Chapter 3

Predictive equations for dimensions of three street tree species in the City of Tshwane, South Africa

Abstract

Tree height, crown height, crown diameter and stem diameter were measured for 282 trees of the indigenous species *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina*. Growth relationships were modelled using age as explanatory variable for stem diameter and stem diameter as explanatory variable for tree height, crown height and crown diameter. Regression coefficients are presented for predicting tree dimensions. There are strong correlations (r^2) for stem diameter and age, and crown diameter and stem diameter ($r^2 \geq 0.74$) for all three the species investigated. Correlations are weaker for tree height and stem diameter ($r^2 \geq 0.63$), and crown height and stem diameter ($r^2 \geq 0.60$) for *Rhus pendulina* but are strong for *Combretum erythrophyllum* ($r^2 \geq 0.83$) and *Rhus lancea* ($r^2 \geq 0.70$) in both instances. *Rhus lancea* and *Rhus pendulina* show similar stem diameter growth rates over time while, *Combretum erythrophyllum* has the fastest stem growth. Regarding tree height and stem diameter, and crown height and stem diameter *Rhus pendulina* is the fastest grower then *Combretum erythrophyllum* and lastly *Rhus lancea*. All three the species have similar growth rates when comparing the crown diameter and stem diameter growth relationship. It is noteworthy that *Rhus lancea* is consistently the slowest growing tree in all the relationships and is also the smallest tree in relation to its stem diameter. The results can be used in forecasting the physical dimensions of these species as a function of time. These dimensional relationships can be used to simulate the dynamic growth of the trees in illustrations of a project when using computer aided design (CAD) applications. The results could also be used in the process of modelling energy use reduction, air pollution uptake, rainfall interception, carbon sequestration and microclimate modification.

Keywords: allometry, growth rate, regression, size relationships, street trees, tree dimensions, tree growth, urban forests

Introduction

The ability to predict the growth of various tree dimensions enables arborists, researchers and urban forest managers to model cost benefit analyses, investigate alternative management scenarios and determine the best management practices for optimising and creating more sustainable urban forests (McPherson *et al.*, 2000 as cited by Peper *et al.*, 2001a). Information relating to crown dimensions can be applied to model carbon sequestration, air pollution uptake, rainfall interception and microclimate amelioration in urban environments (Peper *et al.*, 2001a).

In South Africa information available on dimensional relationships of commonly propagated urban trees is usually qualitative and based on personal observations and often lacks extensive scientific validation. The observations are based on perceptions of rates at which trees grow in different dimensions (Joffe, 1993) and are sometimes even conflicting (Kirsten & Meyer, 1992; Joffe, 1993). Subjective terms such as *slow*, *moderate* or *fast* are used to describe tree growth without the terms being substantiated with quantitative values. In contrast, the results presented here are quantitative and may be used to model tree dimensional growth with statistical methods and were derived from measurements of 282 street trees.

However, several growth rate studies have been conducted in the United States of America. Fleming (1988) (as cited by Peper *et al.*, 2001a) measured trees to develop linear relationships between diameter at breast height (DBH), height, crown spread, and tree age. Ferlich (1992) (as cited by (Peper *et al.*, 2001a) measured 221 trees (12 species) growing in the twin cities of St. Paul and Minneapolis, Minnesota (United States of America) to predict dimensional relationships. McPherson *et al*., (1994) estimated urban tree growth from ring counts on stem cross sections from 543 trees (10 species) growing in Chicago, Illinois (United States of America). A literature search revealed no information related to urban tree growth in a South African context.

Apart from the urban ecological functions that urban trees fulfil they are also used in a landscape architectural context to perform spatial and aesthetic functions (Grey & Deneke, 1978; Arnold, 1980; Larsen & Kristoffersen, 2002). Urban and landscape architectural tree planting demands knowledge of *inter alia* stem diameter, tree height and crown growth with an appropriate estimate of maturity dimensions. Planning tree spacing and tree positioning in relation to structures can be improved with more accurate information on tree growth. Furthermore, accurate information of tree crown growth may provide more realistic and better landscape architectural planting designs (Larsen & Kristoffersen, 2002). It can also be used when implementing computer aided design (CAD) applications where these tree dimensional growth relationships can form the basis for dynamic illustration of a landscape project's vegetation growth over time (Peper *et al.*, 2001b; Larsen & Kristoffersen, 2002) and hence supply two and three dimensional information (see Chapter 4).

The aim of this investigation was to determine the relationships between stem diameter and age, tree height and stem diameter, crown height and stem diameter, crown diameter and stem diameter as well as that of crown base height and stem diameter for the commonly used street trees *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina*.

Methodology

The street trees were measured in the winter and early spring (April - September) of 2002 in the City of Tshwane (25˚ 39' S - 25˚ 50' S; 28˚ 19' E - 28˚ 09' E), Gauteng Province.

The tree height, crown base height (height from the ground to the lowest leaves of the crown) crown height and crown diameter (Figure 3.1) were measured with a 3 m range pole. Crown diameter measurements were taken in two directions, one parallel and the other perpendicular to the centre line of the road. The mean of the two measurements were used to calculate the diameter.

The stem circumferences of the larger street trees (larger than approximately 90 mm diameter) were determined with a tape measure at 50 mm above ground level or just above the basal swelling. Diameter at breast height (DBH), which is measured at 1.37 m above ground level, was not an appropriate measurement since the African savanna species investigated tend to branch at a level lower than this height. Also the City of Tshwane Metropolitan Municipality (Municipality) often planted trees that still had branches below 1.37 m.

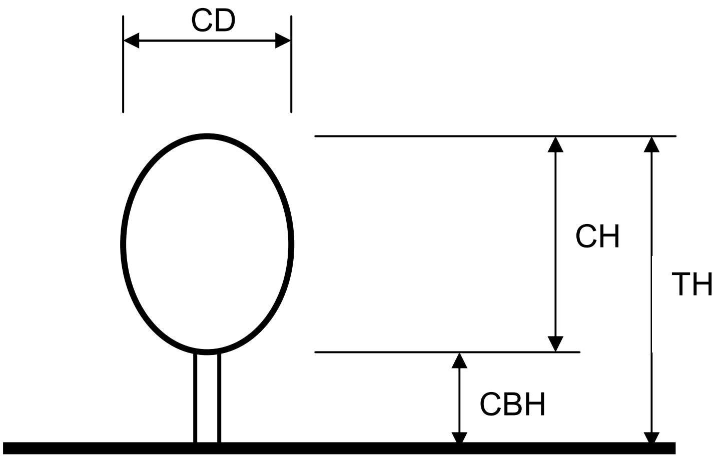


Figure 3.1. The dimensions measured for each tree: tree height (TH), crown height (CH), crown base height (CBH) and crown diameter (CD).

Table 3.1. The minimum ages (years since planting in the streets), maximum ages and ranges of years for which measurements were made for each species

Species	Minimum age (years)	Maximum age (years)	Range (years)
Combretum erythrophyllum	1.2	47.6	46.4
Rhus lancea	1.3	32.6	31.3
Rhus pendulina	3.4	15.6	12.2

The stem diameters of small trees (smaller than approximately 90 mm diameter) were measured with callipers in two directions, one parallel and the other perpendicular to the centre line of the road. The mean of the two measurements were used to calculate the stem diameter and stem circumference.

Selection of the best individual street trees during data gathering for statistical analysis could result in biased data. As is the case with allometry (Clark & Clark, 2000) a biased selection of trees could artificially inflate predictive regression estimates. The problem was avoided in this study by stratified random sampling - the streets were selected at random within the city; and the selection of trees in the streets was performed at random. (See Chapter 4 for a more detailed description of this methodology)

Of the 282 trees measured, 105 (37%) were *Combretum erythrophyllum* (river bushwillow), 107 (38%) *Rhus lancea* (karee) and 70 (25%) *Rhus pendulina* (white karee). All three species are indigenous to South Africa (Joffe, 1993; van Wyk & van Wyk, 1998). Stem diameters ranged from 26 mm to 685 mm, 26 mm to 507 mm and 36 mm to 352 mm for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* respectively.

The majority of the street trees measured grew in non-irrigated managed lawn residential environments. The mean tree to curb distance and road reserve width were 2.1 m and 6.5 m respectively. The mean planting distance was 14 m but driveways and road infrastructure often resulted in irregular planting distances.

These irregular planting distances were not included in the calculation of the mean planting distance.

The trees were planted between 1955 and 2001 and their ages were derived from the planting dates obtained from the Municipality. The planting dates refer to the date at which the trees were physically planted in the streets. The ranges of years and the minimum and maximum ages sampled for each species are shown in Table 3.1. Planting dates for trees planted prior to 1995 were obtained from aerial photographs and personal communication with botanical and horticultural staff since the Municipality kept planting date records only from 1995. In the past the policy was to plant mostly exotic street trees. This rendered it difficult to find old individuals, of which the age was known, of the species investigated. Therefore, two sets of trees from parking lots were incorporated into this study. They are tree sets measured for *Rhus lancea* and *Rhus pendulina* with planting dates of 1970 and 1987 respectively.

Stem diameter was regressed on age, and tree height and crown dimensions were regressed on stem diameter to compute the growth rate of each dimension for each species. In analysing stem circumference growth several growth curve models were tested (see previous chapter): exponential (Zhang, 1997), first degree logistic (Brewer *et al.*, 1985), Gompertz (du Toit, 1979), Lundqvist (Brewer *et al.*, 1985) and Richards family (du Toit, 1979). However, the logarithmic equation (Peper *et al.*, 2001a; Peper *et al.*, 2001b) was considered to provide the most appropriate fit and was therefore used to determine the dimensional growth rates for the individual species in this study. Age and stem diameter were used as dependent variables and the tree dimensions were modelled using the following equation:

$$E(y_i) = a[\log(x_i + 1)]^b \tag{1}$$

where

y_i = observed response for the i^{th} tree, where i = 1,2,…, n;

n = number of observations

x_i = age or stem diameter of the i^{th} tree

a, b = parameters to be estimated

$E(\ )$ = expected values

A description of the statistical models and procedures are presented elsewhere (Peper *et al.*, 2001a; Peper *et al.*, 2001b) as well as in Appendix A. An equation presented in the original publications by Peper *et al.*, (2001a) and Peper *et al.*, (2001b) has been corrected based on e-mail correspondence with P.J. Peper (pjpeper@ucdavis.edu, USDA Forest Service, Center for Urban Forest Research, c/o Department of Environmental Horticulture, University of California, One Shields Avenue, Davis, CA 95616-8587, http://cufr.ucdavis.edu/, 23 April 2003). The altered equation is presented in Table 3.2. It is important to mention that a bias correction was applied (Baskerville, 1972). Statistical analysis was conducted using SAS (SAS® version 8.2, SAS Institute, SAS Campus Drive, Carry, NC 27513).

The growth performance of the species for the observed and estimated (Table 3.2) stem diameter parameters was analysed in terms of annual growth rate (AGR) (Jalota & Sangha, 2000) as follows:

$$AGR = \frac{a - b}{t} \qquad (2)$$

where AGR is the annual growth rate in mm yr^{-1}, a is the largest stem diameter (mm) reading, b is the smallest stem diameter (mm) reading and t is the time period between the readings in years. The mean was used to calculate the growth rate of the observed data.

Results and discussion

The regression coefficients and coefficients of determination (r^2) to predict tree height, crown height and crown diameter growth by stem diameter and stem diameter by tree age are presented in Table 3.2. Stem diameter was the independent variable for tree height, crown height and crown diameter and age was the independent variable for stem diameter.

Table 3.2. Sample size (n), estimated regression coefficients (A, b) and mean standard error (MSE) values for predicting stem diameter, height, crown height, and crown diameter growth as well as coefficients of determination of three South African street tree species. Stem diameter, height, crown height, and crown diameter can be predicted by $\hat{y}_i = EXP\{MSE/2 + (\hat{A} + \hat{b}\log(\log(x_i + 1)))\}$, where $\hat{y}_i$ = the stem diameter, height, crown height, and crown diameter to be estimated, $\log$ is the $\log$ to the base e or natural logarithm of the argument and EXP = the inverse of the natural logarithm and x_i = age or stem diameter

		Stem diameter vs age				Tree height vs stem diameter				Crown height vs stem diameter				Crown diameter vs stem diameter			
Species	n	A	b	MSE	r^2	A	b	MSE	r^2	A	b	MSE	r^2	A	b	MSE	r^2
Combretum erythrophyllum	105	4.58352	2.44085	0.14804	0.76	4.47495	2.48832	0.03518	0.83	2.39606	3.52611	0.06858	0.84	1.12198	4.43068	0.05048	0.91
Rhus lancea	107	4.92616	1.74761	0.057522	0.84	5.12893	2.00494	0.01713	0.79	2.82672	3.09975	0.06706	0.70	1.73045	4.04557	0.04032	0.86
Rhus pendulina	70	4.53425	2.21533	0.051892	0.75	4.25544	2.69111	0.0366	0.63	2.57913	3.47474	0.06883	0.60	2.08542	3.89892	0.04628	0.74

The coefficients of determination of the stem diameter and age relationships are ≥ 0.75 for all the species with *Rhus lancea* having the highest coefficient (0.84). *Combretum erythrophyllum* has the highest coefficient of determination (0.83) for the tree height and stem diameter relationship while that of *Rhus pendulina* (0.63) is the lowest. For the crown height and stem diameter relationship *Combretum erythrophyllum* has the highest coefficient (0.84) thereafter *Rhus lancea* (0.70) and lastly *Rhus pendulina* (0.60). The crown diameter and stem diameter relationship coefficients of determination were ≥ 0.74 for all the species with *Combretum erythrophyllum* having the highest coefficient (0.91).

Pruning of the lowest branches regulates branching height and crown base height (Figure 3.1). In urban forests the lowest branches are pruned for aesthetic purposes and they also often interfere with traffic and are therefore removed (Larsen & Kristoffersen, 2002). Thus the crown base height is a function of cultural activities (which are difficult to measure) rather than natural tree growth. As a result the crown base height measurement data are inappropriate for this analysis and therefore the results are not presented.

The regressions of all three species are shown to enable visual comparisons (Figure 3.2 and Figure 3.3). *Rhus lancea* and *Rhus pendulina* show similar stem diameter growth rates over time while, *Combretum erythrophyllum* has the fastest stem growth (Figure 3.2). Regarding tree height and stem diameter, and crown height and stem diameter *Rhus pendulina* is the fastest grower then *Combretum erythrophyllum* and lastly *Rhus lancea*. All the species have similar growth rates when comparing the crown diameter and stem diameter growth relationship. It is noteworthy that *Rhus lancea* is consistently the slowest growing tree in all the relationships and is also the smallest tree in relation to its stem diameter. Furthermore *Rhus lancea* shows slow growth rates in the height and stem diameter relationship and it may be conjectured that it tends towards a near asymptote.

Tree height, crown height and crown diameter estimates as calculated for stem circumferences ranging from 100 mm to 500 mm (100 mm increments) are presented in Table 3.3 for all the species investigated.

The mean annual stem diameter growth rate for the observed data is 14 mm yr^{-1} (46.4 years) for *Combretum erythrophyllum*, 13 mm yr^{-1} (31.3 years) for *Rhus lancea* and 18 mm yr^{-1} (12.2 years) for *Rhus pendulina*. A growth comparison based on the aforementioned is inappropriate since the ages differ. However, the annual growth rates as based on the calculated stem diameters (see Table 3.2) are presented in Table 3.4. The growth rates were calculated for a 15 year (1 to 16 years) and 30 (1 to 31 year) year period. For the first fifteen years of growth *Combretum erythrophyllum* has the fastest annual growth rate (26 mm yr^{-1}) thereafter *Rhus pendulina* (18 mm yr^{-1}) and lastly *Rhus lancea* (16 mm yr^{-1}). Note that *Rhus lancea* and *Rhus pendulina* have similar but slower annual growth rates when compared with that of *Combretum erythrophyllum*. *Combretum erythrophyllum* has a faster annual growth rate (22 mm yr^{-1}) over a thirty year time period than *Rhus lancea* (12 mm yr^{-1}). There was furthermore, a decline in annual growth rate over the 30 year period when compared to the 15 year period for both

Combretum erythrophyllum and *Rhus lancea*. A thirty-year comparison with *Rhus pendulina* is not possible since it was possible to capture data for only 12.2 years.

The results of stem diameter regressed on tree age, and tree height, crown height and crown diameter regressed on stem diameter are shown for each species in (Figure 3.4 to Figure 3.7). Confidence intervals at a level of 95% to the estimated means of different ages or stem diameters are also shown. It can be noticed that the confidence bounds expand with the increase in tree age. This is a common tendency for all the species and reflects the variability within the species due to the effects of differences in genotype, culture, site conditions, biotic, and abiotic factors that influence the health and growth of a tree (Peper *et al.*, 2001b).

It needs to be emphasised that the regression equations presented are only valid within the range of ages and tree size dimensions covered by the sampling in this study. The extrapolation of data beyond the data range from which the regressions were determined is therefore not recommended. This point was stressed in determining biomass through the use of allometry (Haase & Haase, 1995) and should also be observed when calculating growth rate.

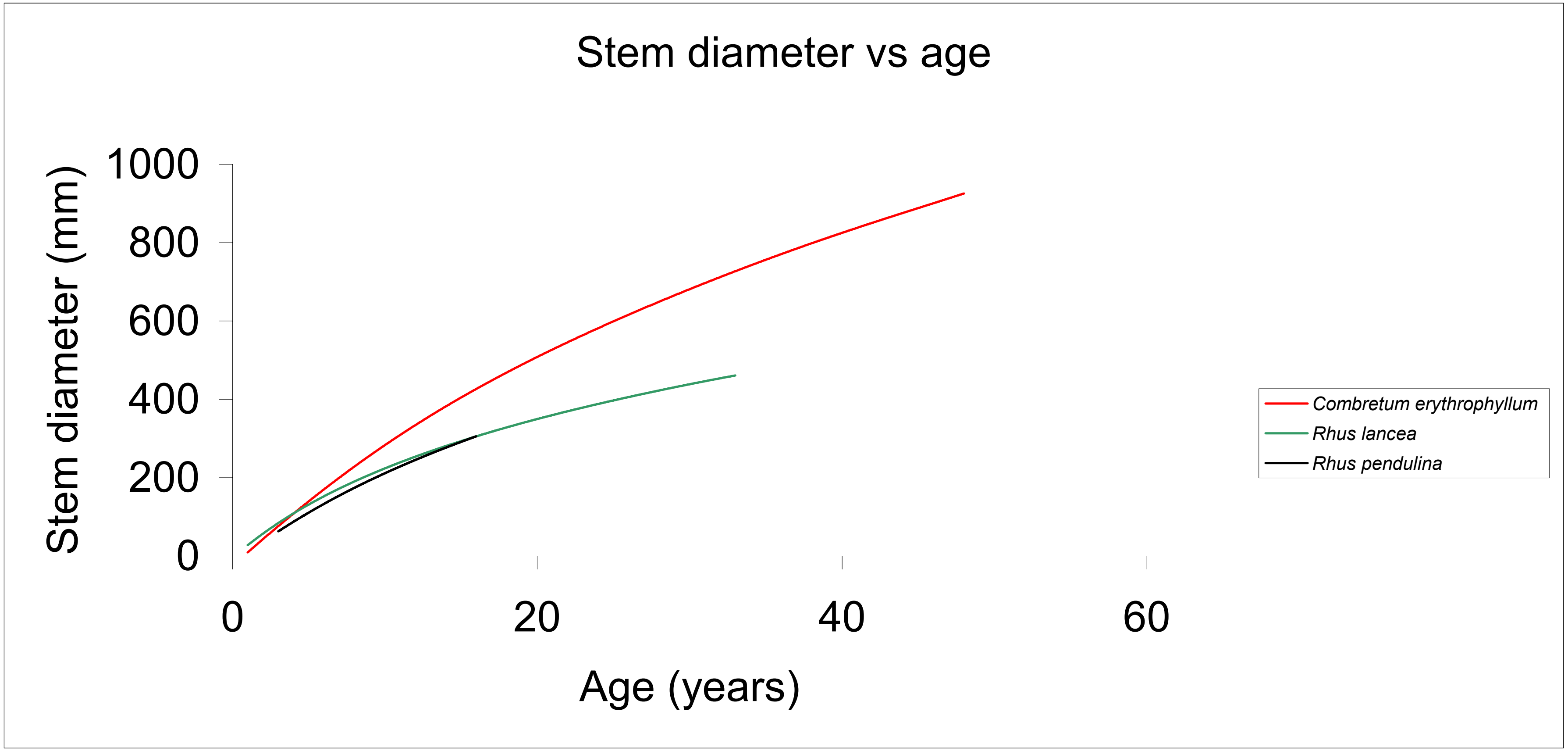
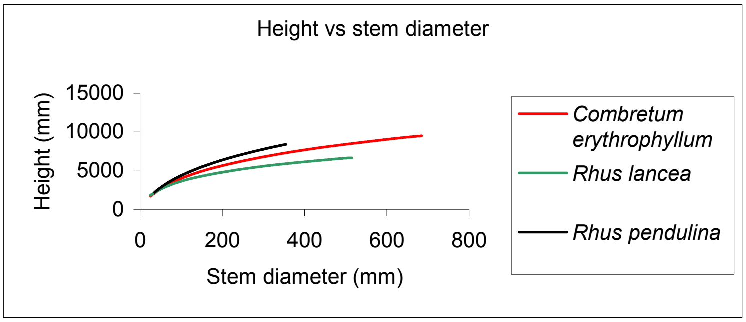


Figure 3.2. Relationship between stem diameter and tree age (years after planting) for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina*. All three the species are shown on one graph to facilitate growth comparisons.

(a)



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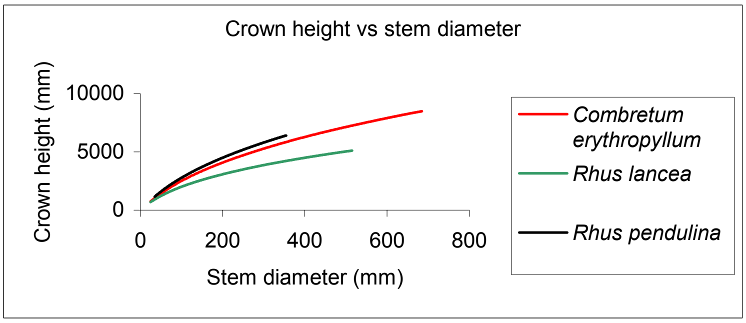

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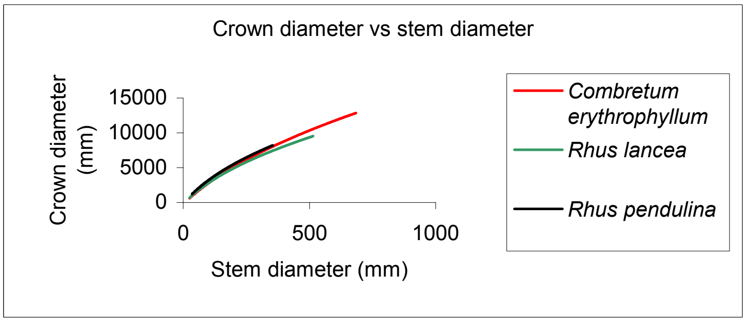


Figure 3.3. Relationships between various tree dimensions,

(a) tree height regressed on stem diameter

(b) crown height regressed on stem diameter

(c) crown diameter regressed on stem diameter for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina*. All three the species are shown on one graph to facilitate growth comparisons.

Table 3.3. Estimated tree height (mm), crown height (mm) and crown diameter (mm) for various stem diameters (100 mm to 500 mm at 100 mm increments) for each species investigated

Species	Tree height					Crown height					Crown diameter				
	Stem diameter					Stem diameter					Stem diameter				
	100 mm	200 mm	300 mm	400 mm	500 mm	100 mm	200 mm	300 mm	400 mm	500 mm	100 mm	200 mm	300 mm	400 mm	500 mm
Combretum erythrophyllum	4016	5675	6812	7696	8428	2497	4077	5281	6278	7139	2761	5111	7074	8791	10333
Rhus lancea	3655	4829	5594	6172	6641	2000	3077	3863	4497	5035	2801	4915	6613	8064	9347
Rhus pendulina	4400	6396	7792	-*	-*	2773	4494	5800	-*	-*	3201	5504	7327	-*	-*

* Largest stem diameter measured for *Rhus pendulina* was 352 mm

Table 3.4. Annual stem diameter growth rate (mm yr^{-1}) derived from stem diameter at 1 year, 16 year and 31 years after planting for a 15 and 30 year period. Stem diameters were calculated with the equation presented in Table 3.2

	15 year time period			30 year time period		
	Diameter at 1 year (mm)	Diameter at 16 years (mm)	AGR	Diameter at 1 year (mm)	Diameter at 31 years (mm)	AGR
Combretum erythrophyllum	14	426	26	14	697	22
Rhus lancea	24	279	16	24	396	12
Rhus pendulina	14	306	18	-*	-*	-*

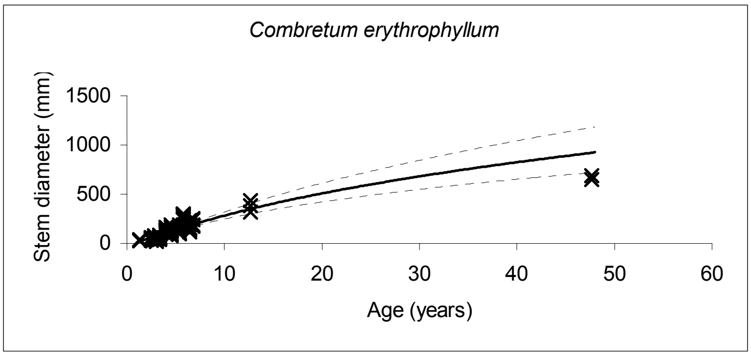
* The oldest trees measured for *Rhus pendulina* were 15.6 years.

An application of the results could be the forecasting of the physical dimensions of the species investigated as well as for planning and assessing the consequences of tree-planting schemes in urban environments (Larsen & Kristoffersen, 2002) (see Chapter 4). In some instances landscapes are designed for a certain lifetime and not to grow indefinitely. This is often the case when new office or commercial developments take place in phases. Here certain areas may be required to be landscaped with the understanding that it be removed with further development in, for example, 10 or 15 years' time. The regression equations presented provide the possibility for developers, landscape architects and quantity surveyors to calculate the estimated size and volume of trees and hence cost of removal when new developments are undertaken. Costs of felling trees involve amongst others: labour, tree felling equipment, front loaders and backhoe tractors and possibly wood chippers as well as the capacity to transport the wood in bulk or chip form to alternative locations. Costs may be excessive especially when removing the trees by hand. The cost of removing trees may become substantial when developing large landscaped areas.

The regression equations presented, furthermore, provide the opportunity to calculate stem growth versus tree height and crown dimension relationships. These relationships are important when designing hard landscaping infrastructure like tree guards and tree rings (influenced by stem growth rates) and the proximity of tree crowns to buildings and other structures. It becomes especially applicable when designing limited lifetime landscapes where, for example, costs need to be saved on amongst others, hard landscaping infrastructure. Necessary cost savings may limit the size of the rings specified while, for example, maximum crown growth is needed. The latter may possibly only be reached at larger stem circumferences which will dictate larger tree rings and will in turn marginally increase the cost of especially large landscape projects. The landscape architectural industry could thus use these equations to calculate the best scenario in terms of aesthetic requirements and budgetary constraints.

The results presented could assist in the estimates of pruning costs associated with various different pruning cycles or the production of waste wood (Peper *et al.*, 2001a). Tree age – stem diameter – crown height and – crown diameter relationships could aid in estimating when certain species will need to be pruned. This is especially applicable information for trees which might cause damage to structures such as, buildings or become hazardous, for example, where trees like *Combretum erythrophyllum* may become too large and make contact with overhead power lines. It could also be used for determining when street trees need to be pruned in relation to overhead telephone lines and other overhead services. The regressions will enable projections to be made as to an estimated future date when trees will need to be pruned and long-term budgets for operational costs could hence be determined.

(a)



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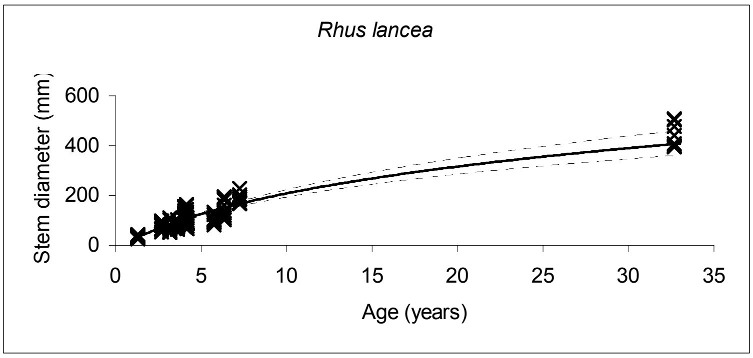

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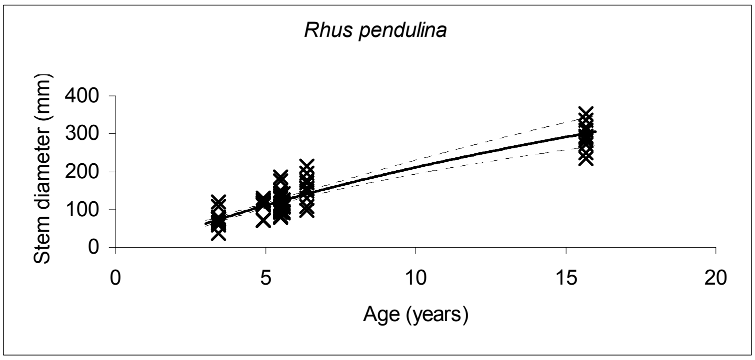
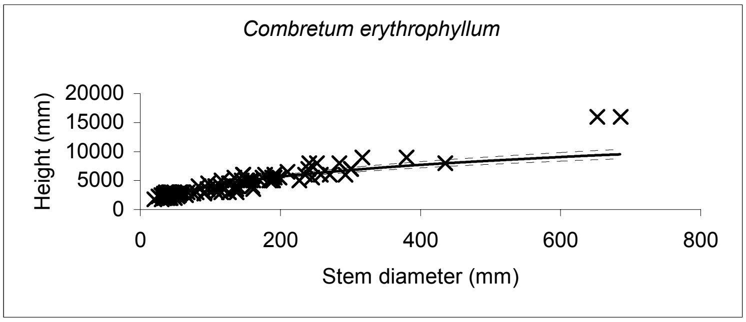


Figure 3.4. Stem diameter regressed on tree age (years) by a logarithmic equation indicating confidence intervals at a level of 95% to the estimated mean. (a) *Combretum erythrophyllum*, (b) *Rhus lancea* and (c) *Rhus pendulina*.

(a)



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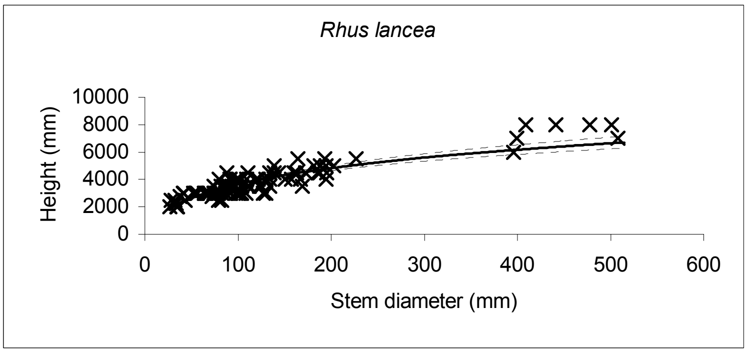

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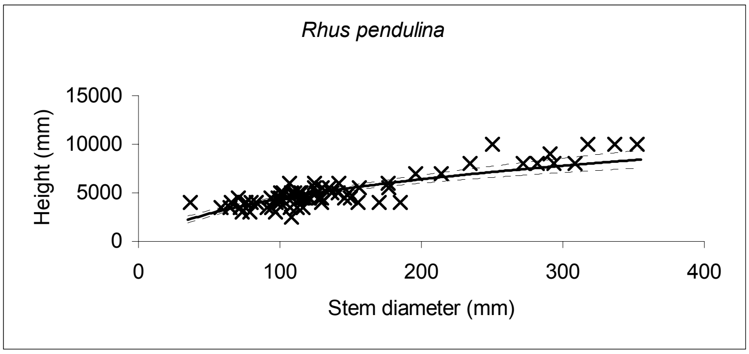
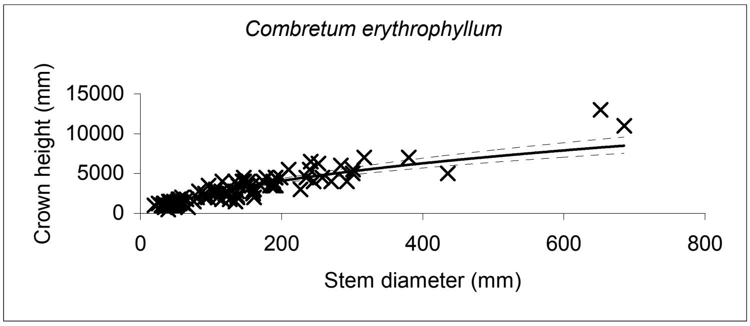


Figure 3.5. Tree height regressed on stem diameter by a logarithmic equation indicating confidence intervals at a level of 95% to the estimated mean. (a) *Combretum erythrophyllum*, (b) *Rhus lancea* and (c) *Rhus pendulina*.

(a)



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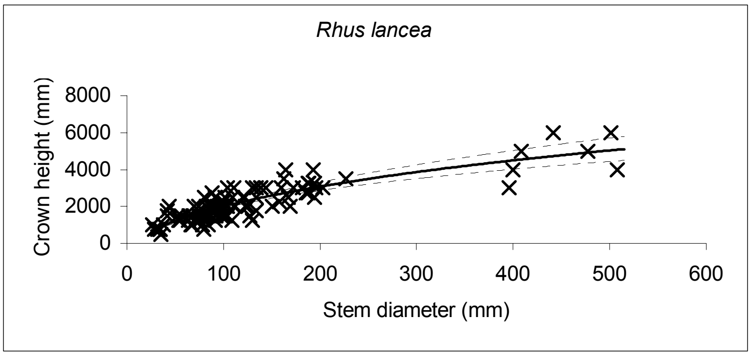

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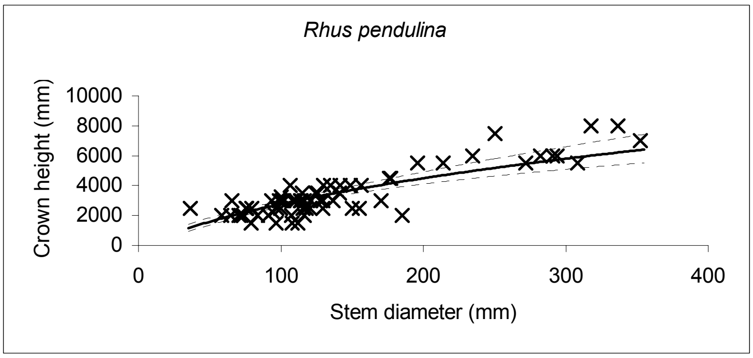
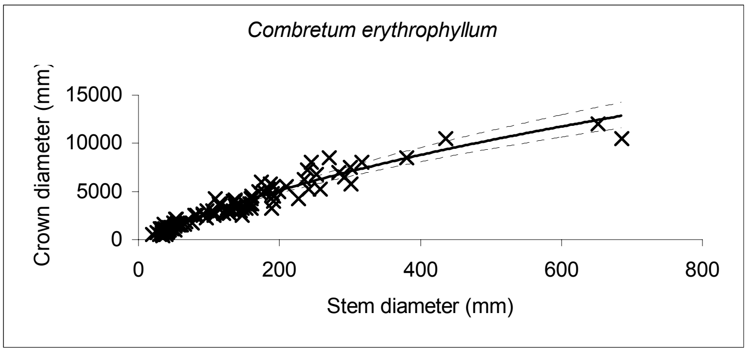


Figure 3.6. Crown height regressed on stem diameter by a logarithmic equation indicating confidence intervals at a level of 95% to the estimated mean. (a) *Combretum erythrophyllum*, (b) *Rhus lancea* and (c) *Rhus pendulina*.

(a)



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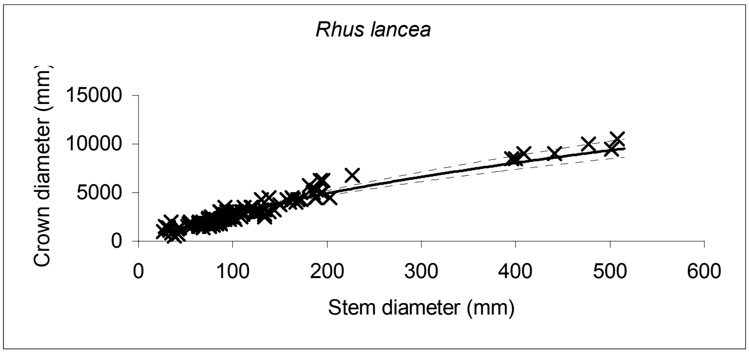

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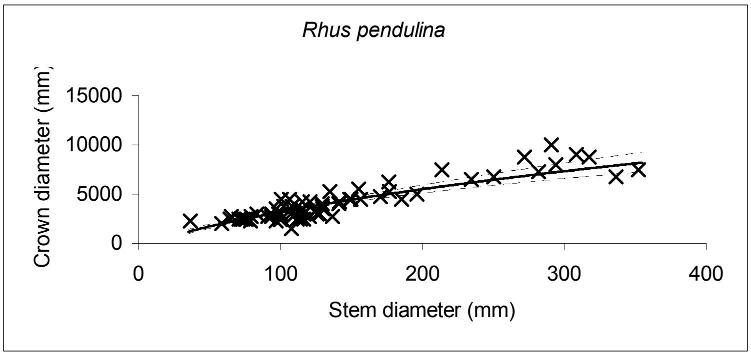

Figure 3.7. Crown diameter regressed on stem diameter by a logarithmic equation indicating confidence intervals at a level of 95% to the estimated mean. (a) *Combretum erythrophyllum*, (b) *Rhus lancea* and (c) *Rhus pendulina*.

Pruning of urban trees also has advantages in that it provides "waste wood" which could be used for harvestable wood products. The harvestable wood could be used for mulching, furniture, and structural timber and also as a substitute for fossil fuels like paraffin or coal. These fossil fuels are extensively used for heating and cooking purposes by the lower income groups in the previously disadvantaged communities and when substituted with bio-fuel (wood), will result in reduction in fossil fuel carbon dioxide emission and hence generate carbon credits. In order to obtain the credits, the quantity of wood will need to be ascertained. The quantification could in part be done with the use of the regression equations presented.

Conclusion

The tree height, crown height and crown diameter were examined in relation to stem diameter growth and stem diameter growth over time was also modelled. No information is available pertaining to these species' dimensional growth in an urban setting, which renders additional significance to the research presented.

The method applied, incorporated stratified random sampling of trees representing various ages, planting locations and different environmental conditions within the City of Tshwane. This makes the equations representative of a fair variety of climate and environmental zones and renders them applicable to a somewhat wider spectrum of environments.

Rhus lancea and *Rhus pendulina* show similar stem diameter growth rates over time while, *Combretum erythrophyllum* has the fastest stem growth. Regarding tree height and stem diameter, and crown height and stem diameter *Rhus pendulina* is the faster grower then *Combretum erythrophyllum* and lastly *Rhus lancea*. All the species have similar growth rates when comparing the crown diameter and stem diameter growth relationship. It is noteworthy that *Rhus lancea* is consistently the slowest growing tree in all the relationships and is also the smallest tree in relation to its stem diameter.

Growth rates were calculated for a 15-year (1 to 16 years) and 30 (1 to 31 year) year period. For the first fifteen years of growth *Combretum erythrophyllum* has the fastest annual growth rate (26 mm yr^{-1}) thereafter *Rhus pendulina* (18 mm yr^{-1}) and lastly *Rhus lancea* (16 mm yr^{-1}). *Combretum erythrophyllum* has a faster annual growth rate (22 mm yr^{-1}) over a thirty year time period than *Rhus lancea* (12 mm yr^{-1}). There was furthermore, a decline in annual growth rate over the 30 year period when compared to the 15 year period for both *Combretum erythrophyllum* and *Rhus lancea*. A thirty-year comparison with *Rhus pendulina* is not possible since it was possible to captured data for only 12.2 years.

These results could be used for forecasting the physical dimensions of the species investigated as well as for planning and assessing the consequences of tree-planting schemes in urban environments. It could assist in the estimates of pruning costs associated with various different pruning cycles or the production of waste wood.

The dimensional relationships could also form a basis for dynamic illustration of the tree growth related to a project when implementing computer aided design

(CAD) applications. The results are furthermore important for determining environmental benefits of the urban trees. Continued collection of data and development of predictive equations for additional tree species will be beneficial for determining best urban forest management practices and could result in optimising environmental benefits resulting in the creation of more habitable urban environments.

References

Arnold, H.F. (1980). *Trees in urban design.* New York: Van Nostrand Reinhold Company.

Baskerville, G.L. (1972). Use of logarithmic regressions in the estimation of plant biomass. *Canadian Journal for Forest Research*, **2:** 49-53.

Brewer, J.A., Burns, P.Y. & Cao, Q.V. (1985). Short term projection accuracy of five asymptotic height-age curves for Loblolly pine. *Forest Science*, **31:** 414-418.

Clark, D.B. & Clark, D.A. (2000). Landscape-scale variation in forest structure and biomass in a tropical rain forest. *Forest Ecology and Management*, **137:** 185-198.

du Toit, S.H.C. (1979). *Analysis of growth curves*. PhD Thesis. Pretoria: University of South Africa.

*Ferlich, L.E. (1992). *Predicting dimensional relationships for Twin Cities shade trees*. Thesis. University of Minnesota. Department of Forest Resources. St. Paul.

*Fleming, L.E. (1988). *Growth estimates of street trees in central New Jersey*. Thesis. Rutgers University, New Brunswick, NJ.

Grey, G.W. & Deneke, F.J. (1978). *Urban forestry*. New York: John Wiley and Sons. 279 pp.

*cited but not seen

Haase, R. & Haase, P. (1995). Above-ground biomass estimates for invasive trees and shrubs in the Pantanal of Mato Grosso, Brazil. *Forest Ecology and Management*, **73:** 29-35.

Jalota, R.K. & Sangha, K.K. (2000). Comparative ecological-economical analysis of growth performance of exotic *Eucalyptus tereticornis* and indigenous *Dalbergia sissoo* in mono-culture plantations. *Ecological Economics*, **33:** 487-495.

Joffe, P. (1993). *The gardener's guide to South African plants*. Cape Town: Tafelberg-Uitgewers Beperk. 368 pp.

Kirsten, K.E. & Meyer, L. (1992). *Keith Kirsten's complete garden manual for South Africa.* Cape Town: Human & Rousseau. 256 pp.

Larsen, F.K. & Kristoffersen, P. (2002). *Tilia* 's physical dimensions over time. *Journal of Arboriculture*, **25:** 209-213.

McPherson, E. G., Nowak, D. J., and Rowntree, R. A. (1994). *Chicago's urban forest ecosystem: results of the Chicago Urban Forest Climate Project*. General Technical Report NE-186. Radnor, PA, United States of America. United States Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

*McPherson, E.G., Simpson, J.R., Peper, P.J., Scott, K.I. & Xiao, Q. (2000). *Tree guidelines for coastal southern California communities*. Local government commission, Sacramento, CA. 140pp

Peper, P.J., McPherson, E.G. & Mori, S.M. (2001a). Predictive equations for dimensions and leaf area of coastal Southern California street trees. *Journal of Arboriculture*, **27:** 169-181.

Peper, P.J., McPherson, E.G. & Mori, S.M. (2001b). Equations for predicting diameter, height, crown width and leaf area of San Joaquin Valley street trees. *Journal of Arboriculture*, **27:** 306-317.

van Wyk, B. & van Wyk, P. (1998). *Field guide to trees of southern Africa.* Cape Town: Struik Publishers. 536 pp.

Zhang, L. (1997). Cross-validation of non-linear growth functions for modeling tree height-diameter relationships. *Annals of Botany*, **79:** 251-257.

*cited but not seen

Appendix A

Statistical model described by Peper *et al.*, (2001a) and Peper *et al.*, (2001b) for the prediction of stem diameter and tree dimensions:

Using age (years after planting) or stem diameter as explanatory variable, tree dimensional growth responses were modelled using the following regression equation:

$$E(y_i) = a[\log(x_i + 1)]^b \qquad (1)$$

where

$y_i =$ observed response for the i^{th} tree, where $i = 1,2,\ldots,n$;

$n =$ number of observations

$x_i =$ age of the i^{th} tree

a, $b =$ parameters to be estimated

$E(\ ) =$ expected value.

$\log =$ natural logarithm (base e)

Visual observations of the data suggests that the errors were of a multiplicative nature (Appendix B), increasing with age or stem diameter; therefore, the error was assumed to be multiplicative, and the responses were logarithmically transformed (natural logarithm) to equalize the variance along the line for the appropriate use of standard least-squares estimation procedures (LSE). The following regression model was used for the transformed response:

$$\log(y_i) = A + b\log(\log(x_i + 1)) + \varepsilon_i \qquad (1')$$

where

$\log =$ natural logarithm (base e)

This model can be rewritten as

$$z_i = A + bv_i + \varepsilon_i$$

where

A, $b =$ parameters to be estimated

$z_i = \log(y_i)$

$v_i = \log(\log(x_i + 1))$

$\varepsilon_i =$ error term

$\log =$ natural logarithm (base e)

Parameter estimation was conducted using SAS (SAS® version 8.2, SAS Institute, SAS Campus Drive, Carry, NC 27513) linear regression routines and the estimated parameters, A and b, are denoted by $\hat{A}$ and $\hat{b}$. The Baskerville (1972) bias correction, $e^{MSE/2}$, was applied to the back-transformed fitted, e^{z_i}, $e^{\hat{z}_i}$:

$$\hat{y}_i = e^{\hat{z}_i} * e^{MSE/2},$$

where

$\hat{z}_i = \hat{A} + \hat{b} v_i$ and

$MSE =$ mean sum of squares from least squares estimation (LSE) procedure.

Therefore, the fitted value of y_i is given by

$$\hat{y}_i = \hat{a}[\log(x_i + 1)]^{\hat{b}}$$

where

$\hat{a} = e^{\hat{A} + MSE/2}$.

and $\log =$ natural logarithm (base e)

Estimates $\hat{A}$ and $\hat{b}$ and MSE are used to predict stem diameter and tree dimensions for each species listed in Table 3.2.