods: A dataset was compiled on the diameter growth rates of nearly 1800 trees from a wide range of published and unpublished sources for the middle North Island. Non-linear quantile regressions were used to model average growth and growth of the fastest 25% of stems, termed rapid growth.

Results: Across the middle North Island, average growth of a 400 mm DBH (diameter at breast height) tree was 1.8 mm $year^{-1}$ and rapid growth was 2.8 mm $year^{-1}$. Overall, the model accounted for 12% of the total variation in growth rate. The effect of size on diameter growth rate was modest but positive. Within-stand competition reduced tawa diameter growth rates, particularly when basal area exceeded 100 m^2 ha^{-1}. Also, climate (winter minimum temperature and annual vapour pressure deficit) had little influence on growth rates and explained <2% of total variation in stem growth. Soil parent material strongly influenced tawa growth rates and explained >10% of variation in stem growth. The fastest growth rates were on soils derived from Tertiary mudstone in inland Taranaki.

Conclusions: Most of the existing data on growth rates of tawa are for trees growing on volcanic substrates. This means that the markedly faster growth on some sedimentary rather than volcanic substrates suggests that growth rates and volume increment may be underestimated for many sites in the middle North Island beyond the Volcanic Plateau. A growth dataset more representative of the range of substrates occupied by tawa is needed for management plans elsewhere in the North Island.

Keywords: Tawa; *Beilschmiedia tawa*; Individual growth model; Competition; Soil parent material

Background

Indigenous forests provided virtually all of the country's timber needs until 1959, after which exotic plantation-grown conifers were the main source of timber (New Zealand Forest Service, 1975). Sustained-yield management of indigenous forest was implemented in some State Forests from 1975 (New Zealand Forest Service, 1977) in response to growing public dissatisfaction with forest clearance and an increasing national awareness of the heritage values of indigenous forest. It largely ended in 1984 with a government decision to halt harvesting in almost all indigenous forests in Crown tenure.

The demand for high-quality indigenous timber persisted, which together with a growing recognition that timber supply and the maintenance of ecological integrity need not be mutually exclusive, led to the Forests Amendment Act 1993. This Act allows the continuing harvest of significant volumes of indigenous timber on

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freehold land under a 'sustainable forest management plan' approved by the Ministry of Primary Industries, setting annual or periodic timber harvest 'at a rate matching the forest's productivity and retaining its natural values and ability to continue to provide a full range of products and amenities in perpetuity' (Ministry of Forestry, 1997). Some 116,000 ha of tawa-dominant forest is potentially available for sustainable management (Ministry of Primary Industries, unpubl. data).

In the past, tawa (*Beilschmiedia tawa* (A.Cunn.) Kirk) was an important hardwood timber and source of pulp fibre for high-grade paper and there is a small continuing demand for specialty uses such as flooring and interior joinery.

Tawa occurs from Northland to the northern South Island of New Zealand, and remains a significant source of hardwood timber in New Zealand. However, it is only important commercially across the middle North Island where it dominates large tracts of indigenous forest and is the subject of sustained-yield management plans approved by the Ministry for Primary Industries. Current legislation (Forests Amendment Act 1993) dictates that tawa can only be exploited by small group or individual tree harvesting. Selective harvesting of tawa may be of interest to forest owners wishing to restore conifer-broadleaved forests by offering the opportunity for some immediate revenue that can support restoration and potentially aid conifer regeneration (Carswell et al. 2007).

Sustainable management for timber production requires reliable tree growth estimates, which are used to calculate annual volume increment and harvest levels. Estimations of volume increment need to incorporate the effects of tree size, within-stand competition, and local environment, as these factors have been shown to influence the growth of tree species (Kunstler et al. 2011; Baribault et al. 2012). A lack of published growth models for indigenous New Zealand forest species means that the sustainable management of these species are difficult to achieve at present. Growth rates for tawa were last summarised by Smale et al. (1986), and there is a need to update this review to incorporate more sites, to determine if growth may be affected by tree size, within-stand competition, climate and soil parent material, and to examine the relative importance of these factors. Also, an understanding of tawa performance on an individual-tree basis is an essential element that can be integrated into stand-level models (e.g., Kunstler et al. 2011). Such models account for mixtures of species, ages and life history strategies. They are also complex, but essential for sustainable 'near-natural' management of indigenous forests.

This study provides improved growth models for tawa that incorporate individual tree characteristics, within-stand competition and stand characteristics, local environment and geographic location, using new and existing data from the middle North Island. This information will allow management guidelines to take account of how key factors affect growth of tawa on different sites and assist landowners in developing Sustainable Management Plans.

Methods

Selection of datasets

Permanent sample plot and increment core datasets containing tawa diameter growth data from tawa-dominant forest were selected from a broad region across the middle North Island, encompassing the Volcanic Plateau, Bay of Plenty, Poverty Bay, and inland Taranaki (Table 1). Elevations range from 160 to 820 m a.s.l. Soil parent materials include volcanic (rhyolitic, basaltic and andesitic) and sedimentary (old sedimentary, Tertiary non-calcareous, and recent alluvial) substrates.

Precipitation, mean annual temperature, winter minimum temperature and vapour pressure deficit were estimated for each plot from thin-plate splines fitted to meteorological data collected at local climate stations (Leathwick et al. 2002). Mean annual temperatures range from 9.5 to 13°C. Mean annual rainfall varies from 1379 to 3390 mm year^{-1}.

Basal area data were available for twenty, 20 × 20 m permanent plots held in the National Vegetation Survey (NVS) databank (https://nvs.landcareresearch.co.nz). For these plots only, the effect of plot-level basal area was incorporated into the size-specific growth model (from Hurst et al. 2007).

Data preparation

A total of 1826 trees was checked for errors following the methods of Hurst et al. (2007). Annual growth rate was calculated by subtracting the initial diameter at breast height 1.4 m above ground (DBH) from the final diameter, then dividing by the measurement period (years). For increment core data, the mean radial increment was doubled to derive diameter increment and divided by the number of growth rings (to be equal to the number of years: Ogden & West, 1981) to derive periodic mean annual growth rate. Only stems that were ≥ 100 mm DBH at the start of monitoring were included in the analysis resulting in the exclusion of 95 stems. Trees with a negative growth rate > 2 mm year^{-1} or with a positive growth rate >15 mm year^{-1} were removed from the dataset resulting in the exclusion of a further 9 stems. In all, 104 stems were removed (5.7% of the original data set) resulting in the 1722 stems that were used in the analyses.

Data analysis

There were differences among study sites in terms of the variables measured or derived (tree, stand or site

Table 1 Number of tawa trees sampled by each dataset and the soil parent materials for those stems

Dataset		Soil type					
Area(s)	**Data type and source**	**Volcanic**			**Sedimentary**		
		Rhyolite	**Basalt**	**Andesite**	**Old**	**Tertiary, non-calcareous**	**Alluvium**
Rotoehu, Mamaku, Whirinaki, Urewera, Waioeka, Kaimanawa, west Taupo	Plots[1]	541					
Pureora	Plots[2]	336			110		
Maungahaumi	Cores[3]	178			43		
Pureora	Plots[4]	152					
central Mamaku	Plots[5]	82					
Horohoro	Cores[6]	8					
Rotorua Lakes	Plots[2]		186				
Kaimai	Plots[2]			30			
Taranaki	Plots[2]			17			3
Matiere	Cores[7]					92	
TOTAL		**1297**	**186**	**47**	**153**	**92**	**3**

[1]Richardson et al. (2009); [2]Husheer (2007); [3]Smale et al. (2009); [4]Smale & Beveridge (2007); [5]Smale (1981); [6]Smale et al. (1997); [7]Svavarsdóttir et al. (1999).

related). Consequently, only tree diameter and annual growth rate were available for all sites, and these parameters formed the basis of the analysis undertaken.

Quantile regression was used to summarise the relationship between tree growth rate (mm year^{-1}) and tree size (DBH), consistent with Hurst et al. (2007). Quantile regression is a technique that can accommodate highly variable tree growth data (Cade & Noon, 2003). The other strength of this approach is that regression lines can be fitted through the median or 'average' of the data (the 0.50 quantile) and any other quantile of the data, which is useful in modelling both average and above-average growth.

Following Hurst et al. (2007), two growth curves were calculated and presented, average tree growth rate and rapid tree growth rate. Average tree growth rate is the fitted line through the median of the dataset (the 0.50 quantile). Rapid tree growth rate is the fitted line through the upper 50% of the dataset (the 0.75 quantile).

Plot-level estimates of climate (winter minimum temperature and annual vapour pressure deficit) and soil parent material type were used to estimate the amount of variation in tawa tree growth that can be explained by tree size, climate, and soil parent material. Mean annual temperature and precipitation were not used in these models as they were strongly correlated with winter minimum temperature and annual vapour pressure deficit, respectively, and did not contribute unique explanatory power to the models. This was achieved using non-linear least squares regression. All analyses were completed using the statistical software package R v. 2.9 (R Development Core Team 2009).

Large tawa trees are uncommon in natural forests (Smale et al. 1986) and it is difficult to estimate growth rates accurately for them. However, all available larger individuals were included in all the models tested. Each modelled relationship shows the tree size above which confidence in the model is limited. This limit is the 95th percentile of the tree diameters in each species per model (after Hurst et al. 2007; i.e., just 5% of data points fall in this diameter region). Fitted lines above this percentile are expected to have low precision.

Results and discussion

Average growth of a mature tree with a DBH of 400 mm was 1.8 mm year^{-1} and rapid growth was 2.8 mm year^{-1} across the whole dataset, (1722 tawa trees) (Figure 1a). Growth was strongly influenced by basal area, i.e., within-stand competition, in the pooled NVS plot data (Figure 1b). A 400 mm tree achieved average growth of 2.4 mm yr^{-1} at low basal area (40 m^2 ha^{-1}), yet this was reduced to as little as 1.3 mm yr^{-1} under high basal area (120 m^2 ha^{-1}; Figure 1b). Smale & Kimberley (1981) found that within-stand competition explained 15% of the variation in tawa growth rate in a 19 year study of the trees in the 1961 selective harvesting trial at north Pureora, Volcanic Plateau. The effect of size on diameter growth rate of tawa was modest but positive, reaching almost 3 mm yr^{-1} at the lowest basal area class.

Most of the measured trees were on soils derived from volcanic substrates, especially rhyolite but there was still sufficient replication for analysis within soil parent material for all categories (i.e., rhyolite, basalt, andesite, old sedimentary, Tertiary non-calcareous sedimentary)

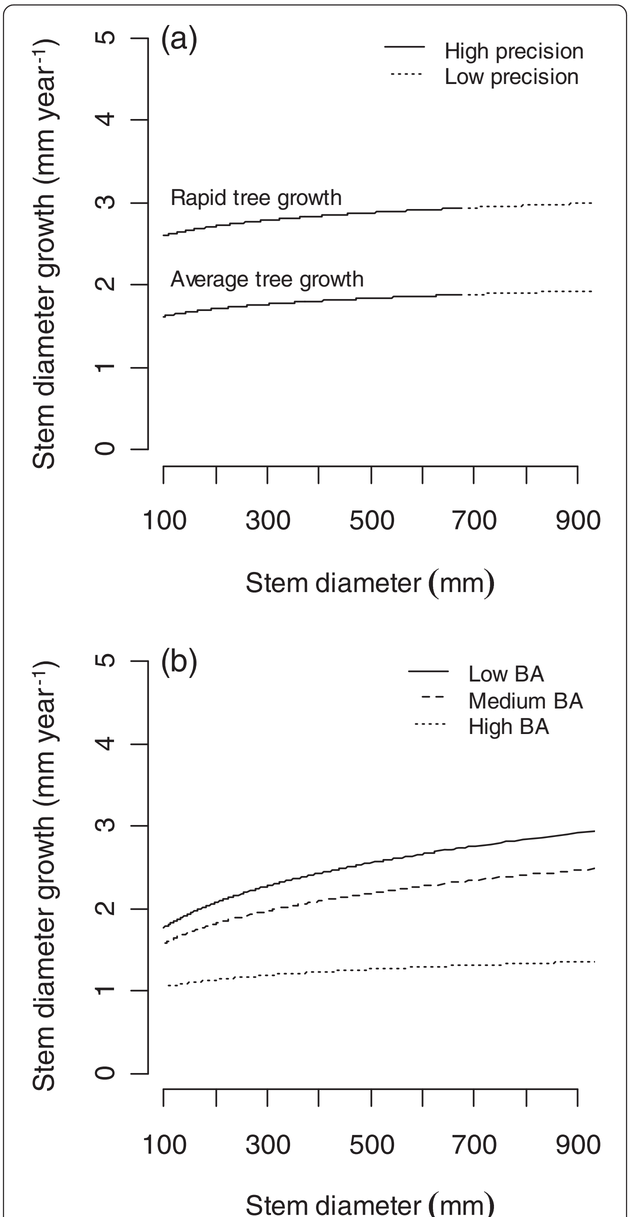

Figure 1 Diameter growth rates of tawa across the middle North Island. (a) overall size-specific models of tawa growth for average trees and for rapidly-growing trees; and **(b)** size-specific average tawa growth from a subset of the data in **(a)** where local basal area (BA) could be modelled (permanent forest plots in Pureora, Kaimai Range (Wharawhara), Rotorua Lakes, Mt Egmont/Taranaki, archived in NVS, see Table 1). Low, Medium and High Basal Area = 38, 58, 130 m^2 ha^{-1}, respectively. Adapted from Hurst et al. (2007).

apart from alluvium (N = 3 trees). There were only modest differences in growth rates among volcanic soil parent material types, but significantly faster growth on soils derived from non-calcareous Tertiary sedimentary rock (mudstone) at Matiere, inland Taranaki (Figure 2). Soil parent materials differ widely in their inherent fertility and in those of the soils they generate (Molloy & Christie, 1988). In general, chemical fertility rankings of soils from these parent materials follow the ranking: basalt > andesite > Tertiary non-calcareous sedimentary > rhyolite > old sedimentary (M. McLeod, pers. com.), so the above results are somewhat unexpected.

Four models were tested to ascertain how much variation in growth was accounted for by size and soil parent material type. Given the above result that most soil parent materials – apart from Tertiary sedimentary – have the same effect on tawa, these models were tested only for a difference between Tertiary sedimentary and all other geologies combined. While the model accounted for only 12% of the total variation in growth rate, the largest contributory factor tested was soil parent material. This factor accounted for most (10%) of the variation and only 2% was accounted for by either tree size or climate (Table 2). Other variables such as crown position (Villegas et al. 2009) that were not tested here also contribute to variation in growth rate.

The non-linear quantile regression growth model (diameter increment = a × DBH^b, where a and b are modelled coefficients) for tawa for average diameter growth is:

$$\text{Diameter increment}\left(\text{mm yr}^{-1}\right) = 1.36 \pm 0.20 \times \text{DBH}^{0.08\pm0.04}$$

and for rapid diameter growth;

$$\text{Diameter increment}\left(\text{mm yr}^{-1}\right) = 2.24 \pm 0.32 \times \text{DBH}^{0.06\pm0.04}.$$

Using the subset of data from the twenty permanent sample plots in which the total basal area for the plots can be determined, the model for average diameter growth using initial DBH and basal area is:

$$\text{Diameter increment}\left(\text{mm yr}^{-1}\right) = 1.68 \pm 0.25 \times \text{DBH}^{0.12\pm0.04} + \text{SumBasalArea} \times -0.0092 \pm 0.0009$$

and for rapid diameter growth:

$$\text{Diameter increment}\left(\text{mm yr}^{-1}\right) = 2.32 \pm 0.25 \times \text{DBH}^{0.16\pm0.03} + \text{SumBasalArea} \times -0.0143 \pm 0.0015$$

Using soil parent material and initial DBH for all stems, the model for average diameter growth on Tertiary and other sedimentary soils is:

$$\text{Diameter increment}\left(\text{mm yr}^{-1}\right) = 5.99 \pm 3.38 \times \text{DBH}^{-0.13\pm0.15}$$

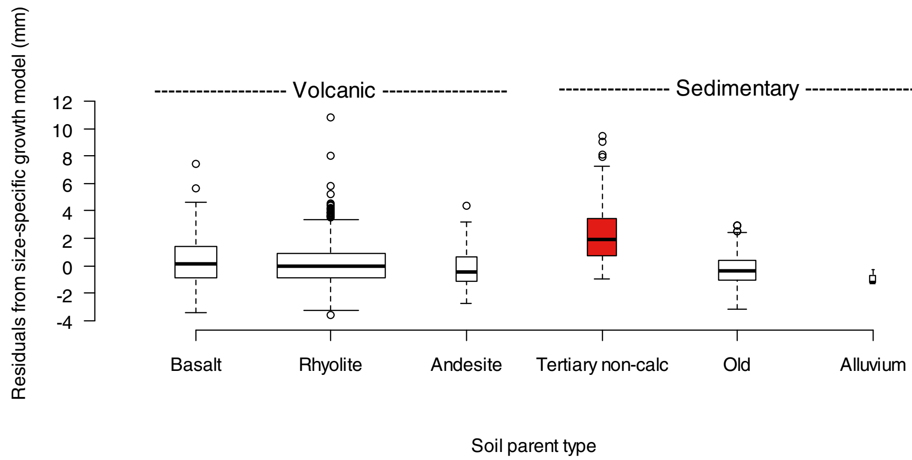

Figure 2 The effect of soil parent material on tawa stem growth rate across the middle North Island. The effect was modelled by fitting a median growth model to all tawa data (Figure 1a) and then examining how the residuals from that model varied with soil parent material. Box width is proportional to the number of observations in each soil parent material type. Basa = volcanic basalt; Rhyo = volcanic rhyolite; Ande = volcanic andesite; Tert = Tertiary sedimentary; Old = older sedimentary; Allu = alluvial. Only residuals on Tertiary Sedimentary were significantly different from all others (shown in red, GLM to test for differences among means $P < 0.05$).

and for rapid diameter growth:

$$\text{Diameter increment } \left(\text{mm yr}^{-1}\right) = 7.13 \pm 4.79 \times \text{DBH}^{-0.09 \pm 0.19}$$

For tawa trees on other soils (volcanic), the model for average diameter growth is:

$$\text{Diameter increment } \left(\text{mm yr}^{-1}\right) = 1.45 \pm 0.21 \times \text{DBH}^{0.05 \pm 0.0.04}$$

and for rapid diameter growth:

$$\text{Diameter increment } \left(\text{mm yr}^{-1}\right) = 2.42 \pm 0.29 \times \text{DBH}^{0.03 \pm 0.04}$$

Average diameter growth rates of tawa are somewhat slower compared with other commercially important indigenous tree species in the North Island of New Zealand. For example, the average diameter growth rate of rimu (*Dacrydium cupressinum* Lamb. is 2.3 mm yr^{-1},

Table 2 Variation in tawa diameter growth rate explained (%) by tree size, soil parent material, and climate

Model	Variation explained (%)
Size + Soil parent material + Winter minimum temperature + Annual Vapour Pressure Deficit	11.7
Size + Soil parent material	10.7
Size + Winter minimum temperature + Annual Vapour Pressure Deficit	1.9
Size	0.5

Variation explained is the coefficients of determination (observed growth correlated against predicted growth, squared) for models of tawa growth in the middle North Island.

which is similar to those of red beech (*Fuscospora fusca* (Hook.f.) Heenan & Smissen – 2 mm yr^{-1}) and hard beech (*F. truncata* (Colenso) Heenan & Smissen – 1.7 mm yr^{-1}), and faster than those of silver beech (*Lophozonia menziesii* (Hook.f.) Heenan & Smissen – 0.9 mm yr^{-1}) (Hurst et al. 2007). As with tawa, growth rates of these species vary widely among regions and with tree size and within-stand competition, However, the relative influence of soil type and climate for these species remains to be demonstrated. A recent analysis of factors affecting silver beech growth confirmed the influence of tree size and within-stand competition on the growth rates of smaller stems, but found elevation, a reflection of the physical environment and climate, more important for larger stems (Easdale et al. 2012).

Conclusions

Soil parent material may provide a simple guide to tawa diameter growth for sustainable forest management planning, with higher growth rates at the one site with Tertiary sedimentary soils. However, information on population dynamics (in terms of recruitment and mortality) as well as diameter growth rates and volume increment (dependent also on tree height and form) of existing trees is also needed for robust, long-term management plans. Data on existing tawa diameter growth rate are strongly biased towards volcanic substrates, and the markedly faster growth on some sedimentary than volcanic substrates suggests that growth rates and volume increment may be underestimated for many sites beyond the Volcanic Plateau. A tawa growth dataset more representative of the range of substrates occupied by tawa is needed for developing sustainable management plans elsewhere in the North Island.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
MCS drafted the manuscript. SJR performed the statistical analyses. JMH compiled the dataset and assisted with data analysis. All authors read and approved the final manuscript.

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