Diameter growth rates of beech (*Nothofagus*) trees around New Zealand

Sarah J. Richardson[1*], Jennifer M. Hurst[1,2], Tomás A. Easdale[1], Susan K. Wiser[1], Alan D. Griffiths[2,3], Rob B. Allen[1]

Abstract

Beech (*Nothofagus*) accounts for a large proportion of the privately owned indigenous forest in New Zealand that is available for timber production. In order to develop management plans for those beech forests there is a need to refine our knowledge on tree growth rates and to take account of tree size, local competition and regional differences. In this article, we use a large dataset on tree growth in unmanaged forests throughout New Zealand to develop size-specific growth models for the four beech species. In particular, we model both normal ("average") and above-average ("rapid") diameter growth rates. We found that average tree diameter growth rates were typically between 1 and 3 mm/yr and rapid tree diameter growth rates ranged between 1 and 5 mm/yr. For stems under 500 mm diameter at breast height, hard and red beech typically grew faster than black-mountain and silver beech. However, for larger trees, the fastest rates were found in black-mountain beech in Southland and silver beech in Nelson-Marlborough. Growth rates of ≥ 10 mm/yr were extremely rare in our dataset and accounted for <0.2% of all trees (27 out of 17,781 trees). Data from thinning trials show that beech trees can achieve growth rates in excess of 6 mm/yr, making a compelling case for further stand thinning to enhance the generally slow growth rates of beech in unmanaged forests.

Key words: *Nothofagus; beech; sustainable yield; individual growth model; NVS Databank; permanent sample plots; timber production; size-specific growth rates; sustainable management*

1. Introduction

New Zealand's beech trees (*Nothofagus* spp.) collectively account for ~40% of tree volume in remaining indigenous forests and constitute a significant source of high quality hardwood timber across the one million hectares of privately owned forests that are eligible for management (Griffiths 2002). While beech has been the focus of silvicultural research for many years, there is still limited information available on individual tree growth rates that takes account of tree size, site conditions and location around New Zealand. Sustainable management of a tree species for timber production requires reliable data on tree growth as these data are used to calculate mean annual volume increment. It is imperative that these estimates of volume increment are as accurate as possible for a species and a region in order to calculate sustainable harvest levels (NZ House of Representatives 2002; MAF 2007). A complication is the variation among individuals of a species within a region or even within a stand. Wardle (1984) highlighted the enormous variation among individuals and populations of mountain and silver beech according to environment, emphasising that growth rates can range from as little as 0.4 mm/yr on thin soils at high elevations to >10 mm/yr on young, nutrient-rich soils in high light. Two of the most significant sources of variation in tree growth rate are tree size and site conditions and these can be incorporated either explicitly, or indirectly, into management plans to refine predictions of volume increment.

Timber from indigenous tree species can be harvested on privately owned land under the 1993 amendment to the Forests Act. Applications to harvest timber must be made to the Sustainable Programmes Directorate of the Ministry of Agriculture and Forestry (MAF) either as a one-off permit or as part of a long-term sustainable forest management plan that is registered against the property

[1]*Landcare Research, PO Box 40, Lincoln 7640, New Zealand*
[2]*School of Forestry, University of Canterbury, New Zealand*
[3]*Sustainable Programmes, MAF, Sir William Pickering Drive, Christchurch, New Zealand*
**Corresponding author: richardsons@landcareresearch.co.nz*

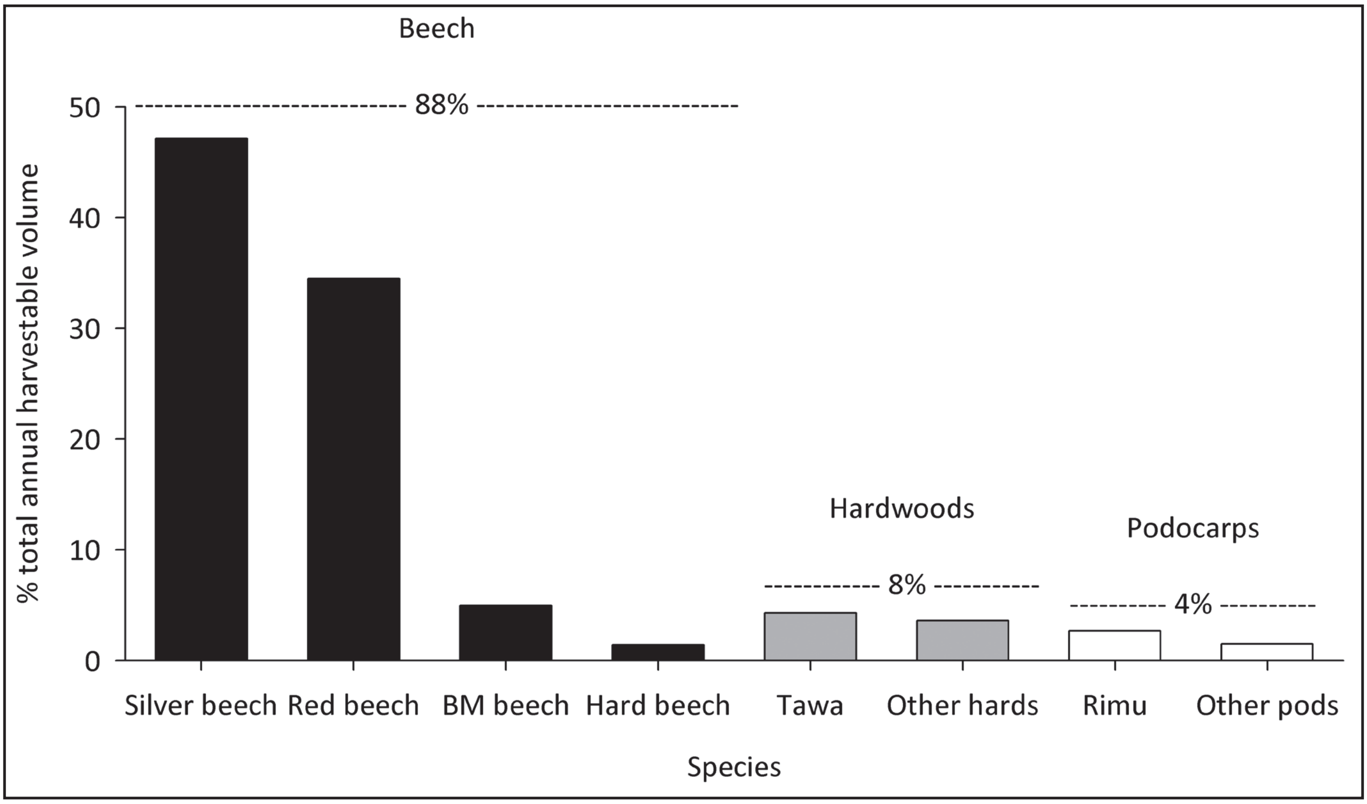

Figure 1. Summary of annual harvestable timber volumes (m3/yr) from indigenous species in New Zealand included on approved sustainable management plans registered with the Indigenous Forestry Unit of MAF in Christchurch, December 2006. Total volume = 80,007 m3.

title. These plans specify a harvest rate on the basis of individual tree growth rates for a property. The *Standards and Guidelines for the Sustainable Management of Indigenous Forests* published by MAF (2007, 3rd edn.) promote the use of permanent sample plots to supply site-specific growth data for use in each management plan. Permanent sample plots require at least five years to yield site-specific data, and while these data are being acquired, MAF (2007) advises basing management on tree diameter growth rate information provided in a suite of publications. While some of these sources provide information on growth rates, the data are rarely size-specific or capture the vastly different rates achieved under contrasting levels of local competition and site conditions. Beech currently accounts for 88% of the annual allowable harvest across all registered and approved sustainable management plans in New Zealand (Figure 1) highlighting the need for accessible data on tree growth rates.

In this article, we present individual tree growth rates for beech trees in New Zealand, specifically for those land districts with active management plans that include beech (Table 1). Our data were derived from a large, nationally significant vegetation-databank held at Lincoln (the National Vegetation Survey Databank; see *4.1. Methods*). This work was developed in close consultation with MAF as part of ongoing operational research into tree growth rates (Hurst *et al*. 2007, unpubl.; Smale *et al*. 2009, unpubl.) and the consequences of stand thinning (Easdale *et al*. 2009, unpubl.). One aspect that interested us was modelling not only average growth, which we expected to be quite low in most unmanaged forests, but also above-average, or rapid growth. Rapid growth is likely to be found on the best sites where there is little competition and high light (Easdale *et al.* 2007) and provides the most optimistic vision for potential beech performance. The goals of our article are first to present and compare average and rapid size-specific growth rates of beech across a range of land districts and second to briefly compare whether rapid growth rates in old-growth forests match those recorded in thinning trials. We present these growth data as graphs, look-up tables and equations to make them directly available for yield modelling and the preparation of sustainable management plans.

*Table 1. Volumes (m3/year standing round-wood) of beech timber by species and land district included on approved sustainable management plans registered with the Indigenous Forestry Unit of MAF in Christchurch, December 2006. Values in bold are those land districts and species where growth models would be desirable to support management; * indicates those land districts and species where data were available to develop a tree-growth model. Inadequate data were available from hard beech to develop models specific to land districts so a single nationwide model was used.*

	Silver beech	Red beech	Black-Mountain	Hard beech
Gisborne	3,610	4,693		
Hawke's Bay	5,653	9,838		
Manawatu-Wanganui		800	15	190
Taranaki			213	
Nelson-Marlborough	4,256 *	10,806 *	545 *	473
Westland	413	1,047	21	453
Canterbury			780 *	
Southland	23,785 *	400	2,384 *	
New Zealand	37,717	27,584	3,958	1,116 *

2. Methods

New Zealand's National Vegetation Survey Databank (NVS; http://nvs.landcareresearch.co.nz/) contains records from ~19,000 permanent vegetation plots, ~2100 of which have been measured at least twice (Wiser *et al*. 2001). Many of these plots are located in indigenous forests and we used the remeasured plots from indigenous forests containing beech to estimate individual tree growth rates. Permanent plots are typically sampled in catchment-based surveys (e.g., Mt Grey, Canterbury 1978) and to avoid bias we only used those surveys where plots were objectively located. Most plots were 20 m x 20 m (400 m^2) in size, and were established by the former New Zealand Forest Service to monitor trends in forest health, such as changes in the abundance of tree species in response to introduced herbivores (Wiser 2009). On each permanent plot, each tree with a diameter at breast height (DBH) ≥ 2.5 cm was permanently marked with a nail and numbered metal tag. Measurements of diameter were made 1 cm above this nail (see Hurst & Allen 2007). Mean annual diameter growth rate (mm/yr) was defined as the change in DBH between two measurements, divided by the number of years between measurements. In all our analyses, we modelled mean annual diameter growth rate relative to tree size (DBH, mm).

Permanent plot datasets of this scale inevitably have some errors and we checked and corrected the data as follows. Errors around the estimate of tree DBH can be made during measurement, recording or data entry. Based on our experience and under ideal permanent plot conditions, we determined that negative growth of >2 mm/yr was more likely to be error than true negative growth, and we removed such values. Similarly, we determined that positive growth >15 mm/yr was error and we removed these values. Black beech (*Nothofagus solandri* var. *solandri*) and mountain beech (var. *cliffortioides*) are frequently confused where the two varieties co-occur. To overcome this identification problem, we pooled these to a single species concept of black-mountain beech (*Nothofagus solandri*).

We modelled growth for species in those land districts where a sustainable forest management plan had been registered with and approved by the then Indigenous Forestry Unit of MAF in Christchurch as of December 2006, and for which we had at least 100 trees. Based on the volumes of each species registered in each land district (Table 1) and the availability of data, we generated seven models: silver, red and black-mountain beech from Nelson-Marlborough; silver and black-mountain beech from Southland; black-mountain beech from Canterbury; and a single model for hard beech pooled nationally. We did not have adequate data to model red and silver beech tree growth in the Gisborne and Hawke's Bay land districts, despite them having considerable volumes of these species registered against management plans. We confined our analyses to stems ≥ 100 mm DBH, and to plots that were below 800-m elevation, as high-altitude forests are not representative of forests managed for timber production.

We chose a power function to describe the relationship between tree size and tree growth rate. This was selected after testing a wide range of forms (linear and several other non-linear forms) and has the advantage of having a strong theoretical basis for describing the relationship between the size of an individual and its growth rate (Richardson *et al*. 2009). The power function allows tree growth rate to increase rapidly with tree size if the data support this, but has the advantage of behaving like a simple linear model if there is not a strong size-effect.

Because we were interested in modelling both average and above-average growth, we used quantile regression to summarise the relationship between tree growth rate and tree size. Quantile regression is a simple technique that accommodates the fact that tree growth data are very variable (Cade & Noon 2003). The other strength of this approach is that it can fit regression lines through the median or "average" of the data (the 0.50 quantile) and any other quantile of the data. In order to describe "rapid" growth of trees, we fitted a regression line that delimited the fastest 25% of trees of a species (the 0.75 quantile). We used the non-linear quantile regression function "*nlrq*" in the "*Quantreg*" package of R v.2.9 (R Development Core Team 2009) to fit a power model to the 0.50 and 0.75 quantiles of the growth data:

$$G = a \times DBH^{b},$$

where G is mean annual diameter increment, a and b are parameters estimated by the model and *DBH* is tree diameter at breast height.

Large trees are usually uncommon in unmanaged forests and are poorly sampled by objectively located plots. Consequently, we had relatively few large trees in our samples compared with smaller size-classes, and relatively less statistical confidence in our fitted growth models for large trees. To account for this in our presentation of the data, we first defined the 95th percentile of tree size for each species in each land district and second, divided our growth curves at that 95th percentile to indicate the tree size above which we had less statistical confidence (see Figures 2 & 3). We also confine our presentation to stems up to 1-m (1,000 mm) DBH as trees larger than this are rare (0.4% of our total sample of 17,781 beech trees).

3. Results

Average growth rates of beech trees increased with tree size in all species and land districts and ranged between 0.7 and 3.0 mm/yr (Figure 2; Table 2). For stems under 500-mm DBH, where we have the greatest confidence in our fitted curves, hard and red beech clearly outperformed silver and black-mountain beech (Figure 2;

Table 2. Tree-diameter growth rates (mm/yr) of beech species around New Zealand modelled as "average" growth (the 0.50 quantile) and "rapid" growth (the 0.75 quantile).

	"Average" growth rates (0.50 quantile)							"Rapid" growth rates (0.75 quantile)						
	Silver		Hard	Red	Black-Mountain			Silver		Hard	Red	Black-Mountain		
Tree DBH (mm)	Nelson-Marl.	Sthlnd	NZ	Nelson-Marl.	Nelson-Marl.	Cantab.	Sthlnd	Nelson-Marl.	Sthlnd	NZ	Nelson-Marl.	Nelson-Marl.	Cantab.	Sthlnd
100	0.7	0.9	1.3	1.5	0.9	1.0	0.7	1.0	2.1	1.8	2.3	1.3	1.5	1.3
200	1.1	1.2	1.6	1.7	1.2	1.3	1.0	1.7	2.4	2.3	2.7	1.8	2.0	1.9
300	1.4	1.4	1.9	1.8	1.5	1.5	1.4	2.2	2.6	2.7	2.9	2.2	2.3	2.5
400	1.7	1.5	2.1	1.9	1.7	1.7	1.6	2.7	2.8	3.0	3.0	2.6	2.5	2.9
500	1.9	1.7	2.3	2.0	1.9	1.9	1.9	3.2	3.0	3.3	3.2	2.8	2.7	3.4
600	2.1	1.8	2.4	2.1	2.0	2.0	2.1	3.6	3.1	3.5	3.3	3.1	2.9	3.7
700	2.4	1.9	2.6	2.1	2.2	2.2	2.4	4.0	3.2	3.7	3.4	3.3	3.1	4.1
800	2.6	2.0	2.7	2.2	2.4		2.6	4.4	3.3	3.9	3.4	3.5		4.4
900	2.8	2.1	2.8	2.2	2.5		2.8	4.8	3.4	4.1	3.5	3.7		4.8
1000	3.0	2.2	2.9	2.3			3.0	5.1	3.5	4.3	3.6			5.1

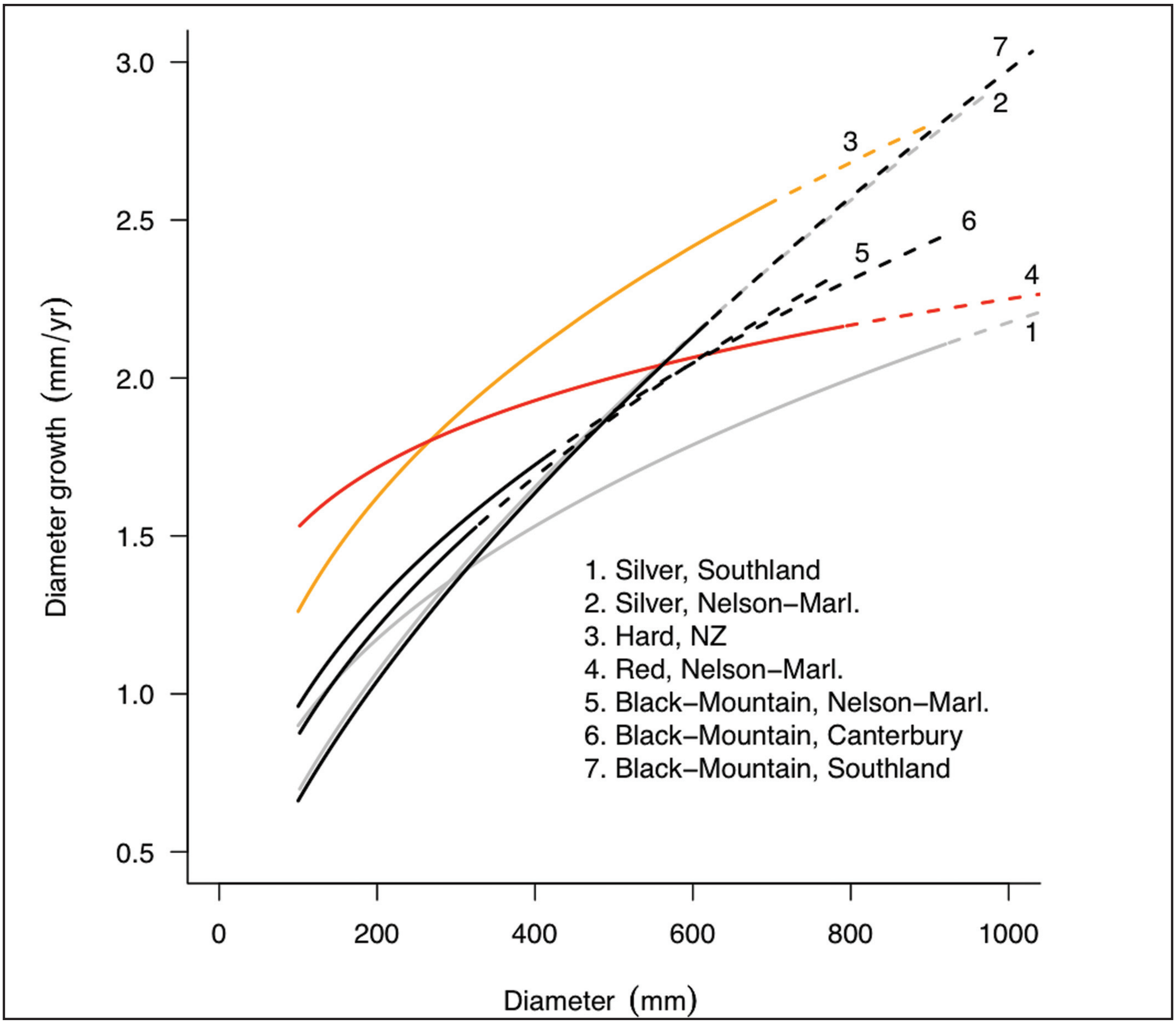

Figure 2. Average size-specific tree growth rates (mm/yr) of New Zealand beeches. These curves are fitted through the median (or 0.50 quantile) of all data for that species and land district. Lines are dashed for large trees beyond the size for which we have strong statistical confidence.

Table 2). Differences among species were less distinct for growth of trees ≥ 500-mm DBH; silver beech in Nelson-Marlborough and black-mountain beech in Southland both achieved growth rates that overlapped with hard and red beech (Figure 2; Table 2).

Rapid growth rates also increased with tree size and ranged across all species and land districts from 1.0 to 5.1 mm/yr (Figure 3; Table 2). For stems under 500-mm DBH, red beech grew faster than the other three species (Figure 3). However, this difference was not sustained through larger stems: the highest rapid growth rates for stems ≥ 500-mm DBH were from black-mountain beech in Southland followed by silver beech in Nelson-Marlborough (Figure 3; Table 2).

Across all our data, less than 0.5% of the stems achieved stem growth rates of ≥10 mm/yr and the prevalence of individuals growing at ≥5 mm/yr was typically less than 5%, with the exception of red beech (Table 3).

4. Discussion

4.1. Application of these data to sustainable forest management plans

Determining tree growth rates for use in a sustainable management plan is challenging because rates vary widely among individual trees over small spatial scales. The two most likely sources of variation are tree size and local competition (Monserud & Sterba 1996) although local environment can also be important. The models presented

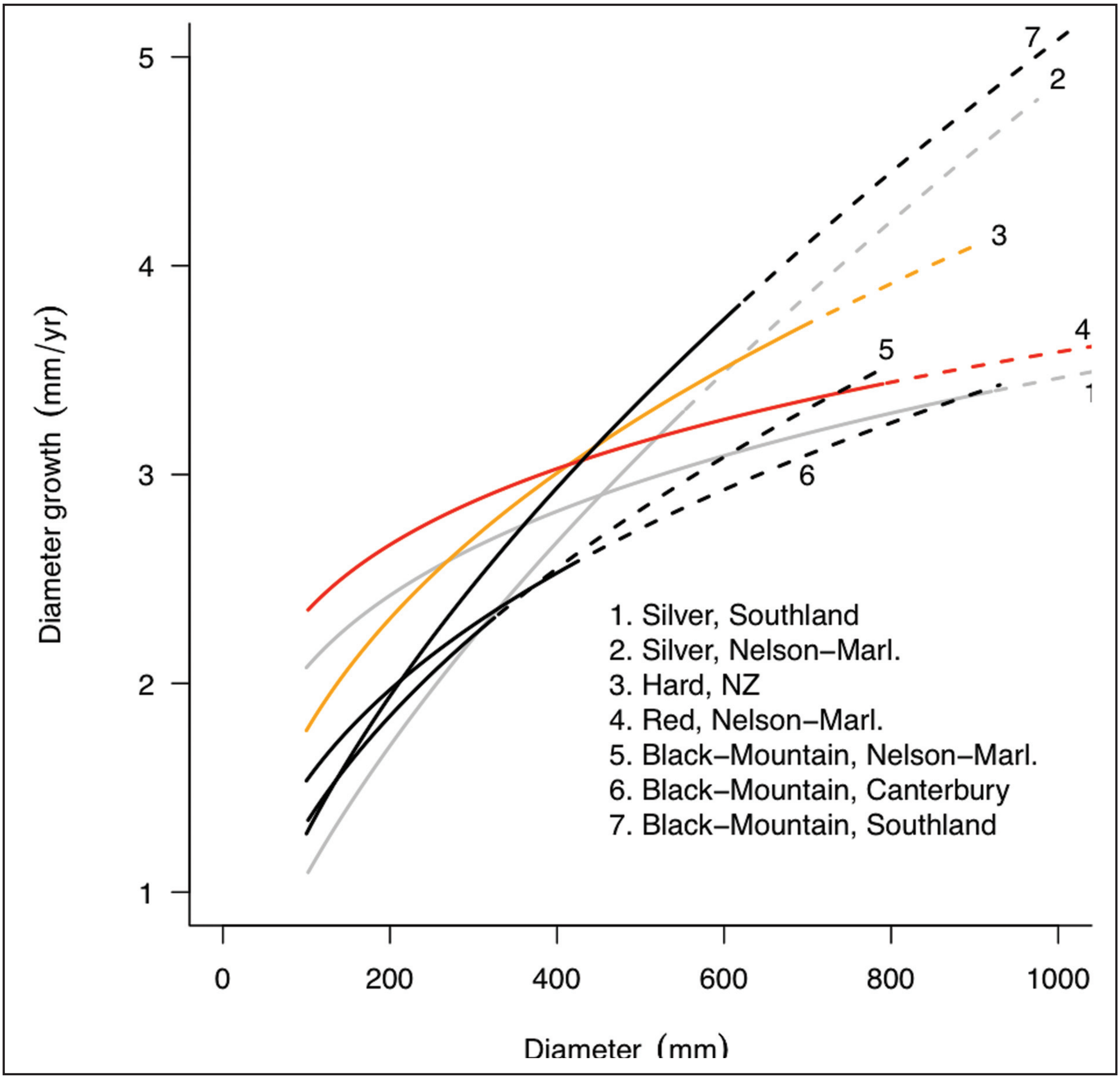

Figure 3. Rapid size-specific tree growth rates (mm/yr) of New Zealand beeches. These curves are fitted through the 0.75 quantile of all data for that species and land district, i.e., 25% of trees have growth rates falling above the regression line. Lines are dashed for large trees beyond the size for which we have strong statistical confidence.

here have the advantage of being sufficiently complex so as to capture the effects of size and a broad concept of local competition and site quality (our "rapid" growth rates) while retaining simplicity for widespread use. We suggest that the growth curves presented here could complement the publications on beech growth rates suggested by MAF (2007) in their *Standards and Guidelines for the Sustainable Management of Indigenous Forests* and be used until plan-specific values from permanent plots become available. The formulae in Table 4 can be pasted directly into MS-Excel and used to convert inventory data on tree sizes into estimates of mean annual diameter growth. We suggest using the "average" tree growth rate formula for most situations in unmanaged forests as it is conservative and straightforward to apply. However, if there are areas within a forest that are recovering from natural disturbance and have low basal area, the "rapid" growth rate formula could be applied (see Wardle 1984). Wardle (1984) points out that all the beeches can achieve growth rates of 10 mm/yr on ideal sites with minimal competition. Our data suggest that such rates are restricted to less than half a percent of trees in old-growth forests and that values of even 5 mm/yr would be exceptional (Table 3).

Table 3. Prevalence of high growth rates in the four beeches from our study.

Species	Total no. trees	No. trees growing ≥ 5 mm/yr	% ≥ 5 mm/yr	No. trees growing ≥ 10 mm/yr	% ≥ 10 mm/yr
Black-Mountain	12,543	166	1.3	15	0.12
Silver	3,493	100	2.9	6	0.17
Red	1,625	99	5.8	6	0.37
Hard	120	5	4.2	0	0
Total	17,781	370	2.1	27	0.15

4.2. Gaps in our knowledge

In this analysis, we matched existing data from permanent plots against land districts where there were registered and approved sustainable management plans with substantial volumes of beech (Table 1). However, we did not have adequate data from low-elevation (<800 m) plots to model red and silver beech growth in the Gisborne and Hawke's Bay land districts, both of which have large volumes (>1000 m^3/yr) of timber registered against plans. Published values for these species in the eastern and central North Island are somewhat higher than or comparable with our values for the Nelson-Marlborough Land District: 2.6-3.6 mm/yr for red beech and 2.7-3.3 mm/yr for silver beech from Rangataua, near Ohakune (630-1200 m elevation; Hocking & Kenderdine 1945); 2-3 mm/yr for high-elevation (740-1110 m) silver beech across the Volcanic Plateau and Urewera Ranges (Richardson *et al*. 2009); 2.4 mm/yr for high-elevation red beech at Waiokotore (1100 m elevation; Ruahine Ranges; Rogers 1989); and 2.8 mm/yr for red beech on Mt Colenso in the Ruahine Ranges (950-1080 m elevation; June & Ogden 1978). Ogden (1975) reported that red beech growth rates ranged between 0 and 10 mm/yr throughout New Zealand but these calculated rates were taken across a wide range of size classes including many large trees that may exaggerate the rate found in more common, smaller trees in most unmanaged forests. Lastly, the gaps in our knowledge will be filled progressively as national-scale networks of plots (e.g. the Land Use and Carbon Analysis System, LUCAS network; Ministry for the Environment 2010) and regional-scale surveys (i.e. there are established permanent sample plots in the Raukumara Ranges that capture areas of lowland beech forest for the Gisborne Land District) are remeasured.

4.3. Comparison of growth rates in old-growth forests with those reported from thinning trials

Thinning young, even-aged beech stands promotes individual tree growth. The effects of thinning are progressive and individual trees grow increasingly faster with lower densities of residual stems. Silver beech achieves mean diameters of 359 mm in under 55 years within stands of 150 stems/ha (Baker & Benecke 2001; Easdale *et al*. 2010) and red and hard beech achieve mean diameters of 432 mm in under 55 years within stands of 150 stems/ha. This means that, on average, individual tree growth rates must be ≥6.5 mm/yr for silver beech and ≥7.8 mm/yr for red and hard beech. These growth rates far exceed the "average" and "rapid" growth rates presented here for old-growth forests (Table 2), emphasising that the potential of beech as a timber species is not being fulfilled in unthinned, unmanaged situations. Fast growth of individual trees does not necessarily translate into maximum stand productivity, as crop scientists have recognised for some time (Weiner 2003), but our assessment of thinning trials indicates that merchantable timber yields are at least four times greater in moderately thinned stands compared with unthinned stands (Easdale *et al*. 2010). The challenge now for the indigenous forestry industry is to reconcile the achievements of thinning trials with the goals of "near-natural" forest management or "ecological silviculture" (Benecke 1996). Positive news on this front has emerged from recent research in Australia where thinning was used to "accelerate" natural succession and restoration of forest structure and ecological processes (e.g. Dwyer *et al*. 2010). Application of these concepts to the New Zealand situation would benefit from new, targeted thinning trials that identify the various benefits and costs of thinning for timber productivity and quality, biodiversity, structural values (e.g., deadwood, variability in size class structures) and biophysical values (e.g., nutrient cycling, carbon sequestration).

Table 4. Functions for estimating size-specific growth rates of beech trees around New Zealand. Growth rates are mean annual diameter growth rate (mm/yr). DBH = tree diameter at breast height; BA = total basal area in the surrounding 400 m2. These functions can be pasted into Excel and by replacing the words "DBH" or "BA" with measured variables, can be used directly to develop management plans.

Species	Land district	Function (for MS-Excel)
Average		
Silver beech	Southland	= 0.15369 * DBH ^ 0.38365
Silver beech	Nelson-Marl.	= 0.03778 * DBH ^ 0.63086
Red beech	Nelson-Marl.	= 0.70295 * DBH ^ 0.16845
Hard beech	New Zealand	= 0.23699 * DBH ^ 0.36303
Black-Mountain beech	Nelson-Marl.	= 0.09539 * DBH ^ 0.47950
Black-Mountain beech	Canterbury	= 0.13754 * DBH ^ 0.42211
Black-Mountain beech	Southland	= 0.03271 * DBH ^ 0.65300
Rapid		
Silver beech	Southland	= 0.74604 * DBH ^ 0.22216
Silver beech	Nelson-Marl.	= 0.04380 * DBH ^ 0.68930
Red beech	Nelson-Marl.	= 0.99984 * DBH ^ 0.18493
Hard beech	New Zealand	= 0.30727 * DBH ^ 0.38074
Black-Mountain beech	Nelson-Marl.	= 0.15412 * DBH ^ 0.46837
Black-Mountain beech	Canterbury	= 0.29107 * DBH ^ 0.36084
Black-Mountain beech	Southland	= 0.08114 * DBH ^ 0.59901

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