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# Growth and carbon sequestration by street trees in the City of Tshwane, South Africa

by

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Soli Deo Gloria

I dedicate this thesis to my beloved parents Pierre and Cecilia

**Titel:** Growth and carbon sequestration by street trees in the City of Tshwane, South Africa

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# Abstract

This study focuses on certain urban forestry aspects of the City of Tshwane (previously Pretoria) and in particular that of growth rate and carbon sequestration estimates of street trees with the aim of quantification of the value of these trees. The relationships between tree height and crown dimensions to stem diameter and tree age, as well as the relationship between stem diameter to tree age enable the development of growth rate equations that predict tree dimensions and carbon storage. This permits the calculation of monetary values of urban trees and thus the modelling of costs and benefits of urban forests.

The main objectives were (1) to develop tree height, crown diameter, crown height, and crown base height to stem diameter relationships for the indigenous street tree species *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina*, (2) to develop tree height, crown diameter, crown height, crown base height and stem diameter to tree age relationships for the above street tree species, (3) to determine the 30 year carbon sequestration estimate and monetary value of 115 000 street trees to be planted mainly in poorer previously disadvantaged communities during the period 2002 to 2008 and (4) to determine the monetary value of the 33 630 *Jacaranda mimosifolia* street trees in the City based on the quantity of carbon stored in the trees.

*Combretum erythrophyllum* had the most rapid growth rate in many instances, thereafter came *Rhus pendulina* and then *Rhus lancea*, which consistently had the slowest growth rate for the investigated parameters. It is estimated that the 115 000 street trees to be planted will sequestrate more than 200 000 tonne $CO_2$ equivalent and have an estimated monetary value of more than US$2 million if a market related $CO_2$ price of US$10.00 per tonne is assumed. The Jacaranda street trees have an estimated carbon stock of 41 978 tonne $CO_2$ equivalent and this would value the Jacaranda urban forest at US$419 786.

**Keywords:** allometry, carbon sequestration, growth rate, stem diameter, street trees, tree dimensions, urban ecology, urban forestry

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# Chapter 1

## Introduction

The City of Tshwane is the administrative capital of the Republic of South Africa and is located in the northwestern region of the province Gauteng. The City's municipal area covers 12% (2 199 km$^2$) of the total area of the province and has a population of 1.98 million, which represents 22.4 % of the total population (8 837 178) of the province (Tshwane IDP 2005. http://www.tshwane.gov.za/ accessed 09/06/2005). Since the first national democratic elections in 1994 the City has embarked on the provision of housing and grey infrastructure for previously disadvantaged communities. During the period 2001 – 2005 the City would have built 42 000 houses for these communities. There are also 81 informal settlements (formerly known as squatter camps or shanty towns) ranging in size from 300 to more than 8 000 families per settlement (Mkhatshwa 2005). Unemployment in the City of Tshwane is at a total of 31.7 % (Tshwane IDP 2005. http://www.tshwane.gov.za/ accessed 09/06/2005).

In 2004 a R1,4 billion housing project was launched for the previously disadvantaged communities of the Winterveld in the north of the City. This is one of several government-funded housing projects in the City. More than R170 million was spent on upgrading of street lighting infrastructure (Mkhatshwa 2004). However, the urban forestry budget was only R17 million for the entire city. This is 1.2 % of R1,4 billion allocated to the Winterveld housing project. Included in the urban forestry budget were salaries, maintenance, transportation, equipment and lastly tree planting.

Since 1995 to the present the City has planted approximately 43 000 street trees (personal communication: B. Dry, Deputy Manager: Urban Forestry, Nursery and Training of the City of Tshwane Metropolitan Municipality, 09/06/2005). This equates to approximately one tree planted per house built for previously disadvantaged people during the period 2001 – 2005 and is much less than one tree planted per house built since the introduction of democracy in 1994.

Monetary budgets allocated to street tree planting in the City of Tshwane have declined since the commencement of democracy in spite of this rapid increase in housing development for the poorer previously disadvantaged population of the city (personal communication: B. Dry, Deputy Manager: Urban Forestry, Nursery and Training of the City of Tshwane Metropolitan Municipality, 2004). Urban forestry is not viewed as fundamentally essential but rather as an aesthetic aspect of the city and therefore is allocated less funding. Yet urban trees provide numerous environmental and social benefits like for example, reducing storm water runoff, improving air, soil and water quality, reducing global warming through amongst others carbon sequestration, providing wildlife habitat, increasing property values, enhancing community attractiveness, promoting human health and well-being as well as reducing crime (Hosty, 2003; MacArthur, 2003; McPherson *et al*., 2002; Murray, 2003).

According to Mr Dry there is a need to quantify these and other benefits that urban trees hold for the City in monetary terms. When arguing for larger budgets the monetary benefits of these trees can then be used to qualify and quantify the benefits in a commonly understood “currency” and hence the importance of planting more trees could be motivated. Equations that predict tree dimensions and carbon storage enable arborists, researchers and urban foresters to model costs and benefits of urban trees (Peper *et al.*, 2001) and could thus be used to model the monetary value of urban trees. The availability of data relating to the relationships between tree height and crown dimensions to stem diameter and tree age as well as data relating to the relationship between stem diameter to tree age could be used for modelling various urban forestry benefits for example: carbon sequestration, energy use reductions, air pollution uptake, rainfall interception as well as the microclimatic amelioration effects of urban trees (Peper *et al.*, 2001). A literature search revealed no information pertaining either to these tree dimensional relationships or to their application in urban forest ecology modelling for a South African context. Hence this study has four main objectives:

1. to develop tree height, crown diameter, crown height, and crown base height to stem diameter relationships for indigenous street tree species,
2. to develop tree height, crown diameter, crown height, crown base height and stem diameter to tree age relationships for indigenous street tree species,
3. to determine the 30 year carbon sequestration estimate and monetary value of 115 000 street trees to be planted mainly in poorer previously disadvantaged communities during the period 2002 to 2008 and

4. to determine the monetary value of the *Jacaranda mimosifolia* street tree population of the City of Tshwane based on the quantity of carbon stored in the trees.

The above objectives have as overarching aim the establishment and commencement of urban forestry research and to initiate a South African urban forestry resource base which may be used for, and supplement future urban forestry ecosystem function modelling and cost benefit analysis in a southern African context. The meta-motivation being able to argue for more trees to be planted in the poorer urban areas of the City of Tshwane and indeed in all of South Africa's cities.

**Thesis format**

The thesis is written in article format with the aim of publication once confidentiality restrictions allow this. As a result of the independent nature of the articles there is some repetition between the chapters. However, Chapters 2, 8 and 9 are not aimed at publication. Appendix A consists of a South African patent written in collaboration with a local patent law firm.

**Chapter sequence**

The following is an introduction to the chapters to follow:

Chapter 2 describes some of the field data collection methodology. It also includes a discussion of the selection of an appropriate growth equation that was applied in Chapters 3, 4 and 6. The results presented in Chapter 5 are based on the calculations derived from the application of this equation in Chapter 3.

Chapter 3 provides a method for determining tree height, crown dimensional and stem diameter growth that can in turn be related to tree age. This chapter is important in that it provides a basis to calculate the future costs and benefits of urban trees.

Chapter 4 relates tree height and crown dimensions to tree age. The dimensional growth rates thus derived enables urban foresters, arborists, horticulturists and landscape architects to correctly position trees in relation to other spatial elements and utilities in view of future tree growth. It also enables computer aided design (CAD) applications to dynamically simulate the growth of trees over time in relation to other landscape, architectural and utility elements.

Chapter 5 presents a direct application of some of the findings in Chapter 3 to the urban forestry, horticultural, arborists and especially the landscape architectural industry. A literature search revealed no information that could be applied to the growth rate of tree stems in confined spaces. This chapter attempts to address the issue. It is also intended for publication in a landscape architectural industry magazine so as to be of direct value to practitioners.

Chapter 6 is an application of the growth equations presented in Chapter 3. The aim of the chapter was to apply the growth rate results to derive carbon sequestration rates and this was applied to the City of Tshwane's urban forest. A carbon based monetary value for the trees to be planted by this City is projected.

Chapter 7 presents results that aim to quantify the carbon stored in the *Jacaranda mimosifolia* urban forest in the City of Tshwane and thence to derive a monetary value based on that quantity.

Chapter 8 provides a comparison between the growth rates and carbon sequestration rates determined in the previous chapters and that found in the literature for other countries. This is done to provide an international perspective on the local results.

Chapter 9 provides a perspective on urban forest carbon sequestration where it is applied to certain aspects of the Kyoto Protocol and the United Nation Framework Convention on Climate Chance (UNFCCC).

Appendix A is a commercial application of the carbon sequestration equations. This shows that the research presented in this thesis has an additional commercial application beyond those discussed in the previous chapters.

## Conclusion

Urban forestry is defined as *the art, science and technology of managing trees and forest resources in and around urban community ecosystems for the physiological, sociological, economical and aesthetic benefits trees provide society* (Konijnendijk *et al*., 2005). It is hoped that this thesis will contribute to the body of knowledge as defined above so as to benefit especially the South African communities at large and on an individual basis.

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# Chapter 2

## Field measurements and methodology to select a growth equation for three indigenous street tree species

### Introduction

The field measurements that consist of the variables that were investigated during field work and the methodology of statistical analysis conducted to select a growth equation for three indigenous street tree species are discussed below. More detailed field data collection methodology is presented in the various related chapters (Chapters 3, 4 and 6). This chapter's focus is, however, on the methodology of the selection of an appropriate growth equation. Six growth equations were investigated to determine which one is the most appropriate in predicting stem circumference growth for three street tree species. The equations were subjectively chosen based on biological and statistical characteristics. In this section some of the attributes of the equations are evaluated and the rationale for the selection of the most suitable equation is discussed. The selected appropriate growth equation will be used for further data analysis and generation of results in the chapters to follow (Chapters 3 to 6).

## Methodology

### *Field Data Collection*

The street trees were measured in the winter and early spring (April - September) of 2002 in the Pretoria area in the City of Tshwane, in the province of Gauteng. The measurements were made between Ovenbush Street (25˚ 39' 08.7'' S - 28˚ 15' 21.7'' E) in the suburb Doornpoort in the north and Piering Street (25˚ 50' 04.7'' S - 28˚ 14' 58.3'' E) in the suburb Erasmuskloof in the south, as well as between Pretoria East Cemetery (25˚ 49' 36.2'' S - 28˚ 19' 20.8'' E) in Pretorius Park suburb in the east and Brits Street (25˚ 40' 40.8'' S - 28˚ 09' 05.4'' E) in the suburb of Pretoria North to the west of the city.

Three species, *Combretum erythrophyllum* (Burch.) Sond. (river bushwillow), *Rhus lancea* L.f. (karee) and *Rhus pendulina* Jacq. (white karee) were investigated. All the species are indigenous to South Africa and when fully grown are approximately 7 m to 12 m tall (Joffe, 1993; van Wyk & van Wyk, 1998). In total 282 trees were measured of which 105 were *Combretum erythrophyllum*, 107 *Rhus lancea* and 70 *Rhus pendulina*. 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. Measurements were also taken of 95 trees of a fourth species namely *Olea europea* subspecies *africana*. However, when the obtained planting dates were applied to the data it proved that the results were less accurate and the data for this species were thus omitted.

Each data set consisted of the data of the trees measured in a street. With some exceptions, ten trees were measured per street. Where applicable, a total of 50 variables were measured or noted for 377 trees (18 850 data values). Some aspects of the importance and influences of the below mentioned factors to the urban forest have been addressed in Chapter 8. Variables that were measured or noted consisted of the following:

- Dataset identification value,
- Date of measurement with the view of further additions to the data at a later stage than that gathered for this thesis,
- Suburb and street in which trees were measured,
- Closest cross street perpendicular to the street in which the measurements were taken at the first and last tree measured,
- Road reserve width,
- Tree curb distance,
- Between tree distance,
- Direction in which tree sequence was measured,
- Planting date,
- Sequence,
- Species,
- Tree height,
- Height of maximum crown diameter,
- Height of first leaves measured from ground level,
- Crown diameters measured in two perpendicular directions taken at the height of maximum crown diameter,

- Crown diameters of the first leaves measured in two perpendicular directions taken at the height of first leaves,
- Stem diameter (two perpendicular measurements) for up to five stems or circumference at breast height was measured. Trees with more than five diameter measurements were not measured,
- Stem diameter or circumference at 200 mm above ground level,
- Stem diameter or circumference at 50 mm above ground level or just above the basal swelling,
- Latitude and longitude of each tree was noted in degrees, minutes and seconds with the aim of future re-measurements,
- Global Positioning System accuracy level,
- Tree shape,
- The ground surface type surrounding the measured tree,
- The landuse in which the trees where located,
- The position of the tree in relation to the adjacent street,
- Perpendicular streets that were crossed during measurements
- Notes that could influence data analysis,

The measured 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 minimum and maximum ages are 1.2 years to 47.6 years, 1.3 years to 32.6 years and 3.4 years to 15.6 years for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* respectively. 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.

Not all of the measured data gathered during field work warranted further in depth statistical analysis and were thus not presented in this thesis. Crown diameters at height of first leaves was, for example, a function of cultural pruning practices and proved to be inappropriate to be considered for statistical analysis and hence, were not included in this thesis.

*Selection of growth equation*

The selection of an appropriate growth equation was done by using the data gathered for stem circumference. The stem circumference of the larger street trees (larger than approximately 90 mm diameter) was determined with a tape measure at 50 mm above ground level or just above the basal swelling. Although initially measured, diameter at breast height (DBH) (measured at a height of 1.37 m) was not an appropriate measurement since the biomass regression equation used (Shackleton, 1997) requires stem diameter measurements at ground level. Also the City of Tshwane Metropolitan Municipality (hereafter Municipality) often planted trees that still have branches below 1.37 m. Furthermore, the African savanna species investigated tend to branch at a level lower than this height.

The 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 was used to calculate the diameter and circumference. Diameters of these smaller trees were also measured at 50 mm above ground level or just above the basal swelling

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 by stratified random sampling. Stratification of the city was by tree age and the streets were selected at random within age group; and the selection of trees in the streets was performed at random.

Growth equations were applied to the data in order to select the most appropriate equation for further use in this study. The data was processed in SAS® (SAS® version 8.2, SAS Institute, SAS Campus Drive, Cary, NC 27513) together with the S T Kromme (du Toit, 1979) statistical procedure. The following equations were applied to the data:

Exponential (Zhang, 1997):

$$Circ = a * e^{(\frac{-b}{t+c})}$$

First degree logistic (Brewer *et al.*, 1985):

$$Circ = a(1 + b\exp(ct))^{-1}$$

Gompertz (du Toit, 1979):

$$Circ = a\exp(-b(c^{t}))$$

Logarithmic (Peper *et al.*, 2001):

$$Circ = a(\log(t+1))^{b}$$

Lundqvist (Brewer *et al.*, 1985):

$$Circ = a\exp(-bt^{-c})$$

Richards family (du Toit, 1979):

$$Circ = a(1 - b(c^{t}))^{\alpha}$$

where

$Circ$ = stem circumference (mm)

$a, b, c$ = parameters to be estimated from the data

$t$ = time (tree age in years)

$\alpha$ = transformation constant which can be used to transform the Richards family equation into the different members of the family.

Various initial values were tested in the process of determining the most appropriate constants. A requirement in this process was that the selected initial values should result in no less than three iterations (personal communication, M.J. van der Linde, November 2002, Department of Statistics, University of Pretoria.). An exception was the Gompertz equation applied to the data of *Combretum erythrophyllum*, which iterated only twice. Initial values that were selected are those which resulted in a high coefficient of determination and from which constants of reasonable magnitudes could be derived. This selection procedure was applied to all the equations for all three the species. However, a coefficient of determination and constants of reasonable magnitude could not be obtained for Lundqvist and Gompertz equations that were applied to the data of *Combretum erythrophyllum* (Table 2.1).

The first criterion for selecting an equation is that of selecting the equation with the highest coefficient of determination. The second criterion is whether the slope of the curve beyond the data range suggests or reaches an imminent asymptote. The most appropriate curve should suggest continued growth due to the relatively young tree stands that were measured. The third criterion is the slope of the curve beyond the data range. It is anticipated that the steepest slope being the most appropriate fit to the data due to the relatively young ages of the trees that was measured.

## Results

### *Coefficient of determination*

The coefficient of determination (Tables 2.1 - 2.3) derived for the equations applied to the *Combretum erythrophyllum* data ranged from -1.35 to 0.88 with the exponential, Richards and the logarithmic equations giving the best coefficients. For *Rhus lancea* and *Rhus pendulina* the coefficient of determination for all the equations applied to a species had a set value, being 0.91 and 0.84 respectively.

*Visual assessment of the growth curves*

Growth projections for 5 years beyond the last data value were made for ease of visual analysis. Figure 2.1 to Figure 2.3 show the different growth curves as applied to *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* data where stem circumference (mm) is regressed on tree age (years).

When analysing the curves for *Combretum erythrophyllum* the results indicate that all the curves, except for the logarithmic curve, either have reached an asymptote or approach an asymptote at the last data value (Figure 2.1). The logarithmic equation suggests continued stem growth beyond the measured data range and has the steepest slope of all the curves in this range. The parameter ($b$) for the Gompertz and Lundqvist equations for the data of *Combretum erythrophyllum* were inapplicable (Table 2.1) and these equations were discarded for this species.

Table 2.1. The constants for six different growth equations and their coefficient of determination for *Combretum erythrophyllum*

| **Equation** | ***a*** | ***b*** | ***c*** | $\alpha$ | **Coefficient of determination** |
|---|---|---|---|---|---|
| Exponential | 225.9 | 9.9561 | 0.85136 | | 0.88 |
| First degree logistic | 192.67 | 16.971 | -0.31423 | | 0.83 |
| Gompertz | 44.521 | 0.72370E+76 | 1 | | -1.35 |
| Logarithmic | 76.992 | 2.0618 | | | 0.84 |
| Lundqvist | 44.415 | 0.21355E+06 | -47.995 | | 0.06 |
| Richards family | 208.47 | 1 | 0.88872 | 1.8841 | 0.87 |

Table 2.2. The constants for six different growth equations and their coefficient of determination for *Rhus lancea*

| **Equation** | ***a*** | ***b*** | ***c*** | $\alpha$ | **Coefficient of determination** |
|---|---|---|---|---|---|
| Exponential | 220.2 | 16.655 | 4.5164 | | 0.91 |
| First degree logistic | 140.79 | 11.116 | -0.27437 | | 0.91 |
| Gompertz | 143.96 | 2.7885 | 0.86406 | | 0.91 |
| Logarithmic | 62.699 | 1.9031 | | | 0.91 |
| Lundqvist | 1785.2 | 5.4558 | -0.21933 | | 0.91 |
| Richards family | 149.94 | 0.74087 | 0.90385 | 2.3171 | 0.91 |

Table 2.3. The constants for six different growth equations and their coefficient of determination for *Rhus pendulina*

| **Equation** | ***a*** | ***b*** | ***c*** | $\alpha$ | **Coefficient of determination** |
|---|---|---|---|---|---|
| Exponential | 193.12 | 13.776 | 3.0324 | | 0.84 |
| First degree logistic | 95.840 | 11.111 | -0.3634 | | 0.84 |
| Gompertz | 105.36 | 3.0485 | 0.81812 | | 0.84 |
| Logarithmic | 60.036 | 2.16 | | | 0.84 |
| Lundqvist | 565.58 | 5.1111 | -0.37702 | | 0.84 |
| Richards family | 106.67 | 0.20221 | 0.82701 | 13.851 | 0.84 |

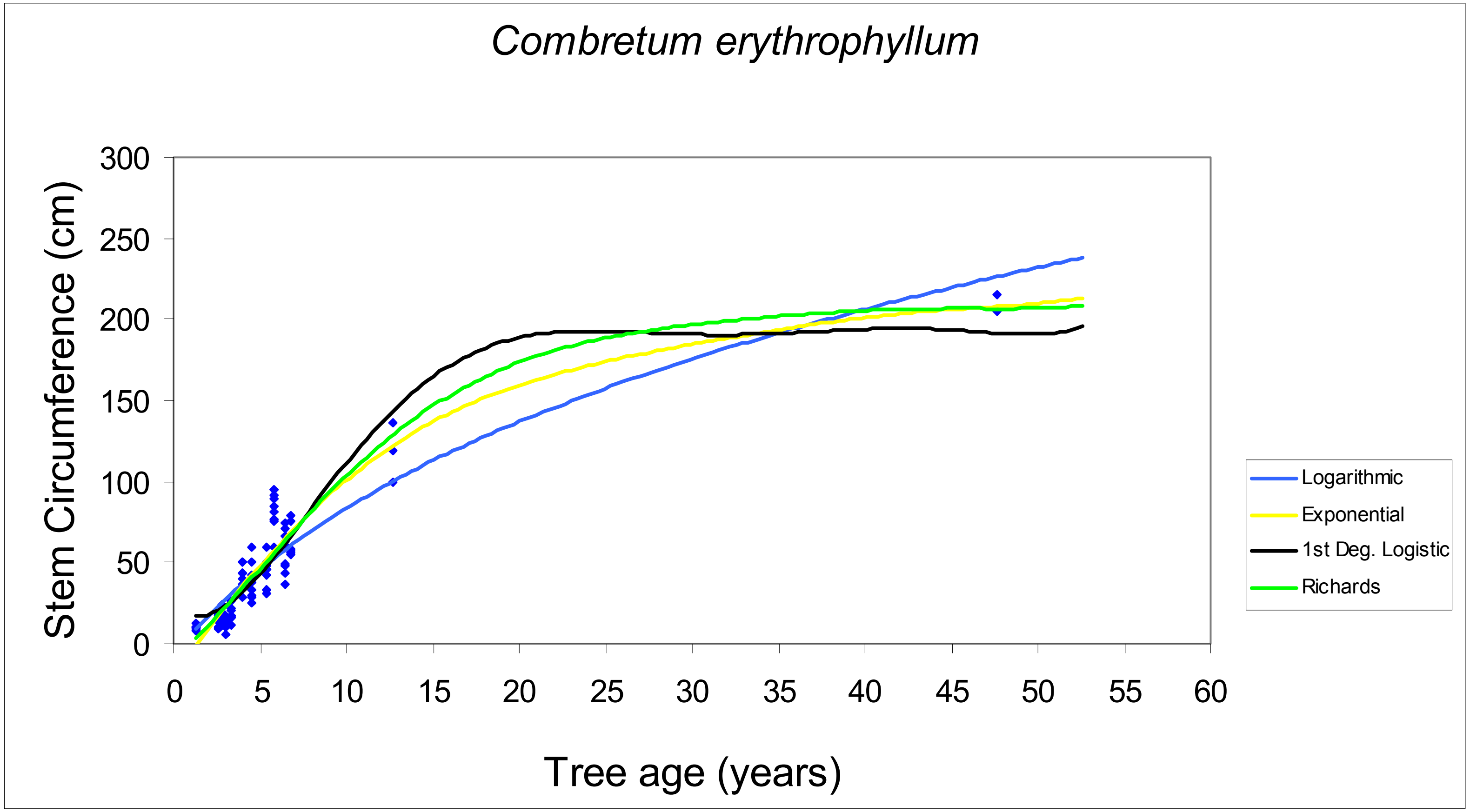

Figure 2.1. Four different growth curves as applied to *Combretum erythrophyllum* data where stem circumference (cm) is regressed on tree age (years). Growth projections for five years beyond the last data value were made for ease of visual analysis.

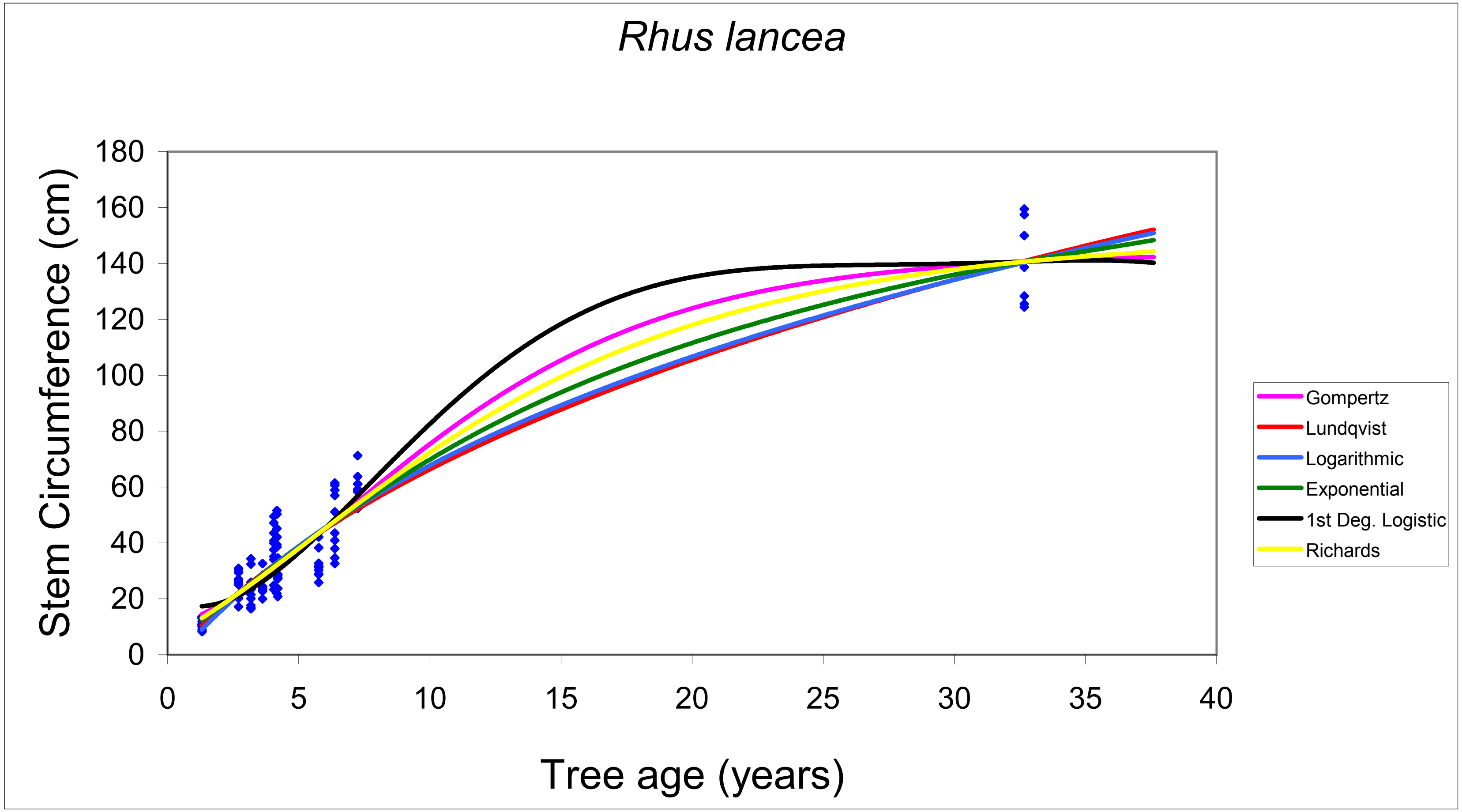

Figure 2.2. Six different growth curves as applied to *Rhus lancea* data where stem circumference (cm) is regressed on tree age (years). Growth projections for five years beyond the last data value were made for ease of visual analysis.

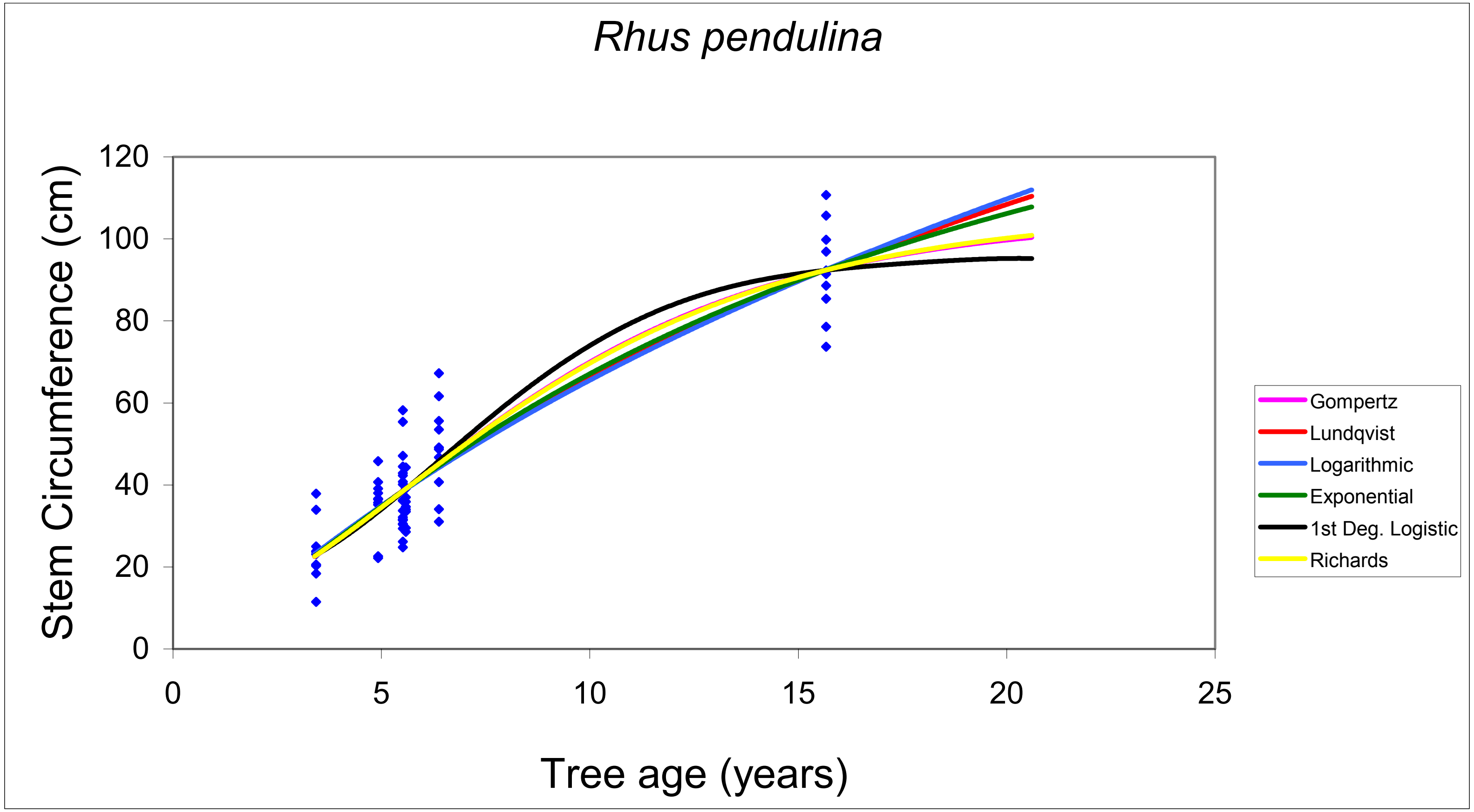

Figure 2.3. Six different growth curves as applied to *Rhus pendulina* data where stem circumference (cm) is regressed on tree age (years). Growth projections for five years beyond the last data value were made for ease of visual analysis.

When analysing the curves for *Rhus lancea* the Richards, Gompertz and first degree logistic curves suggest that asymptotes could occur soon after the last data value while the logarithmic, exponential and Lunqvist curves indicate continued stem growth beyond the last data value. The Lunqvist and thereafter the logarithmic and exponential equations produce the steepest slopes after the last data value.

In the case of *Rhus pendulina*, the first degree logistic, Gompertz and Richards curves suggest impending asymptotes while the logarithmic, Lundqvist and exponential curves show a steeper slope beyond the data processed. However, the logarithmic equation has the steepest slope and the least indication of reaching an asymptote soon beyond the data range.

**Discussion**

The aim of the comparison between the equations was to determine which equation would provide the most realistic prediction for stem circumference. The assessment of the best growth predictor relies therefore, on an analysis of the curves and an evaluation of their coefficient of determination.

The first criterion used was that of the coefficient of determination (Table 2.1 - 2.3). For *Combretum erythrophyllum* firstly exponential, thereafter Richards and thirdly the logarithmic equation gave the best coefficients. However, the differences between these values are small and in this instance the coefficient of determination is not as important as the slope of the curves (Figure 2.1).

All the equations for both *Rhus lancea* and *Rhus pendulina* gave the same coefficient of determination (of 0.91 and 0.84 respectively). Therefore, the coefficient of determination could not contribute in the selection of the most appropriate equation for these two species.

A second criterion used for the analysis of the curves is whether the equation provides an asymptote. The equations that predict asymptotic values at or immediately after the last data recorded could be discarded. The rational being that the trees still increase in stem circumference beyond this point and any equation that suggest otherwise does not reflect the biological growth of these species appropriately.

The third criterion used in the analysis is that of the slope of the curves beyond the range of the data. When a realistic age estimate (personal communication, A.E. van Wyk, November 2002, Botany Department, University of Pretoria) of an older and larger tree was included in the data, a steeper curve was obtained than that produced with the captured data. An example for *Combretum erythrophyllum* is shown in Figure 2.4. The dotted line is the logarithmic regression based on the captured data, while the line in bold is the logarithmic regression based on the addition of one extra data point of an older and larger tree. The circumference of the tree was 4710 mm and its age was 100 years. The additional data point suggest a faster growth rate than that predicted by the regression based on the captured data. It is therefore the author's opinion that the growth rates suggested by all the equations based on the initial captured data are conservative.

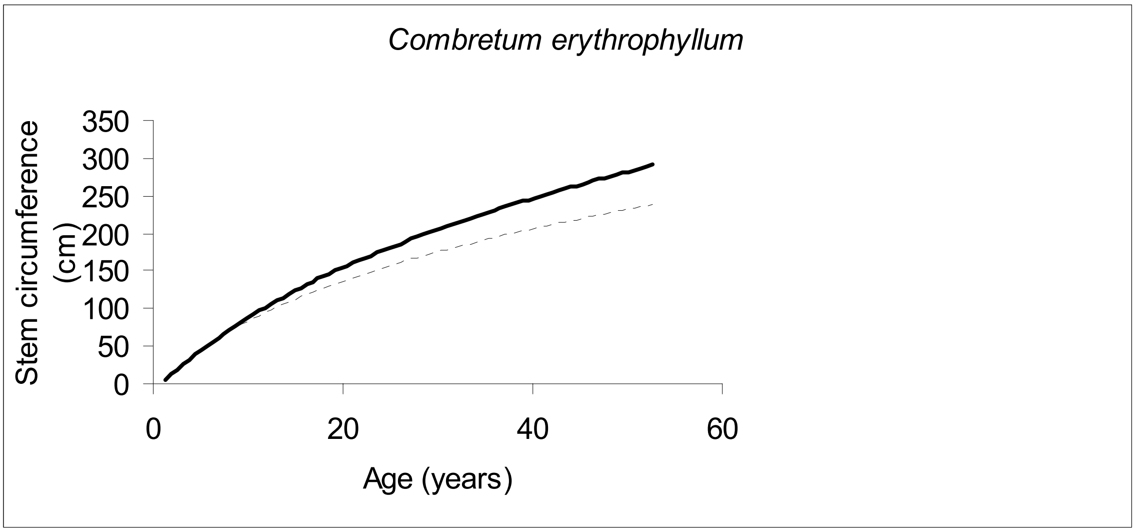

Figure 2.4. Growth curves for *Combretum erythrophyllum* showing the logarithmic regression based on the addition of one extra data point of an older and larger tree (line in bold) and the contrasting logarithmic regression based on the captured data (dotted line).

Therefore, the equation that predicts continued growth with the steepest slope beyond the range of the data is considered to be more appropriate.

In applying these criteria the logarithmic equation is the most applicable for *Combretum erythrophyllum*. For *Rhus lancea* the Lundqvist equation meets the criteria the best, thereafter the logarithmic and the exponential equations. For *Rhus pendulina* the logarithmic equation meets the criteria better than the Lundqvist and exponential equations.

If a single equation is to be selected for all three species, the logarithmic equation is the most appropriate since it meets the criteria the best for *Combretum erythrophyllum* and *Rhus pendulina* and on the basis of the slope is a close second best to the Lundqvist equation for *Rhus lancea*.

## Conclusion

The aim of the analysis was to determine which equation predicts stem circumference growth the most realistically. The coefficient of determination, the asymptotes and the slope of the curves were used as criteria to select the most suitable equation. The logarithmic equation met the requirements best and was therefore chosen as the most appropriate equation for predicting stem circumference growth for all the species. In the following chapters the logarithmic equation will be used to determine the growth rates for *Combretum erythrophyllum, Rhus lancea* and *Rhus pendulina* street trees.

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# 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.

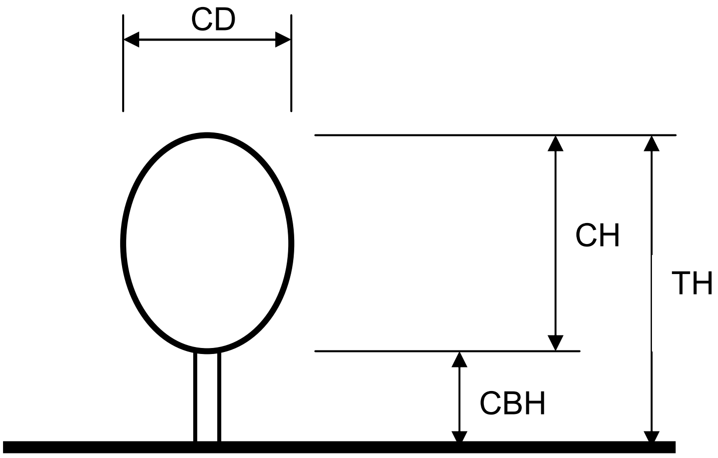


Figure 3.1. The dimensions measured for each tree: tree height (TH), crown height (CH), crown base height (CBH) and crown diameter (CD).

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:

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

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:

$$AGR = \frac{a-b}{t} \tag{2}$$

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.

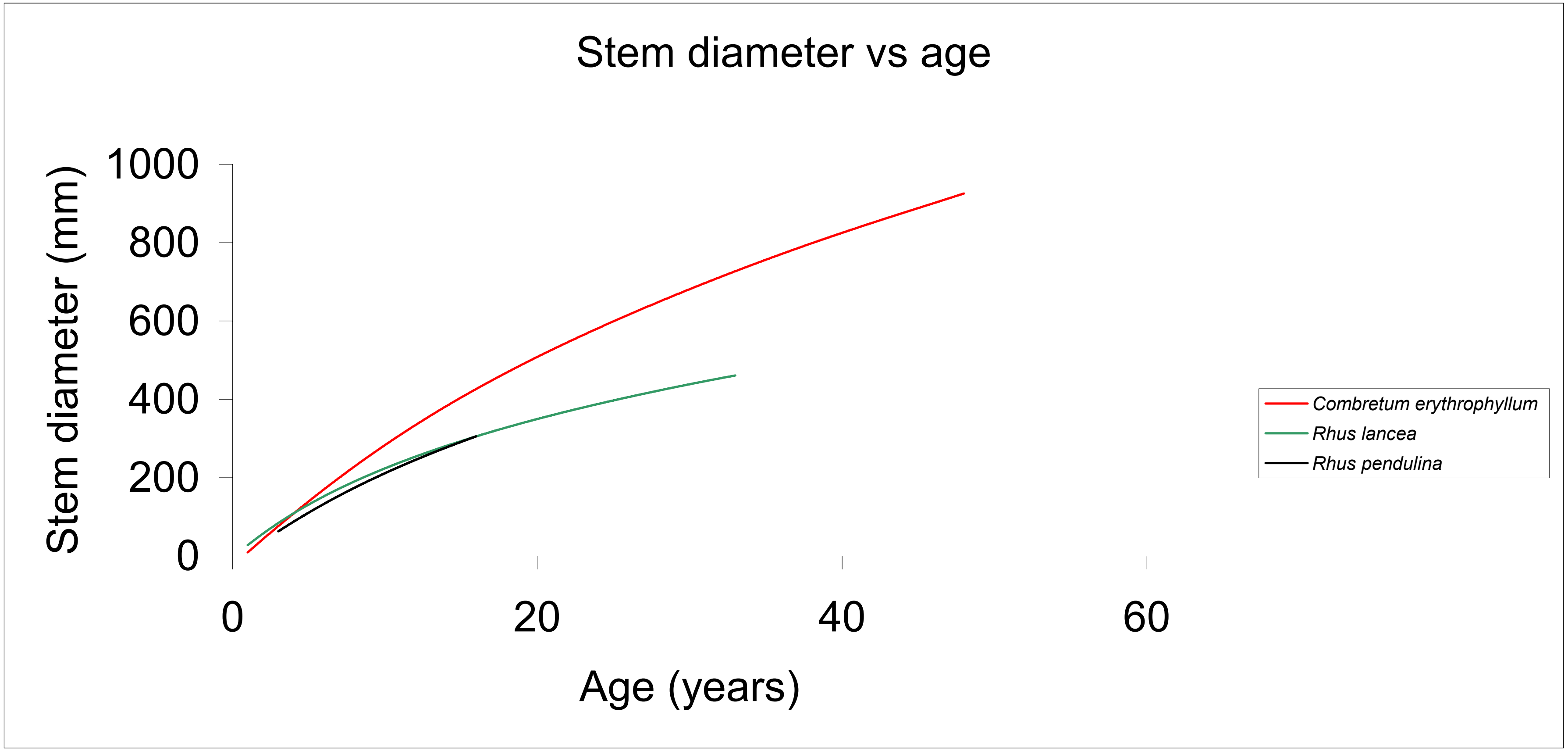
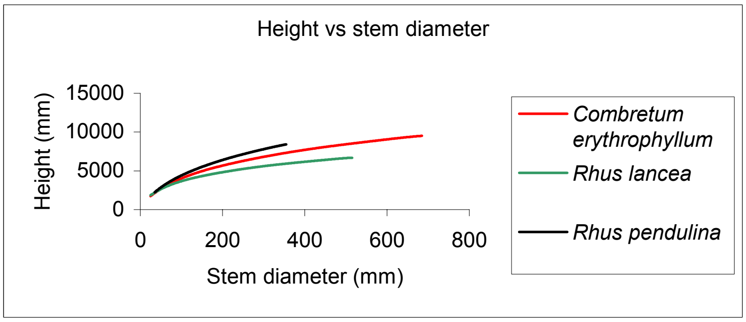
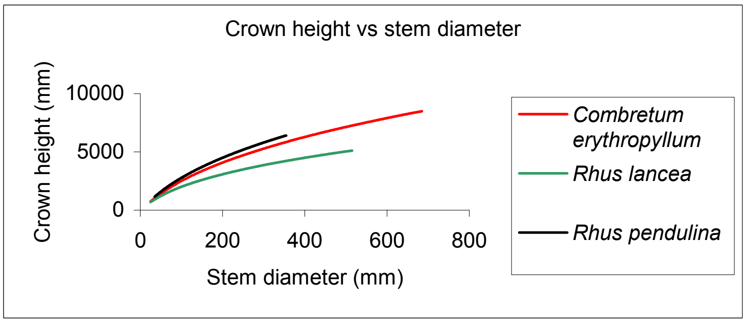


Figure 3.2. Relationship between stem diameter and tree age (years after planting) for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina*. All three the species are shown on one graph to facilitate growth comparisons.

(a)



(b)



(c)

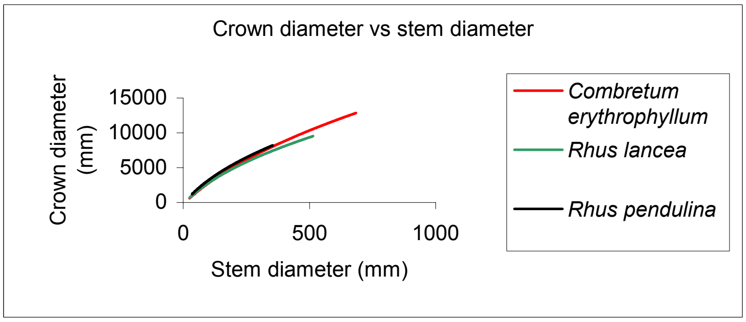


Figure 3.3. Relationships between various tree dimensions,

(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 | -* | -* | -* |

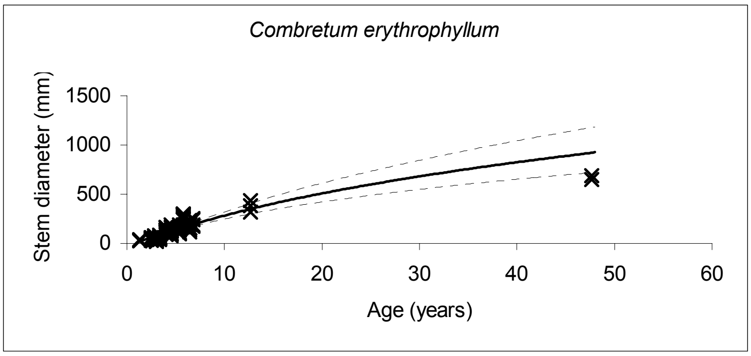
* The oldest trees measured for *Rhus pendulina* were 15.6 years.

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.

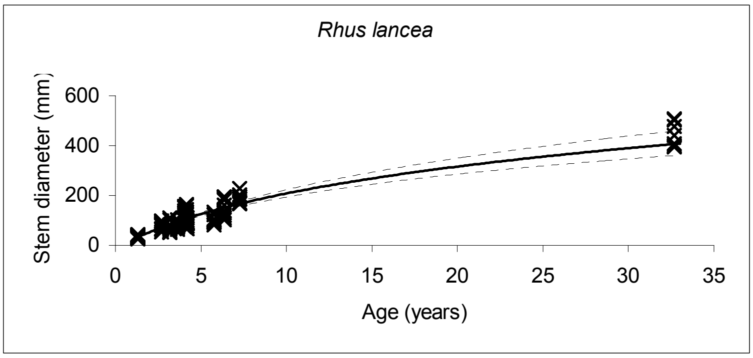
The regression equations presented, furthermore, provide the opportunity to calculate stem growth versus tree height and crown dimension relationships. These relationships are important when designing hard landscaping infrastructure like tree guards and tree rings (influenced by stem growth rates) and 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)



(b)



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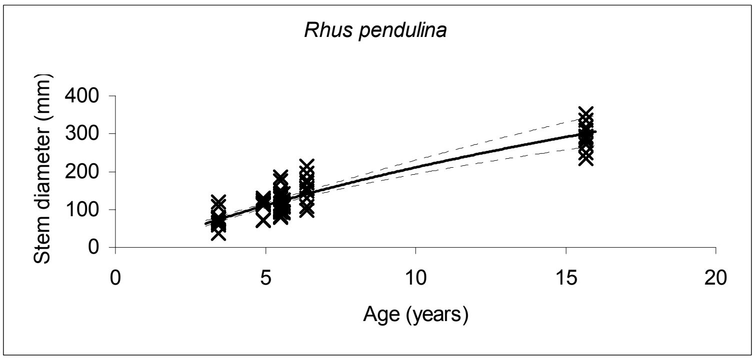
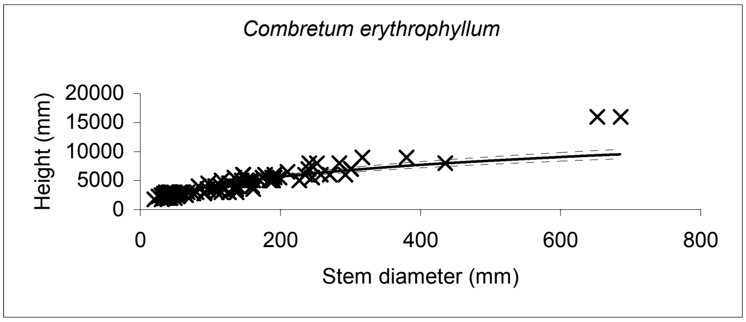
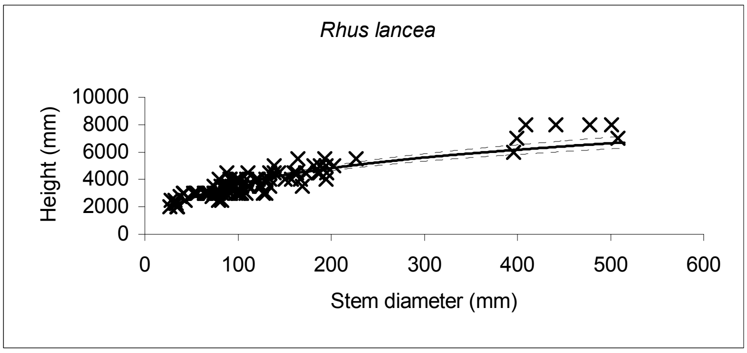


Figure 3.4. Stem diameter regressed on tree age (years) by a logarithmic equation indicating confidence intervals at a level of 95% to the estimated mean. (a) *Combretum erythrophyllum*, (b) *Rhus lancea* and (c) *Rhus pendulina*.

(a)



(b)



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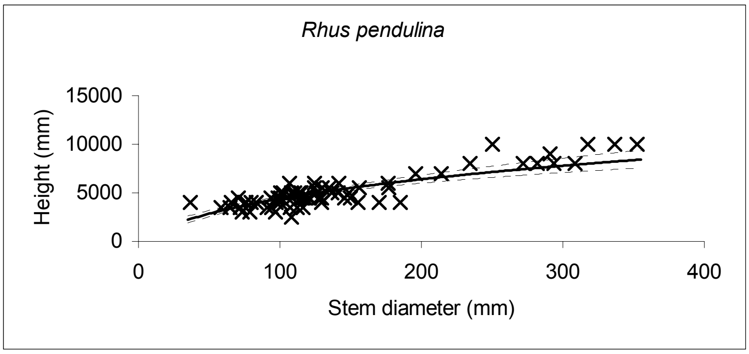
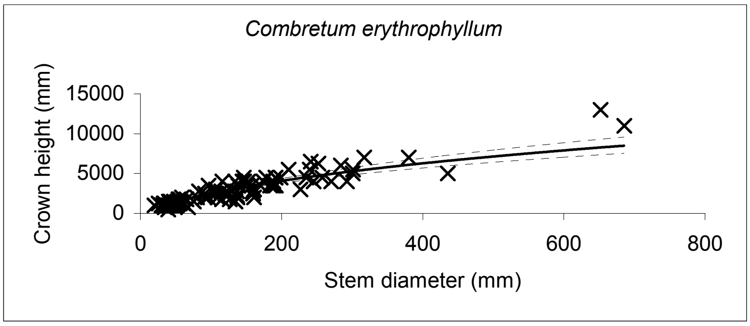


Figure 3.5. Tree height regressed on stem diameter by a logarithmic equation indicating confidence intervals at a level of 95% to the estimated mean. (a) *Combretum erythrophyllum*, (b) *Rhus lancea* and (c) *Rhus pendulina*.

(a)



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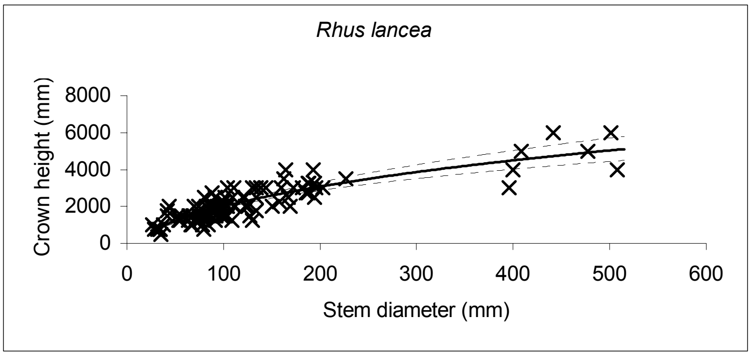

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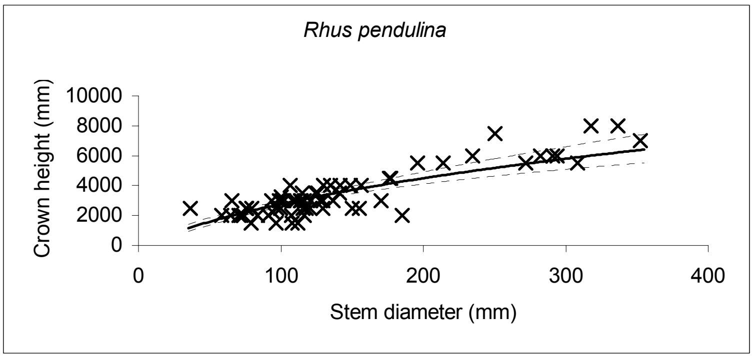
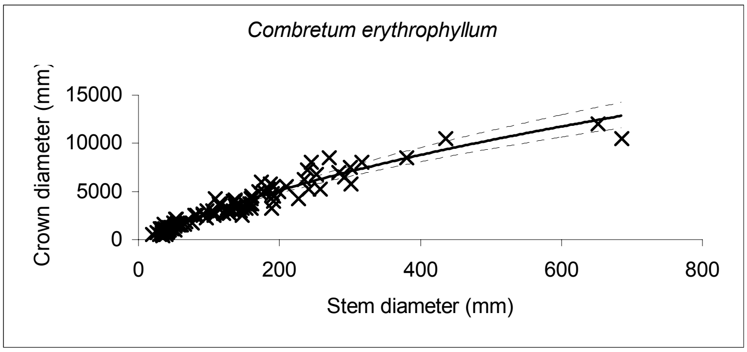


Figure 3.6. Crown height regressed on stem diameter by a logarithmic equation indicating confidence intervals at a level of 95% to the estimated mean. (a) *Combretum erythrophyllum*, (b) *Rhus lancea* and (c) *Rhus pendulina*.

(a)



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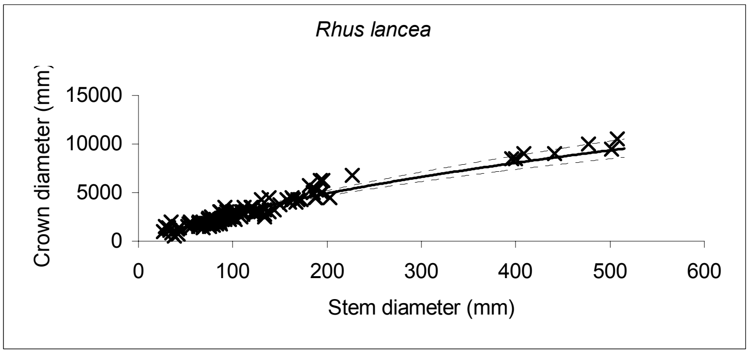

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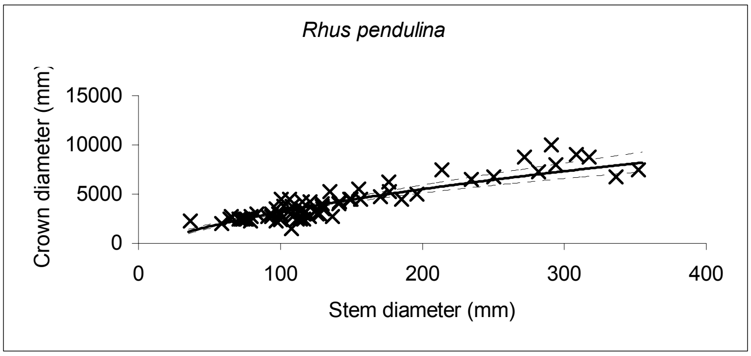

Figure 3.7. Crown diameter regressed on stem diameter by a logarithmic equation indicating confidence intervals at a level of 95% to the estimated mean. (a) *Combretum erythrophyllum*, (b) *Rhus lancea* and (c) *Rhus pendulina*.

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.

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## 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:

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

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:

$$\log(y_i) = A + b\log(\log(x_i + 1)) + \varepsilon_i \tag{1'}$$

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.

# Chapter 4

## Predicting the growth in tree height and crown size of three street tree species in the City of Tshwane, South Africa

### Abstract

The aim of the study was to determine the relationships between tree height and age, crown height and age, crown diameter and age as well as for crown base height and age for the commonly used street trees *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina*. Using years after planting as the explanatory variable, values for tree height, crown height and crown diameter were modelled using a logarithmic relationship. The relationships for predicting tree height, crown height and crown diameter were applied to compare size and growth for the species 10, 15 and 30 years after planting. It was observed that *Combretum erythrophyllum* and *Rhus pendulina* have virtually the same tree height at ages of 10 and 15 years whereas *Rhus lancea* is considerably smaller at the same age. In terms of mean annual growth rate, *Combretum erythrophyllum* starts with a mean annual tree height growth rate of 912 mm yr$^{-1}$ for the first five years of growth while that of *Rhus lancea* is 786 mm yr$^{-1}$ and *Rhus pendulina* has a mean annual growth rate of 894 mm yr$^{-1}$. However *Rhus pendulina* has the same mean annual growth rate (467 mm yr$^{-1}$) for the five to ten year period than that of *Combretum erythrophyllum* while *Rhus pendulina* has the fastest mean annual tree height growth rate (317 mm yr$^{-1}$) for the 10 to 15 year period. Mean annual crown height growth rate analysis for the first five years of tree growth ranked the species in the same order as the tree height growth rate for the same period. *Combretum erythrophyllum* has the fastest mean annual crown diameter growth rate for the first five years of growth (709 mm yr$^{-1}$), when compared to that of *Rhus lancea* (655 mm yr$^{-1}$) and that of *Rhus pendulina* (664 mm yr$^{-1}$). These 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, regression, size relationships, street trees, tree dimensions, tree growth, urban forests

## Introduction

Information relating to tree height, crown diameter, crown height and crown base height dimensions can be applied to model air pollution uptake, microclimate amelioration, carbon sequestration and rainfall interception in urban environments (Peper *et al.*, 2001a).This information on tree dimensions also enables the calculation of the growth of tree height and tree crown dimensions and their inter-relationships, which permit urban foresters to calculate, amongst others, the costs and benefits of the urban forest. It furthermore enables the analysis of alternative management scenarios to determine the optimal management practices with the aim of creating more sustainable urban forests (McPherson *et al.*, 2000 as cited by Peper *et al.*, 2001a).

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

Apart from the urban ecological functions that urban trees fulfil they are also used in a landscape architectural context to derive spatial and aesthetic functions (Grey & Deneke, 1978; Arnold, 1980; Larsen & Kristoffersen, 2002). Urban and landscape architectural tree planting demands knowledge of *inter alia* tree height and crown growth. 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).

The aim of the research presented here was to determine the relationships between tree height and age, crown height and age, crown diameter and age as well as that of crown base height and age 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, Gauteng Province. The measurements were made between the suburbs Doornpoort (Ovenbush Street: 25˚ 39' 08.7'' S - 28˚ 15' 21.7'' E) in the north and Erasmuskloof (Piering Street: 25˚ 50' 04.7'' S - 28˚ 14' 58.3'' E) in the south, as well as between Pretorius Park (Pretoria East Cemetery: 25˚ 49' 36.2'' S - 28˚ 19' 20.8'' E) in the east and the suburb of Pretoria North (Brits Street: 25˚ 40' 40.8'' S - 28˚ 09' 05.4'' E) to the west of the city. The tree height, crown base height (height from the ground to the lowest leaves of the crown) and crown diameter were measured with a 3 m range pole (Figure 4.1). 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 was used to calculate the diameter.

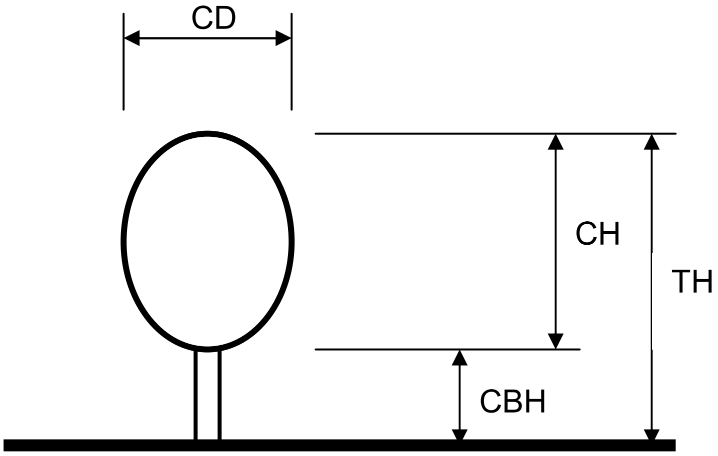


Figure 4.1. The dimensions measured for each tree: tree height (TH), crown height (CH), crown base height (CBH) and crown diameter (CD).

During data gathering the selection of the largest individual street trees during data gathering for statistical analysis can easily result in biased data, which could artificially inflate predictive regression estimates (Clark & Clark, 2000). The problem was avoided in the current study by stratified random sampling. Apart from the necessary stratified age distribution, the streets were selected at random within each age group and the selection of trees in the streets was also performed at random. For this purpose a random number between one and ten from a random number table was used and where possible the first tree to be measured from the beginning of a street block was selected based on the random number. Thereafter every second tree was measured. However, when many trees occurred in a street every third or fourth tree was measured depending on the total number of trees in the street. If there were, however, only a few trees that could be measured, then each consecutive tree was measured. Trees with obvious defects that could have hampered growth or trees with growth abnormalities were not measured.

The aim was to collect data for 10 individual trees per street, which also results in 10 measurements per age group since all the trees in a street were planted at the same time. Measuring 10 trees per street was not always possible due to a limited number of trees per street. Where there were more than one age group of a certain species per street then the second age group was only measured if it were clearly distinguishable by size and if it represented a desired age category.

Of the 282 trees measured, 105 were *Combretum erythrophyllum* (river bushwillow), 107 *Rhus lancea* (karee) and 70 *Rhus pendulina* (white karee). All three species are indigenous to South Africa (Joffe, 1993; van Wyk & van Wyk, 1998). However, *Rhus pendulina* does not naturally occur in the Gauteng Province since its distribution is mostly limited to the Orange River valley and a short distance upstream in some of its tributaries.

When collecting the data for *Combretum erythrophyllum* trees, trees in 13 streets in seven suburbs were measured. Five streets had less than 10 trees that could be measured per street. *Rhus lancea* data were collected in 10 suburbs and 10 streets as well as one parking lot area (see below). There was only one site where less than ten trees per street were measured for *Rhus lancea*. Data for *Rhus pendulina* was collected in seven suburbs and seven streets in which 10 trees were measured per street.

The measured trees were planted between 1955 and 2001 and their ages were derived from the planting dates obtained from the City of Tshwane Metropolitan Municipality (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 4.1. 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 the species investigated, of which the age was known. 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. The tree age distribution of a species depended on the planting strategy of the Municipality. This strategy did not dictate definite numbers per species to be planted each year within the city, which resulted in data that was not evenly distributed per tree age.

The majority of the measured street trees grew in non-irrigated managed lawn residential environments. The average 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 tree height and crown dimensions were regressed on age to compute the growth rate of each dimension for each species. In analysing stem circumference growth several growth curve models were tested (see Chapter 2): 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 to stem circumference versus age data and was therefore used to determine the dimensional growth rates for the individual species in this study. Age was used as independent variable and the tree height and crown 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, $i$ = 1,2,…, $n$;

$n$ = number of observations

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

$a, b$ = parameters to be estimated

$E(\ )$ = expected values

$\log$ = natural logarithim

A description of the statistical models and procedures are presented elsewhere (Peper *et al.*, 2001a; Peper *et al.*, 2001b) as well as in Chapter 3. 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 4.2. 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 estimated tree dimension parameters (Table 4.3) was analysed in terms of mean annual growth rate (AGR) (Jalota & Sangha, 2000) as follows:

$$AGR_5 = \frac{a-b}{t} \qquad (2)$$

where $AGR_5$ is the mean annual growth rate in mm yr$^{-1}$, $a$ is the largest tree dimension (mm), $b$ is the smallest tree dimension (mm) and $t$ is a five year time period between the measurements.

## Results

The ranges of years and the minimum and maximum ages of each species are shown in Table 4.1. The regression coefficients and coefficients of determination ($r^2$) to predict tree height, crown height and crown diameter growth by age are presented in Table 4.2 and the curves derived by fitting the logarithmic equation to the data of the three species are illustrated in Figure 4.2 to Figure 4.4. Tree height, crown height and crown diameter regressed on tree age with confidence intervals at a level of 95% to the estimated means are shown for each species. The coefficients of determination for the height and age relationship are 0.73, 0.66, and 0.67 for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* respectively. The coefficient of determination for the crown height and age relationship for *Combretum erythrophyllum* is 0.74, but is lower for *Rhus lancea* (0.54) and *Rhus pendulina* (0.59). Coefficients of determination for the crown diameter and age relationship are 0.74, 0.75, and 0.69 for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* respectively.

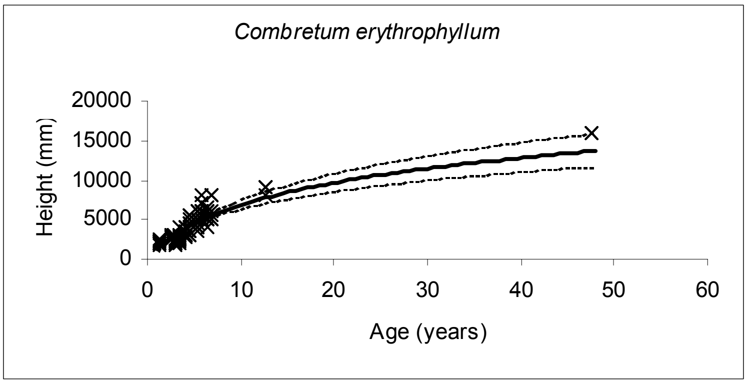
Table 4.1. The minimum age (years since planting in the streets), maximum age and range of years for which measurements were made for each species

| 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 |

Table 4.2. Sample size ($n$), estimated regression coefficients ($A$, $b$) and mean standard error ($MSE$) values for predicting height, crown height, and crown diameter growth as well as coefficients of determination ($r^2$). 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 $\hat{y}_i$ = height, crown height, or crown diameter to be estimated, $\log$ is the natural logarithm of the argument and $EXP$ = the inverse of the natural logarithm and $x_i$ = age

| | | Height vs age | | | | Crown height vs age | | | | Crown diameter vs age | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | $n$ | $A$ | $b$ | MSE | $r^2$ | $A$ | $b$ | MSE | $r^2$ | $A$ | $b$ | MSE | $r^2$ |
| *Combretum erythrophyllum* | 105 | 7.56927 | 1.4186 | 0.05714 | 0.73 | 6.76034 | 2.04386 | 0.1129 | 0.74 | 6.65704 | 2.46067 | 0.16217 | 0.74 |
| *Rhus lancea* | 107 | 7.83069 | 0.7411 | 0.02771 | 0.66 | 7.02305 | 1.10703 | 0.10113 | 0.54 | 7.17049 | 1.51863 | 0.07633 | 0.75 |
| *Rhus pendulina* | 70 | 7.54832 | 1.44173 | 0.03256 | 0.67 | 6.87739 | 1.78497 | 0.07126 | 0.59 | 6.93671 | 1.95978 | 0.05492 | 0.69 |

(a)



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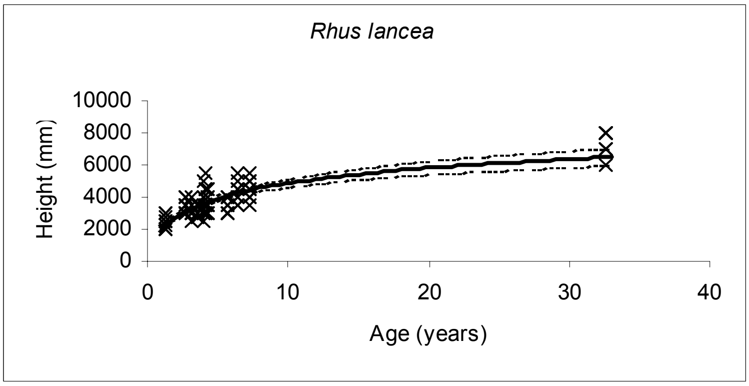

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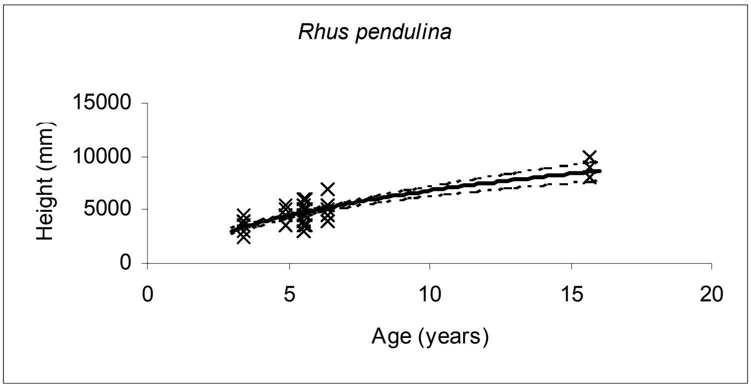
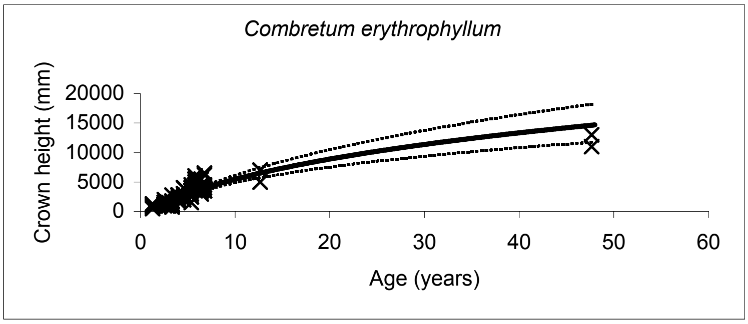


Figure 4.2. Tree height regressed on tree age (years) by a logarithmic equation indicating confidence intervals at a level of 95% to the estimated mean. (a) *Combretum erythrophyllum*, (b) *Rhus lancea* and (c) *Rhus pendulina*.

(a)



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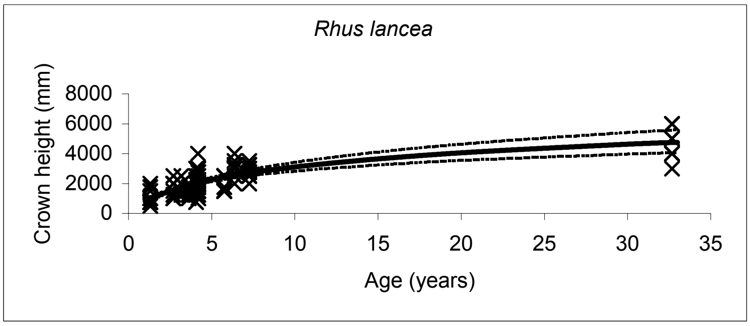

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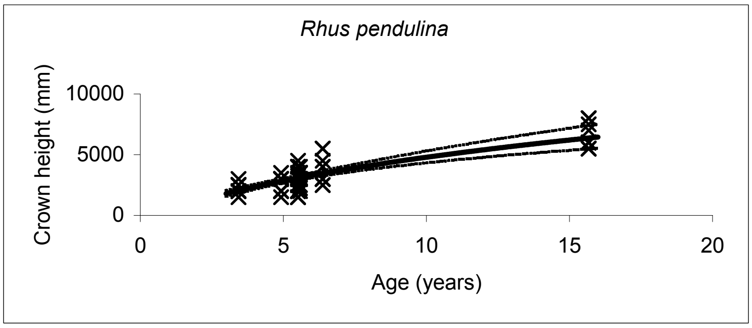
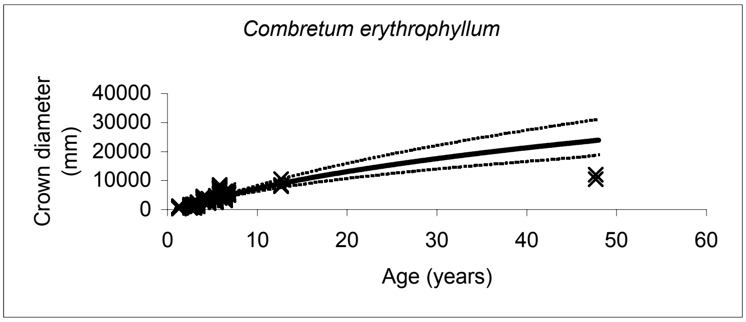
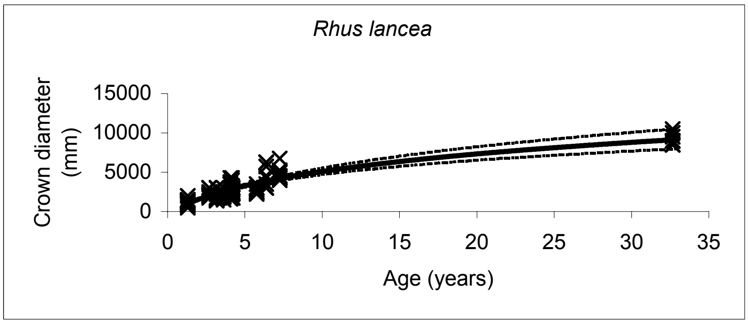


Figure 4.3. Crown height regressed on tree age (years) by a logarithmic equation indicating confidence intervals at a level of 95% to the estimated mean. (a) *Combretum erythrophyllum*, (b) *Rhus lancea* and (c) *Rhus pendulina*.

(a)



(b)



(c)

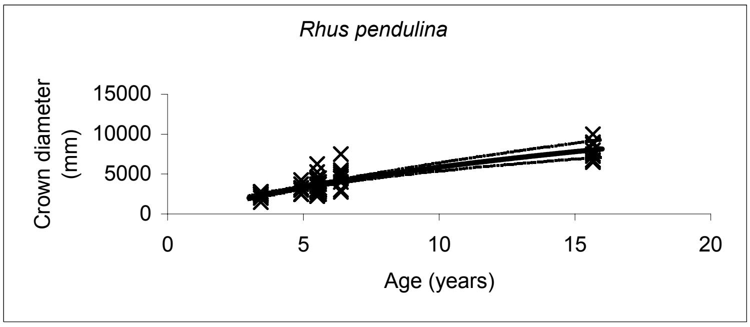


Figure 4.4. Crown diameter regressed on tree age (years) by a logarithmic equation indicating confidence intervals at a level of 95% to the estimated mean. (a) *Combretum erythrophyllum*, (b) *Rhus lancea* and (c) *Rhus pendulina*.

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

The regressions of all three species are shown in Figure 4.5 to enable comparisons and the prediction of tree sizes for 10, 15 and 30 years after planting. Annual growth rates at five-year intervals are shown in Table 4.3.

When comparing the species in terms of a height and age relationship it is observed that *Combretum erythrophyllum* and *Rhus pendulina* have virtually the same tree height at 10 and 15 years of age when trees of both species have a mean tree height of approximately 7 m and 8 m respectively. The tree height of *Rhus lancea* is much lower at the same ages (Figure 4.5a and Table 4.4).

Regarding crown height one notices that *Rhus pendulina* starts with a similar crown height growth to that of *Combretum erythrophyllum* but shows a slower growth rate towards the upper end of the curve (Figure 4.5b). Judging by the slope of the curves it may be conjectured that this divergence will continue with time. Concerning crown diameter growth rate one observes that *Combretum erythrophyllum* grows faster than *Rhus pendulina*, which in turn grows faster than *Rhus lancea*.

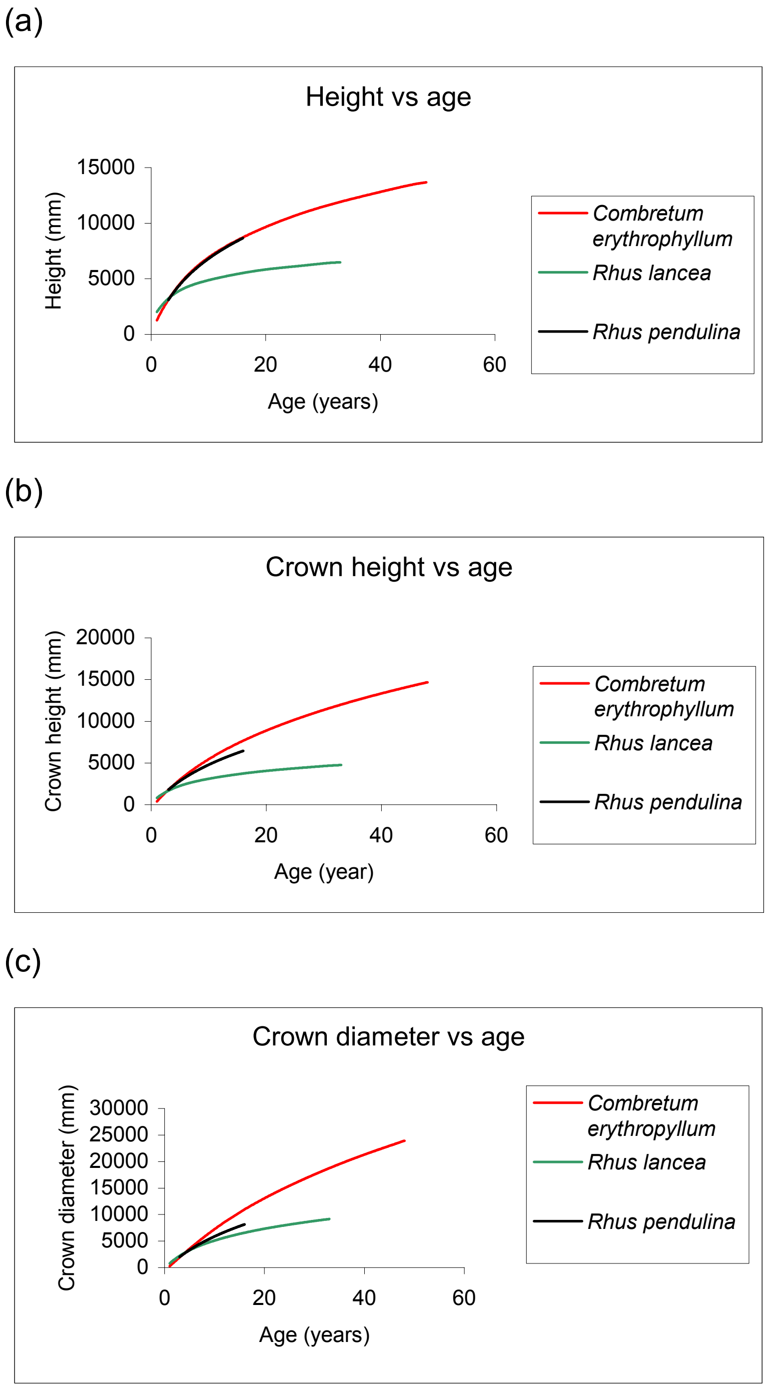


Figure 4.5. Tree height, crown height and crown diameter are regressed on tree age for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina*. All three the species are shown on one graph to facilitate growth comparisons. Tree height versus age (a), tree crown height versus age (b) and tree crown diameter versus age (c).

Table 4.3. Mean annual growth rate (mm $yr^{-1}$) calculated with five year intervals for tree height, crown height and crown diameter for each of the tree species investigated.

| | Tree height (mm $yr^{-1}$) | | | Crown height (mm $yr^{-1}$) | | | Crown diameter (mm $yr^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| Years | *Combretum erythrophyllum* | *Rhus lancea* | *Rhus pendulina* | *Combretum erythrophyllum* | *Rhus lancea* | *Rhus pendulina* | *Combretum erythrophyllum* | *Rhus lancea* | *Rhus pendulina* |
| 0 - 5 | 912 | 786 | 894 | 601 | 450 | 569 | 709 | 655 | 664 |
| >5 - 10 | 467 | 190 | 467 | 490 | 143 | 388 | 743 | 365 | 511 |
| >10 - 15 | 315 | 111 | 317 | 377 | 83 | 283 | 624 | 252 | 387 |
| >15 - 20 | 240 | 78 | -* | 309 | 59 | -* | 537 | 194 | -* |
| >20 - 25 | 195 | 60 | -* | 264 | 46 | -* | 474 | 159 | -* |
| >25 - 30 | 165 | 49 | -* | 232 | 38 | -* | 426 | 135 | -* |
| >30 - 35 | 143 | -* | -* | 207 | -* | -* | 389 | -* | -* |
| >35 - 40 | 126 | -* | -* | 187 | -* | -* | 358 | -* | -* |
| >40 - 45 | 113 | -* | -* | 172 | -* | -* | 332 | -* | -* |

*No data available

Table 4.4. Predicted sizes are shown for 10, 15 and 30 years after planting

| | Height (m) | | | Crown height (m) | | | Crown diameter (m) | | |
|---|---|---|---|---|---|---|---|---|---|
| Species | 10y | 15y | 30y | 10y | 15y | 30y | 10y | 15y | 30y |
| *Combretum erythrophyllum* | 6.89 | 8.47 | 11.47 | 5.45 | 7.33 | 11.36 | 7.26 | 10.37 | 17.56 |
| *Rhus lancea* | 4.87 | 5.43 | 6.36 | 3.10 | 3.65 | 4.62 | 5.09 | 6.35 | 8.79 |
| *Rhus pendulina* | 6.80 | 8.39 | -* | 4.78 | 6.20 | -* | 5.87 | 7.80 | -* |

*Oldest *Rhus pendulina* trees measured were 15.6 years.

*Rhus lancea*, in comparison with the other species, shows a tendency to reach near asymptotic growth rates relatively early in its growth development for all three tree dimensions analysed and is also the smallest tree.

*Combretum erythrophyllum* starts with a mean annual tree height growth rate of 912 mm yr$^{-1}$ for the first five years of growth while that of *Rhus lancea* is 786 mm yr$^{-1}$ and *Rhus pendulina* has a mean annual growth rate of 894 mm yr$^{-1}$. However, *Rhus pendulina* has the same mean annual growth rate (467 mm yr$^{-1}$) for the five to ten year period than that of *Combretum erythrophyllum* while *Rhus pendulina* has a marginally faster mean annual tree height growth rate (317 mm yr$^{-1}$) for the 10 to 15 year period (Table 4.3). *Combretum erythrophyllum*'s mean annual tree height growth rate declines from 912 mm yr$^{-1}$ in the first five years to 113 mm yr$^{-1}$ in the five years between the ages 40 years and 45 years. However, *Rhus lancea*'s mean annual tree height growth rate declines from 786 mm yr$^{-1}$ in the first five years to 49 mm yr$^{-1}$ in the five years between the ages 25 years and 30 years. *Rhus pendulina* also shows a decline in its mean annual tree height growth rate from 894 mm yr$^{-1}$ in the first five years to 317 mm yr$^{-1}$ in the five years between the ages 10 years and 15 years.

The mean annual crown height growth rate analysis for the first five years shows that *Combretum erythrophyllum*, *Rhus lancea*, and *Rhus pendulina* have mean annual growth rates of 601 mm yr$^{-1}$, 450 mm yr$^{-1}$ and 569 mm yr$^{-1}$ respectively (Table 4.3). *Combretum erythrophyllum* has the fastest mean annual crown height growth rate while that of *Rhus lancea* being the slowest. *Combretum erythrophyllum*'s mean annual crown height growth rate declines from 601 mm yr$^{-1}$

in the first five years to 172 mm yr$^{-1}$ in the five years between the ages 40 years and 45 years. However, *Rhus lancea*'s mean annual crown height growth rate declines from 450 mm yr$^{-1}$ in the first five years to 38 mm yr$^{-1}$ in the five years between the ages 25 years and 30 years. *Rhus pendulina* furthermore, also shows a decline in mean annual crown height growth rate from 569 mm yr$^{-1}$ in the first five years to 283 mm yr$^{-1}$ in the five years between the ages 10 years and 15 years.

*Combretum erythrophyllum* has the fastest mean annual crown diameter growth rate for the first five years of growth (709 mm yr$^{-1}$), when compared to that of *Rhus lancea* (655 mm yr$^{-1}$) and that of *Rhus pendulina* (664 mm yr$^{-1}$) (Table 4.3). Consequently *Combretum erythrophyllum* also has the fastest mean annual crown diameter growth rate when compared to the *Rhus* species. *Rhus lancea* shows a consistently slower mean annual crown diameter growth rate in comparison to *Rhus pendulina*. *Combretum erythrophyllum*'s mean annual crown diameter growth rate declines from 709 mm yr$^{-1}$ in the first five years to 332 mm yr$^{-1}$ in the five years between the ages 40 years and 45 years. However, *Rhus lancea*'s mean annual crown diameter growth rate declines from 655 mm yr$^{-1}$ in the first five years to 135 mm yr$^{-1}$ in the five years between the ages 25 years and 30 years. *Rhus pendulina*, also shows a decline in mean annual crown diameter growth rate from 664 mm yr$^{-1}$ in the first five years to 387 mm yr$^{-1}$ in the five years between the ages 10 years and 15 years.

The mean annual growth rate during the period 40 to 45 years for *Combretum erythrophyllum*'s tree height is 113 mm yr$^{-1}$ while its mean annual crown height growth increase for the same period is 172 mm $yr^{-1}$ and the crown diameter increase is 332 mm $yr^{-1}$. The mean annual growth rate during the period 25 to 30 years for *Rhus lancea*'s tree height is 49 mm $yr^{-1}$ while its mean annual crown height growth increase for the same period is 38 mm $yr^{-1}$ and the crown diameter increase is 135 mm $yr^{-1}$. The mean annual growth rate during the period 10 to 15 years for *Rhus pendulina*'s tree height is 317 mm $yr^{-1}$ while its mean annual crown height growth increase for the same period is 283 mm $yr^{-1}$ and the crown diameter increase is 387 mm $yr^{-1}$ (Table 4.3).

## Discussion

The tree crown dimensions of *Combretum erythrophyllum* increases faster than the tree height at older tree ages. This crown height growth may be attributed to the drooping lower branches of older trees, which results in larger crown height growth increments when compared to tree height. However, the mean annual crown height growth increment increases are less than that of the mean annual tree height growth increment increases for both *Rhus lancea* and *Rhus pendulina*. Relatively larger crown diameter growth compared to tree height and crown height growth suggests that the older trees may have reached near asymptotic tree height growth levels while still growing laterally in tree crowns.

Data for only 15 years is presented for *Rhus pendulina* but it has been reported that certain trees of this species have reached an age of more than 25 years in the City of Tshwane (personal communication: A.E. van Wyk, Botany Department, University of Pretoria, South Africa). This is an additional 10 years of growth which was not reported on in this study and predictions as to growth trends for trees older than 15 years that are based on the results presented, should be done with caution.

It should be noted that *Rhus lancea* starts with the largest dimensions in all instances (Figure 4.5) as well as with a relatively high comparable initial annual growth rate (Table 4.3). This could possibly be ascribed to the fact that *Rhus lancea* trees were in some instances planted in the streets when they were already four years old. This practice was not consistent and accurate ages of the trees when planted in the streets could not be obtained. However, in the analysis it was assumed that all the trees were three years old when planted in the streets (personal communication: S. Paul, City of Tshwane Metropolitan Municipality, 8 April 2002). This may overestimate the size of *Rhus lancea* trees when first planted and therefore may also result in a faster growth rate at an early age.

It can be noticed in Figure 4.2 to Figure 4.4 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 effects of differences in site conditions, genotype, culture, biotic, and abiotic factors that influence the health and growth of a tree (Peper *et al.*, 2001b).

The regression equations presented are only valid within the sampled range of ages and tree size dimensions. Extrapolations of data beyond the data range from which the regressions were determined are therefore not recommended. This point was emphasized in determining biomass through the use of allometry by

Haase & Haase (1995) and should also be taken into consideration when calculating the growth rate of other parameters.

*Application of tree dimensional growth rates*

Calculated annual growth rate (AGR) can be used to enable computer aided design (CAD) simulations (Peper *et al.*, 2001b; Larsen & Kristoffersen, 2002) in the landscape architectural industry. Annual growth rates of trees provide landscape architects and architects with tree dimensions at various ages. Tree growth can then be digitally simulated. When presenting the quantitatively derived CAD simulations, the tree growth can be viewed in context of the designed landscape and related architecture. This can result in simulating how the landscape will change over time as the trees increase in age. The visual presentation will allow both architects and clients a more realistic dynamic simulation of their investment.

Annual growth rate may also provide the designer with quantitatively derived tree age to tree dimensions relationships, which will provide more realistic landscape architectural plans, elevations and perspectives and hence provide more accurate presentation drawings. This method contrasts with the current practice of drawing trees at 75% of their maximum tree dimensions, irrespective of the growth rate of the specific species, when representing trees in presentation and technical drawings.

When placing trees next to or underneath structures like for example buildings and overhead power lines, one will also be able to determine at what estimated age the trees may become problematic. This will in turn also provide the opportunity to calculate long-term pruning and tree maintenance cost as well as, if necessary, alter the designed planting plan or alternatively the choice of tree species to accommodate the associated structures better (McPherson *et al*., 2004). It should be noted that although annual growth rate calculations are quantitatively derived they are still estimates.

Annual growth rate calculations can furthermore be used when predicting the future heating and cooling energy savings from positioning trees in relation to one or two story buildings. Interior building temperature can be moderated by positioning trees strategically on the northern and western side of buildings. This is due to the shade that the trees project on the buildings in summer and when choosing a deciduous tree, the sun which it allows to reach the buildings in winter (McPherson *et al*., 2004). The dimensional growth rates of trees could thus be used in models that predict and calculate, for example, potential air-conditioning energy savings.

Crown and tree dimensional growth rates are used amongst others to calculate rainfall interception and air pollution uptake by urban trees. The regression equations presented in this chapter can be used to model the increase in rainfall interception and air pollution uptake of a young urban forest. It therefore provides a basis from which the rainfall interception and air pollution uptake of recently planted street trees in previously disadvantaged Township areas in the City of Tshwane and elsewhere in South Africa could be modelled. Modelling rainfall interception and air pollution uptake may provide additional information as to the value of the urban forest in monetary terms, which could motivate further urban forest programmes (Maco *et al*., 2004). It is recommended that further studies be done on leaf surface area models, accompanied by meteorological modelling in order to establish *locally* derived rainfall interception and air pollution uptake models. The calculation of monetary benefits and detailed methodology for such modelling could be found elsewhere (Maco *et al*., 2004; http://cufr.ucdavis.edu, accessed April 2005).

## Conclusion

The tree height, crown height and crown width of three street tree species were examined. When comparing the species in terms of a height and age relationship it is observed that *Combretum erythrophyllum* and *Rhus pendulina* have virtually the same tree height growth rate. After 10 and 15 years trees of both species have a mean tree height of approximately 7 m and 8 m respectively. The growth rate of *Rhus lancea* is much slower.

In terms of mean annual growth rate, *Combretum erythrophyllum* starts with a mean annual tree height growth rate of 912 mm yr$^{-1}$ for the first five years of growth while that of *Rhus lancea* is 786 mm yr$^{-1}$ and *Rhus pendulina* has a mean annual growth rate of 894 mm yr$^{-1}$. However, *Rhus pendulina* has the same mean annual growth rate (467 mm yr$^{-1}$) for the five to ten year period as that of *Combretum erythrophyllum* while *Rhus pendulina* has the fastest mean annual tree height growth rate (317 mm yr$^{-1}$) for the 10 to 15 year period.

Mean annual crown height growth rate analysis for the first five years of tree growth shows that *Combretum erythrophyllum*, *Rhus lancea*, and *Rhus pendulina* have a mean annual growth rate of 601 mm $yr^{-1}$, 450 mm $yr^{-1}$ and 569 mm $yr^{-1}$ respectively. *Combretum erythrophyllum* has the fastest mean annual crown height growth rate while that of *Rhus lancea* is the slowest.

*Combretum erythrophyllum* has the fastest mean annual crown diameter growth rate for the first five years of growth (709 mm $yr^{-1}$), when compared to that of *Rhus lancea* (655 mm $yr^{-1}$) and that of *Rhus pendulina* (664 mm $yr^{-1}$). Consequently, *Combretum erythrophyllum* also has the fastest mean annual crown diameter growth rate when compared to the *Rhus* species. *Rhus lancea* shows a consistently slower mean annual crown diameter growth rate in comparison to *Rhus pendulina*.

These results could be used for forecasting physical dimensions of the species investigated as well as for planning and assessing the consequences of tree-planting schemes in urban environments. In comparison *Rhus lancea* is for example, better suited to be used in landscape projects where space is restricted and where a slower growth rate is desired. *Combretum erythrophyllum* on the other hand, is suitable for larger open spaces and for landscapes where fast tree growth rates are required. The use of *Combretum erythrophyllum* as street trees in the narrower residential road reserves, especially the smaller streets of the City of Tshwane's previously disadvantaged Townships is, however, questionable. This is because this tree species tends to become very large and may be inappropriate for such small spaces.

The mean tree planting distance of 14 m could be reconsidered for *Rhus lancea* when considering its slow growth rate. This distance could successfully be reduced to 8 m or 10 m, which should result in a more aesthetically pleasing street appearance for this species.

The dimensional relationships presented could form a basis for dynamic illustration of the tree growth related to a project when implementing computer aided design (CAD) applications. The results are also important for determining environmental benefits of the urban trees. A literature search revealed no information pertaining to these species' dimensional growth over time in an urban or natural setting, which renders additional significance to the research presented.

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# Chapter 5

## Incremental stem diameter growth results applied to tree grids and tree rings used in the landscape architectural industry

**Note: This chapter is intended for publication in the Urban Green File.**

Tree grids and tree rings pose certain challenges to the designer of landscapes especially those designing hard landscapes like roads, parking areas and pavements. Two main challenges are tree stem growth and lateral root growth. Figure 5.1 illustrates how the stem growth of *Celtis africana* trees in the City of Tshwane has exceeded the growth space provided by tree rings and has caused damage to both the rings and the trees. This situation could possibly have been prevented if the designer or urban forester had knowledge of the sizes that tree stems reach at certain ages. There is little quantitative knowledge in South Africa relating to tree stem size in relation to the age of indigenous trees. This could lead to inappropriate use of tree rings and tree grids.

One of the main reasons why knowledge about stem growth rate for South African indigenous trees is lacking is because many indigenous trees have been cultivated, domesticated and introduced to local markets over recent decades and the physical growth characteristics of these new-fashioned trees have not yet been studied and published. Apart from the lack of knowledge about the growth rate characteristics of indigenous trees one also needs to bear in mind that urban forests have been established in more or less the last 150 years in the City of Tshwane. One hundred and fifty years are in some instances less than the maximum age that indigenous trees planted in the city could attain. Unlike European and Middle Eastern urban forests there has therefore been less possibilities and opportunities to study and obtain information about South African urban forests and in particular the more recently domesticated indigenous urban forest species (Konijnendijk, 2000). This chapter therefore has as its specific aim to provide the architecture, landscape architecture and urban forestry industry with quantified relationships between stem diameter size and tree age values, which directly relate to tree grids and rings.

The indigenous trees to be discussed are *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina*. The oldest data available for the trees were 47.50 years 32.50 years and 15.50 years respectively. The restricted ages and hence restricted stem diameter ranges of the trees are due to the urban forest limitations alluded to above. What furthermore limited the ages and hence the stem diameter sizes were the fact that the City of Tshwane Metropolitan Municipality has only focused on indigenous street tree plantings since the middle 1990s. This rendered limitations as to the oldest street trees obtainable for inclusion in the data sets and hence two sets of parking lot trees were incorporated for *Rhus lancea* and *Rhus pendulina* in an attempt to widen the age and stem diameter range.

The methodology and statistical procedure of obtaining the stem diameter to age relationships have been discussed in Chapter 2 and Chapter 3. Two manufacturers of tree grids and tree rings were consulted for this study. They are Townscapes manufacturing the “Baltimore Tree Grids” (grids) made of cast iron (Figure 5.2) and Vanstone producing the “Pavement Tree Rings” (rings) of concrete (Figure 5.3). The grids are manufactured with inner diameters of 300 mm, 460 mm, 600 mm, and 800 mm while rings are produced with inside diameters of 460 mm, 550 mm, and 610 mm (Table 5.1). Although not all the various tree grid sizes are currently in production they will still be used in this discussion.

Table 5.1 shows the estimated mean tree ages at which the various species’ stem circumferences will exceed the inner diameter of the specific grid or ring. The 800 mm diameter grid provides sufficient growth space for approximately 38 years’ growth for a *Combretum erythrophyllum* tree. Few landscapes are, however, designed to have such a short life span, therefore using a grid or ring that limits growth beyond a certain age will be short sighted. Table 5.1, although still incomplete, gives some indication as to the time of unhampered tree growth within the grids and rings for the three species. For certain environments it may be appropriate to envisage a landscape life time of only a few years. This will justify the use of smaller diameter rings and grids, which will save on project costs. Due to the difference in growth rates the following should be born in mind: If a grid of 300 mm diameter is used then *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* will outgrow that diameter in approximately 10.75 years, 18.50 years and 15.75 years respectively.

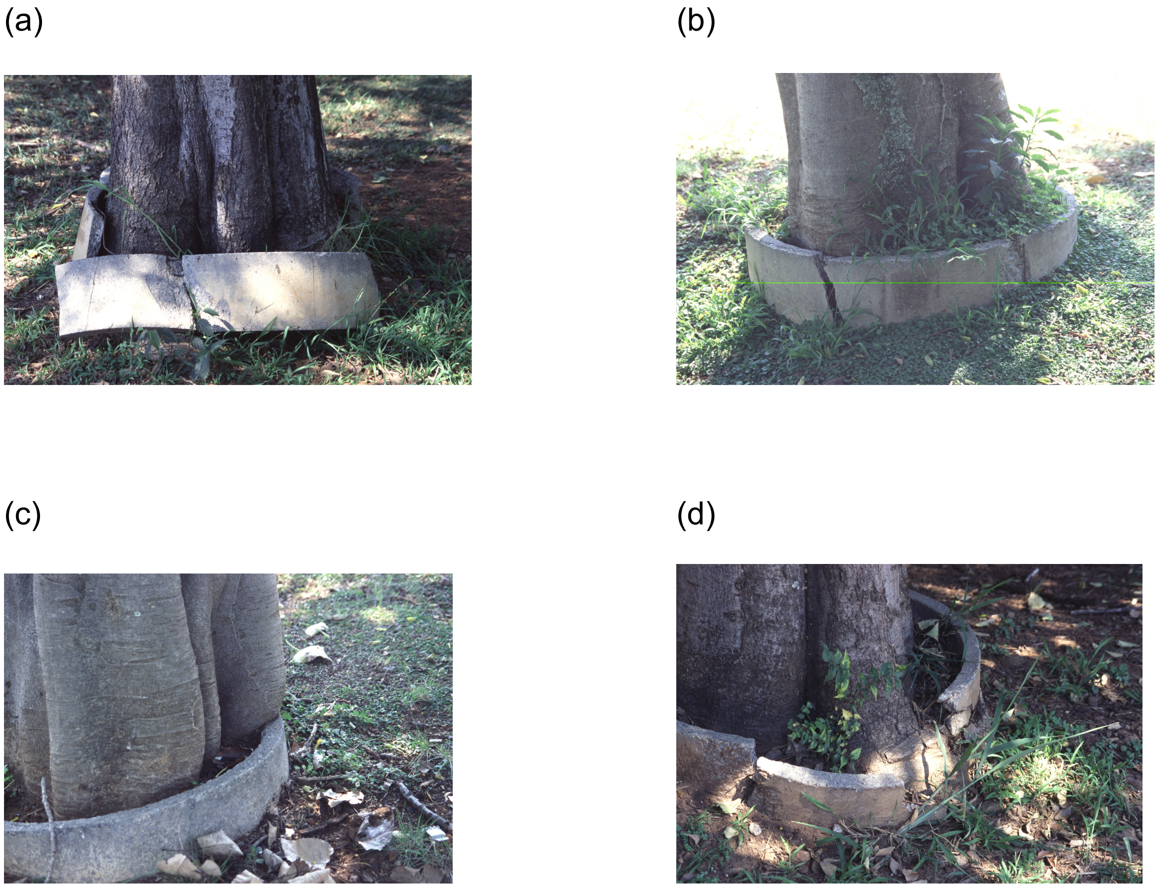
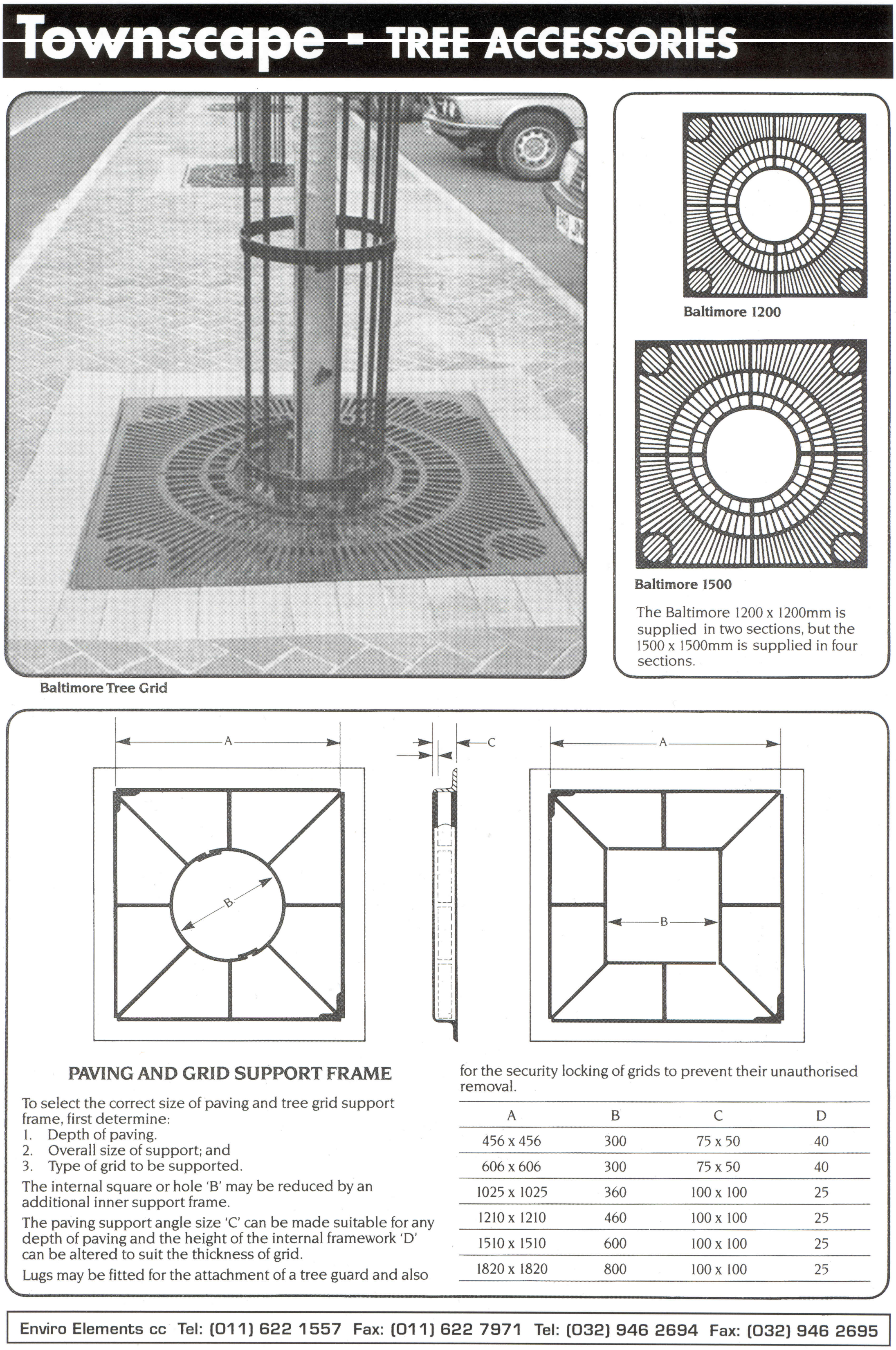


Figure 5.1. Tree rings are broken in (a) and (b) due to a *Celtis africana*'s lateral stem growth and basal stem swelling, whilst in (c) tree ring impedes stem growth, and in (d) surface lateral root growth damages a tree ring as can be seen on the right hand side of the tree ring.



# Townscape - TREE ACCESSORIES

**Baltimore Tree Grid**

**Baltimore 1200**

**Baltimore 1500**

The Baltimore 1200 x 1200mm is supplied in two sections, but the 1500 x 1500mm is supplied in four sections.

## PAVING AND GRID SUPPORT FRAME

To select the correct size of paving and tree grid support frame, first determine:

1. Depth of paving.
2. Overall size of support; and
3. Type of grid to be supported.

The internal square or hole 'B' may be reduced by an additional inner support frame.

The paving support angle size 'C' can be made suitable for any depth of paving and the height of the internal framework 'D' can be altered to suit the thickness of grid.

Lugs may be fitted for the attachment of a tree guard and also for the security locking of grids to prevent their unauthorised removal.

| A | B | C | D |
|---|---|---|---|
| 456 x 456 | 300 | 75 x 50 | 40 |
| 606 x 606 | 300 | 75 x 50 | 40 |
| 1025 x 1025 | 360 | 100 x 100 | 25 |
| 1210 x 1210 | 460 | 100 x 100 | 25 |
| 1510 x 1510 | 600 | 100 x 100 | 25 |
| 1820 x 1820 | 800 | 100 x 100 | 25 |

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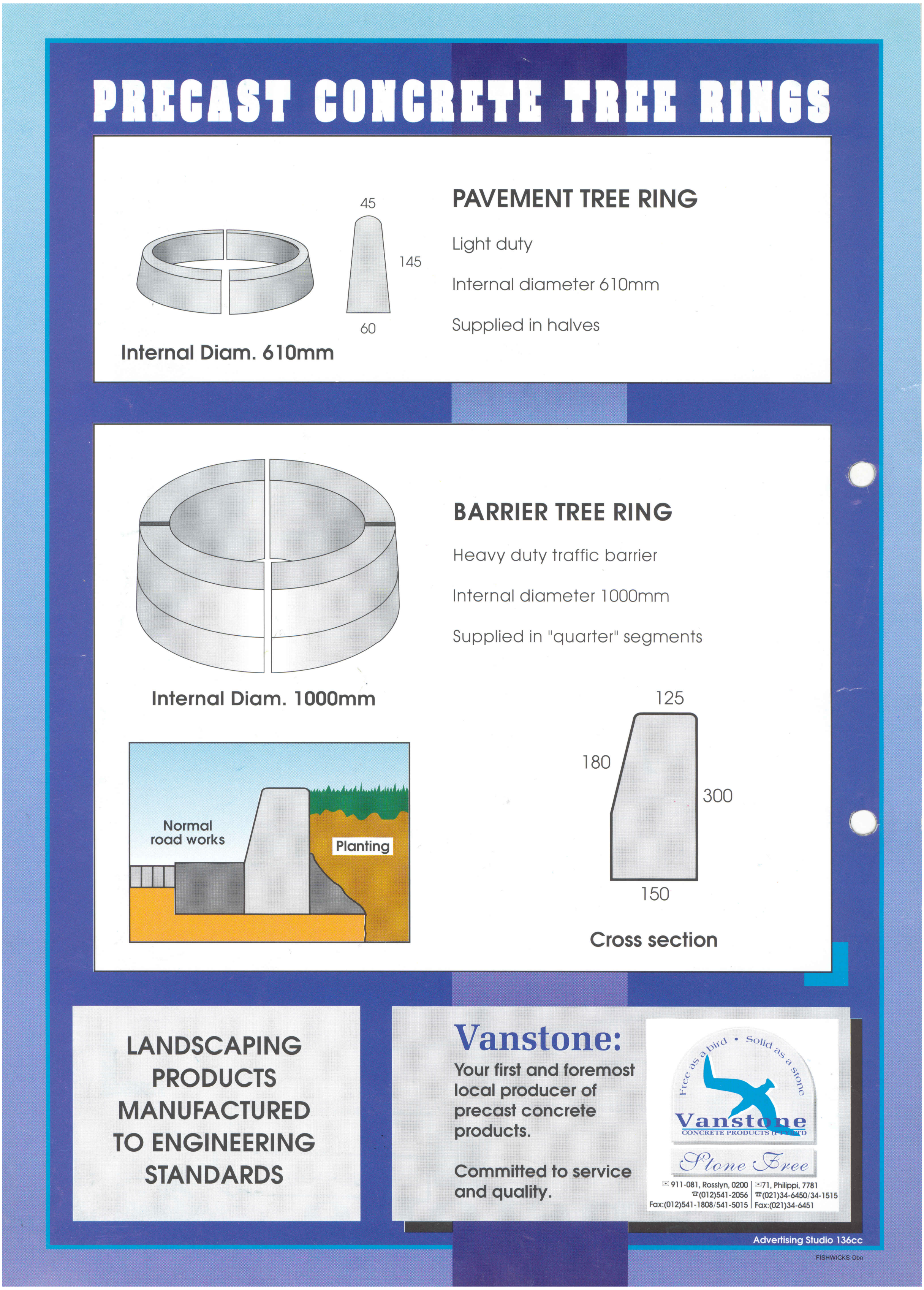
Figure 5.2. Townscape Baltimore Tree Grid



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Supplied in "quarter" segments

Internal Diam. 1000mm

Cross section

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Figure 5.3. Vanstone Pavement Tree Ring

Table 5.1. This table shows the mean estimated tree age of three indigenous street tree species in the City of Tshwane at which their stem diameter will exceed the inner diameter of both the Baltimore Tree Grids and the Pavement Tree Rings

| **Species** | **Baltimore Tree Grids** | | | | **Pavement Tree Rings** | | |
|---|---|---|---|---|---|---|---|
| | 300 mm ϕ | 460 mm ϕ | 600 mm ϕ | 800 mm ϕ | 460 mm ϕ | 550 mm ϕ | 610mm ϕ |
| *Combretum erythrophyllum* | 10.75 yr | 17.75 yr | 25.25 yr | 38.25 yr | 17.25 yr | 22.50 yr | 25.75 yr |
| *Rhus lancea* | 18.50 yr | 33.00 yr*# | -** | -** | 33.00 yr*# | -** | -** |
| *Rhus pendulina* | 15.75 yr* | -** | -** | -** | -** | -** | -** |

| | |
|---|---|
| ϕ | Inside diameter of tree grids and tree rings |
| yr | Age of tree in years |
| * | Marginally extrapolated beyond the data range |
| # | Upper confidence interval used |
| ** | No data available |

This suggests that it would be inappropriate to use the 300 mm diameter grid for all three the species if they were used in a landscape with a life expectancy of, for example, 15 years but would on the other hand be appropriate if the landscape life expectancy is 10 years or less. This implies that species specific tree rings and grids need to be chosen when designing landscapes, which in turn necessitates species specific knowledge of stem diameter growth to age relationships.

The tree ages in Table 5.1 are estimates based on statistical calculations and should not be viewed as absolutes but rather as approximations. Furthermore, the growth rates of trees may increase with higher managed irrigation and fertilization practices and these are not accounted for in the data set on which the results are based. When considering highly managed (regularly irrigated and fertilized) trees, the results in Table 5.1 may be viewed as conservative. This study did not consider the growth of surface lateral roots that may damage or be restricted by tree grids and rings. Often these lateral roots may become problematic to these landscape elements before the actual stem growth is impeded.

When considering long-term landscapes it should be recognised that trees like *Combretum erythrophyllum* and *Rhus lancea* have life expectancies of approximately 100 years and more than 200 years respectively (A.E. van Wyk, personal communication, Department of Botany, University of Pretoria, City of Tshwane, South Africa). It is therefore advised that architects, landscape architects and urban foresters should choose the appropriate tree grid or ring for the expected lifetime of a project or if budgets are constrained, to choose the appropriate tree so that suitably smaller tree rings and grids can be used.

## References

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# Chapter 6

## Carbon sequestration estimates of indigenous street trees in the City of Tshwane, South Africa

### Abstract

Amelioration of global warming presents opportunities for urban forests to act as carbon sinks and thereby be accounted in the carbon trade industry. The City of Tshwane Metropolitan Municipality is planting 115 200 indigenous street trees in the period 2002 to 2008. These trees hold a carbon credit potential in their future growth. In order to calculate the carbon sequestration potential, the growth rate of *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* were determined. Combined species growth regressions of *Combretum erythrophyllum* - *Rhus lancea* and *Rhus lancea* - *Rhus pendulina* are also presented. *Combretum erythrophyllum* has the fastest growth rate while that of *Rhus lancea* and *Rhus pendulina* are slower. The results from growth regression relationships were used in a generic allometric biomass regression to calculate the carbon sequestration rate of each species, which was extrapolated to determine the total quantity of carbon to be sequestrated by the street trees over a 30-year period (2002 to 2032). It is estimated that the tree planting will result in 200 492 tonne $CO_2$ equivalent reduction and that 54 630 tonne carbon will be sequestrated. The carbon dioxide reductions could be valued at more than US$2 million. This illustrates that carbon trade could become a valuable source of revenue for the urban forestry industry.

**Keywords**: allometry, carbon sequestration, growth rate, regression, stem diameter, street trees, trade, urban forestry

## Introduction

Concern over global warming has resulted in an international investigation into methods of ameliorating the green house effect (IPCC, 2000). Because plants act as carbon sinks, fixing carbon through the process of photosynthesis, focus has been on terrestrial vegetation to facilitate carbon sinks (IPCC, 2000; Brown, 2002). A carbon sink is defined as the process or mechanism that removes carbon dioxide (greenhouse gas) from the atmosphere (IPCC, 2000). Carbon is sequestrated and stored in tree tissue at different rates and quantities depending on factors such as growth rate, tree species, size at maturity and life span (Nowak *et al.*, 2002a).

Urban trees and forests have a significant potential to act as carbon sinks (McPherson *et al.*, 1994; Freedman *et al.*, 1996; McPherson & Simpson, 1999; Nowak & Crane, 2002; Nowak *et al.*, 2002a; Nowak *et al.*, 2002b). However, compared to natural forests (Brown *et al.*, 1997; Ter-Milkaelian & Korzukhin, 1997; Brown, 2002), less research has been done on urban forest carbon dioxide sequestration and urban tree biomass allometry and there is a general lack of information on urban tree species in this regard (McPherson *et al.*, 1994; Peper & McPherson, 1998). A literature search revealed no information regarding urban forest carbon dioxide sequestration and urban tree biomass allometry in a South African context.

The City of Tshwane Metropolitan Municipality (Municipality), South Africa, is in a process of establishing 115 200 indigenous street trees in the urban areas of previously disadvantaged communities such as Atteridgeville, Ga-Rankuwa, Mabopane, Mamelodi, Soshanguve, Temba, and Winterveld (personal communication with S. Paul, City of Tshwane Metropolitan Municipality, 8 April 2002). The tree-planting programme commenced in 2002 and is due for completion in 2008. In an urban setting, the geographical areas of these previously disadvantaged communities are known as "Townships" (suburbs). As the legacy of historically politically motivated urban development strategies, they are mostly the habitation of the poor and are generally denuded of vegetation. Street trees hold the prospect of carbon sequestration and aesthetic transformation of these vegetation-impoverished areas.

In order to estimate carbon sequestration benefits it is necessary to calculate the quantities of carbon that can potentially be sequestrated by future growth. If sufficient quantities of carbon will be sequestrated, the Municipality may engage in carbon trade. In this process, the carbon sequestration potential of these trees are traded and the income thus generated could provide finances for further tree planting. The carbon trade industry could become an important source of revenue for urban forestry. Further information about carbon trading is available at www.pointcarbon.com , www.co2e.com , http://unfccc.int .

Current methods of modelling urban forest carbon sequestration often employ allometric equations from which tree biomass and consequently carbon sequestration may be derived (Peper & McPherson, 1998; McPherson & Simpson, 1999; Nowak & Crane, 2002; Nowak *et al.*, 2002b). Through allometric equations tree diameter, usually at breast height, or other easily measurable variables are related to standing volume of biomass (dry mass) (Haase & Haase, 1995; Nelson *et al.*, 1999; Keller *et al.*, 2001; Ketterings *et al.*, 2001). Approximately fifty percent of the biomass can be ascribed to carbon (Scholes & Walker, 1993; McPherson & Simpson, 1999; Gifford, 2000; McPherson *et al.*, 2001; Nowak *et al.*, 2002b).

When the street trees are young the standing carbon stock is not substantial. However, the growth of the trees represents a potential increase in biomass and hence carbon sequestration. The aim of this study was therefore to:

(1) develop generic combined species growth rate regressions based on the data captured from three indigenous street tree species,

(2) to estimate the potential rate of carbon sequestration of three indigenous street tree species as well as the potential rate of carbon sequestration of the generic combined species regressions and then,

(3) to calculate the total quantity of carbon that could be sequestrated by the 115 200 street trees after a 30-year growth period in the City of Tshwane's Townships.

The rate of carbon sequestration is dependent on the growth rate therefore these two aims of the study are closely related. Growth rates for the three indigenous species were determined in Chapter 3.

## Methodology

### *Field data collection*

The stem circumferences of street trees were measured in the winter and early spring (April - September) of 2002 in the Pretoria area in the City of Tshwane (25° 39' S - 25° 50' S; 28° 19' E - 28° 09' E), in the province of Gauteng. The stem circumference of the larger street trees (larger than approximately 90 mm diameter) was 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 biomass regression equation used requires stem diameter measurements at ground level. Also the Municipality often planted trees that still have branches below 1.37m. Furthermore, the African savanna species investigated tend to branch at a level lower than this height.

The 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 was used to calculate the diameter and circumference.

Three species, *Combretum erythrophyllum* (river bushwillow), *Rhus lancea* (karee) and *Rhus pendulina* (white karee) were investigated. All the species are indigenous to South Africa and when fully grown are approximately 7 m to 12 m tall (Joffe, 1993; van Wyk & van Wyk, 1998). In total 282 trees were measured of which 105 were *Combretum erythrophyllum*, 107 *Rhus lancea* and 70 *Rhus pendulina*. The height of the trees when first planted in streets varied, but in general, is approximately two meters (personal communication with S. Paul, City of Tshwane Metropolitan Municipality, 8 April 2002).

The majority of the trees were growing in residential, non-irrigated, managed lawn environments. The average planting distance is 14 m. Driveways and road infrastructure often resulted in irregular planting distances. The irregular planting distances were not included in the calculation of an average planting distance. Mean tree to curb distance and road reserve width were 2.1 m and 6.5 m respectively.

With some exceptions ten trees were measured per street (see Chapter 3 and Chapter 4). 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. This problem was avoided 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 3 and Chapter 4).

### *Determining growth rate*

A literature search revealed no growth rate equations for any indigenous urban trees, therefore generic growth equations could not be used for carbon sequestration calculations. As a result the individual species' growth rates had to be determined. The trees were planted between 1955 and 2001 and their ages were derived from the planting dates which were obtained from the Municipality. The planting dates refer to the date at which the trees were physically planted in the streets. The ranges of minimum and maximum ages of the species are 1.2 years to 47.6 years, 1.3 years to 32.6 years and 3.4 years to 15.6 years for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* respectively. Hence, data for 46.4 years, 31.3 years and 12.2 years age range periods for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* respectively, was used in the calculations. Planting dates for trees planted prior to 1995 were obtained from aerial photographs and personal communication with botanical and horticultural staff since the Municipality did not keep planting date records prior to 1995. In the past, the policy was to plant mostly exotic street trees. This rendered it difficult to find old individuals of the species investigated of which the age was known. 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.

Both stem diameter and stem circumference were regressed on age to compute the growth rate of each species. Two combined species regressions for a *Combretum erythrophyllum* - *Rhus lancea* combination and a *Rhus lancea* - *Rhus pendulina* combination are also presented. Several growth curve models were tested (see Chapter 2): 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 (see Chapter 2) and was used to determine the growth rates for the individual and the combined species.

Age was used as independent variable and stem diameter or stem circumference was 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 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 Chapter 3. 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 Dept. Env. Hort., Univ. of California, One Shields Avenue, Davis, CA 95616-8587, http://cufr.ucdavis.edu/, 23 April 2003). The altered equation is presented in Table 6.1. 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).

*Carbon sequestration*

Very few allometric biomass regressions exist for southern African tree species (Dayton, 1978; Rutherford, 1979; Scholes, 1987; Chidumayo, 1990; Goodman, 1990; Tietema, 1993; Shackleton, 1997) and no biomass allometry could be found for indigenous urban trees in the literature. The Municipality would not allow destructive harvesting and therefore species-specific biomass regressions could not be derived. Instead, the following generic equation presented by Shackleton (1997) for South African savanna trees was used for biomass calculations:

$$\log b = 2.397(\log c) - 2.441 \qquad (2)$$

with $r^2 = 0.94$; $p < 0.00001$; $n = 94$

where *b* is the biomass (kg) and *c* the stem circumference (cm) at ground level.

The stem circumference and its upper and lower confidence intervals as calculated using equation (1), were used in the above biomass regression (equation (2)) to calculate the biomass for an individual tree. Because equation (1) gives an age - stem circumference relationship and equation (2) a stem circumference – biomass relationship, an age – biomass relationship could be obtained. Stem diameter, although not measured for the larger trees, could be incorporated in this relationship since it is a function of stem circumference.

The carbon calculations are based on the whole tree biomass estimates, which include both below and above ground biomass. However, 5.4% leaf biomass was subtracted from the total above ground biomass (Rutherford, 1982) as calculated by equation (2). In calculating root biomass a root : shoot ratio of 0.78 is assumed (Scholes & Walker, 1993). A conservative carbon content of the above ground biomass is assumed as 45 % and root carbon as 42% of root biomass (Scholes & Walker, 1993).

Carbon sequestration estimates, stem circumference and stem diameter were regressed on tree age (Appendix A). The estimates in Appendix A were calculated based on 0.25 year (3 months) intervals. These small age intervals were used so that the interpolation of the derived variables (sequestrated carbon, stem circumference, stem diameter) could also be determined with intervals smaller than one year. This makes deductions from the tables (Appendix A) more accurate and makes it more user-friendly for general use than had one year intervals been used. The confidence intervals are also provided.

### *Tshwane' s carbon sequestration*

Tree age - carbon relationships were used to calculate the total quantity of carbon that could be sequestrated by the 115 200 street trees after a 30 year period (2002 - 2032). No growth or biomass regressions could be found in the literature, therefore the calculated growth rate and carbon regression equations presented were applied to the nine additional species that are being planted in the Townships (Table 6.2). *Combretum erythrophyllum* and *Rhus lancea* combined species regression was used to calculate growth rates and carbon sequestration rates for species of intermediate size (*Galpinia transvaalica*, *Olea europaea* subsp. *africana*, *Warburgia salutaris*) (van Wyk, 1984; Joffe, 1993). *Combretum* *erythrophyllum* equation was applied for larger trees (*Combretum krausii*, *Ekebergia capensis*) (van Wyk, 1984; Joffe, 1993) and *Rhus lancea* equation was applied to this species only.

The oldest trees in the *Rhus pendulina* data set were 15.6 years and could therefore not be used for 30 year projections, consequently *Rhus lancea* and *Rhus pendulina* combined species regression was used to determine the carbon sequestration for *Rhus pendulina* as well as for that of *Acacia caffra*, *Heteropyxis natalensis*, *Rhus leptodictya*, and *Vepris lanceolata*. In some instances, the growth rates determined for the three species investigated as well as that of the combined species growth rate regressions correlated with the natural growth rates of the nine species that were not investigated and for which carbon values were determined (van Wyk, 1984; Joffe, 1993). Annual carbon gain is calculated as the quantity of carbon fixed per year (kg C yr $^{-1}$) over a 30-year period (2002 - 2032) (Table 6.2).

## Results and discussion

### *Growth rate*

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 regression coefficients and coefficients of determination ($r^2$) to predict stem diameter and stem circumference growth by age are presented in Table 6.1. The coefficients of determination are 0.76, 0.84 and 0.75 for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* respectively (Table 6.1). For the *Combretum erythrophyllum* - *Rhus lancea* and *Rhus lancea* - *Rhus* *pendulina* combined species regressions the coefficients of determination are 0.77 and 0.80 respectively. The logarithmic regression models fitted to the data are shown in Figure 6.1 to Figure 6.3.

In Figure 6.3 all the curves presented make a visual growth rate comparison possible. In general *Combretum erythrophyllum* has the highest growth rate, thereafter the combined species regression of C*ombretum erythrophyllum* - *Rhus lancea*, then *Rhus lancea*, *Rhus pendulina* and lastly that of the *Rhus lancea* - *Rhus pendulina* combined species regression. The growth rate of the combined species regression of *Rhus lancea* and *Rhus pendulina* is lower than both that of the two species individually. This can be attributed to the nature of the logarithmic equation's fit to the combined data set. Initially *Rhus pendulina* has the lowest growth rate but it equals the growth rate of *Rhus lancea* towards the upper end of the curve. Visual consideration of the slope of its ascent, may lead one to conjecture that it will have a faster growth rate than *Rhus lancea* beyond the range of the data.

Carbon sequestration rate is related to growth rate. Therefore the faster a tree grows, the faster it fixes carbon from the atmosphere into plant tissue. As a consequence, the growth rate comparison is an important indicator as to which species sequestrates carbon the fastest.

The statistical model used to fit the data, accounted for the variability within the data values. It can be noticed that the confidence bounds expand with the increase in tree age (Figure 6.1 and Figure 6.2). This is a common tendency for all the species and reflects the variability within the species due to effects of differences in genotype, culture, site conditions, biotic, and abiotic factors that influence the health and growth of a tree (Peper *et al.*, 2001a).

The regression equations presented are only valid within the range of ages and stem circumferences of the data collected in this study. Extrapolation with the aim of obtaining data beyond the collected data range is, therefore, not recommended. This point was made by Haase & Haase (1995) in determining biomass through the use of allometry and should also be observed when calculating growth rate.

Table 6.1. Sample size ($n$), estimated regression coefficients ($A$, $b$) and mean standard error ($MSE$) values for predicting stem diameter growth as well as coefficients of determination. Stem 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 to be estimated , $\log$ is the natural logarithm of the argument and $EXP$ = the inverse of the natural logarithm and $x_i$ = age, stem circumferences or stem diameter

| | Stem circumference vs. age | | | | | Stem diameter vs. age | | | |
|---|---|---|---|---|---|---|---|---|---|
| Species | $n$ | $A$ | $b$ | MSE | $r^2$ | $A$ | $b$ | MSE | $r^2$ |
| *Combretum erythrophyllum* | 105 | 4.58352 | 2.44085 | 0.14804 | 0.76 | 3.43879 | 2.44085 | 0.14804 | 0.76 |
| *Rhus lancea* | 107 | 4.92616 | 1.74761 | 0.057522 | 0.84 | 3.78143 | 1.74761 | 0.057522 | 0.84 |
| *Rhus pendulina* | 70 | 4.53425 | 2.21533 | 0.051892 | 0.75 | 3.38952 | 2.21533 | 0.051892 | 0.75 |
| Combined *C. erythrophyllum R. lancea* | 212 | 4.76982 | 2.05338 | 0.11204 | 0.77 | 3.62509 | 2.05338 | 0.11204 | 0.77 |
| Combined *R. lancea R. pendulina* | 177 | 4.87405 | 1.78049 | 0.059088 | 0.80 | 3.72932 | 1.78049 | 0.059088 | 0.80 |

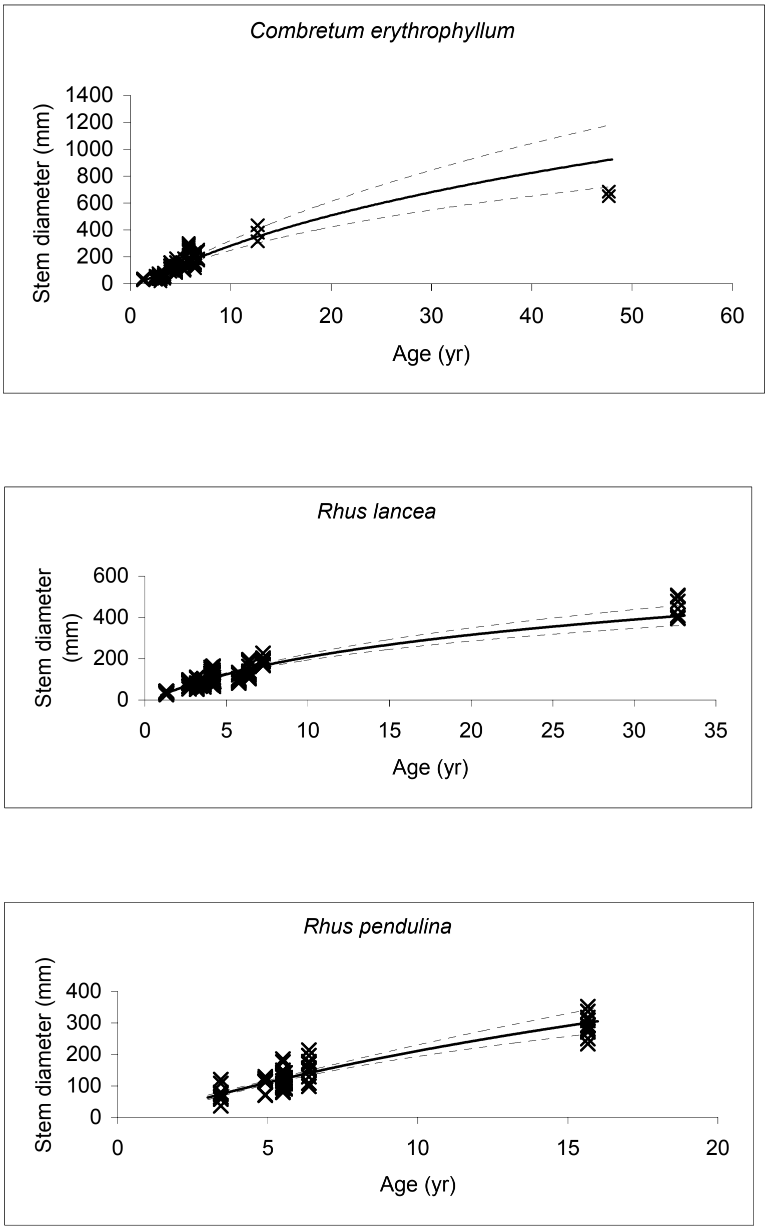
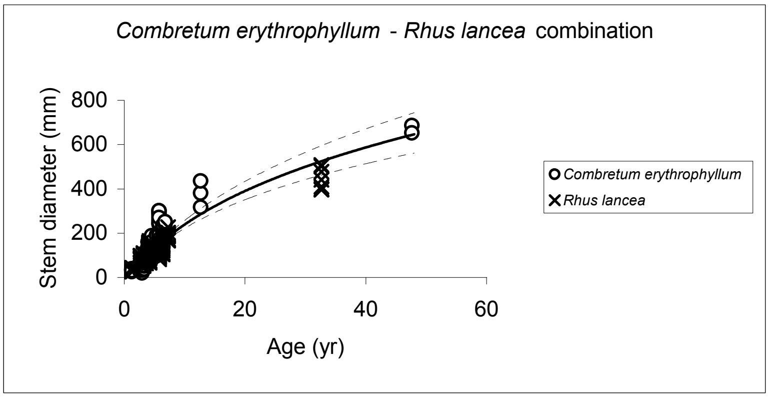


Figure 6.1. Stem diameter logarithmically regressed against tree age (years) (Table 6.1) for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina*. The dotted lines represent the confidence intervals at a level of 95% to the estimated means.



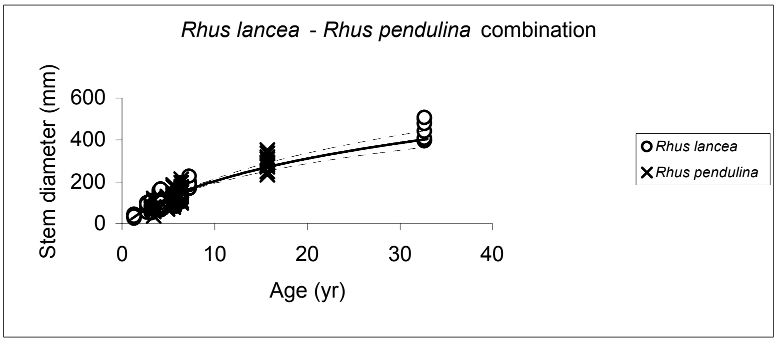


Figure 6.2. Stem diameter logarithmically regressed against tree age (years) (Table 6.1) for *Combretum erythrophyllum* - *Rhus lancea* and *Rhus lancea* - *Rhus pendulina* combinations. The dotted lines represent the confidence intervals at a level of 95% to the estimated means.

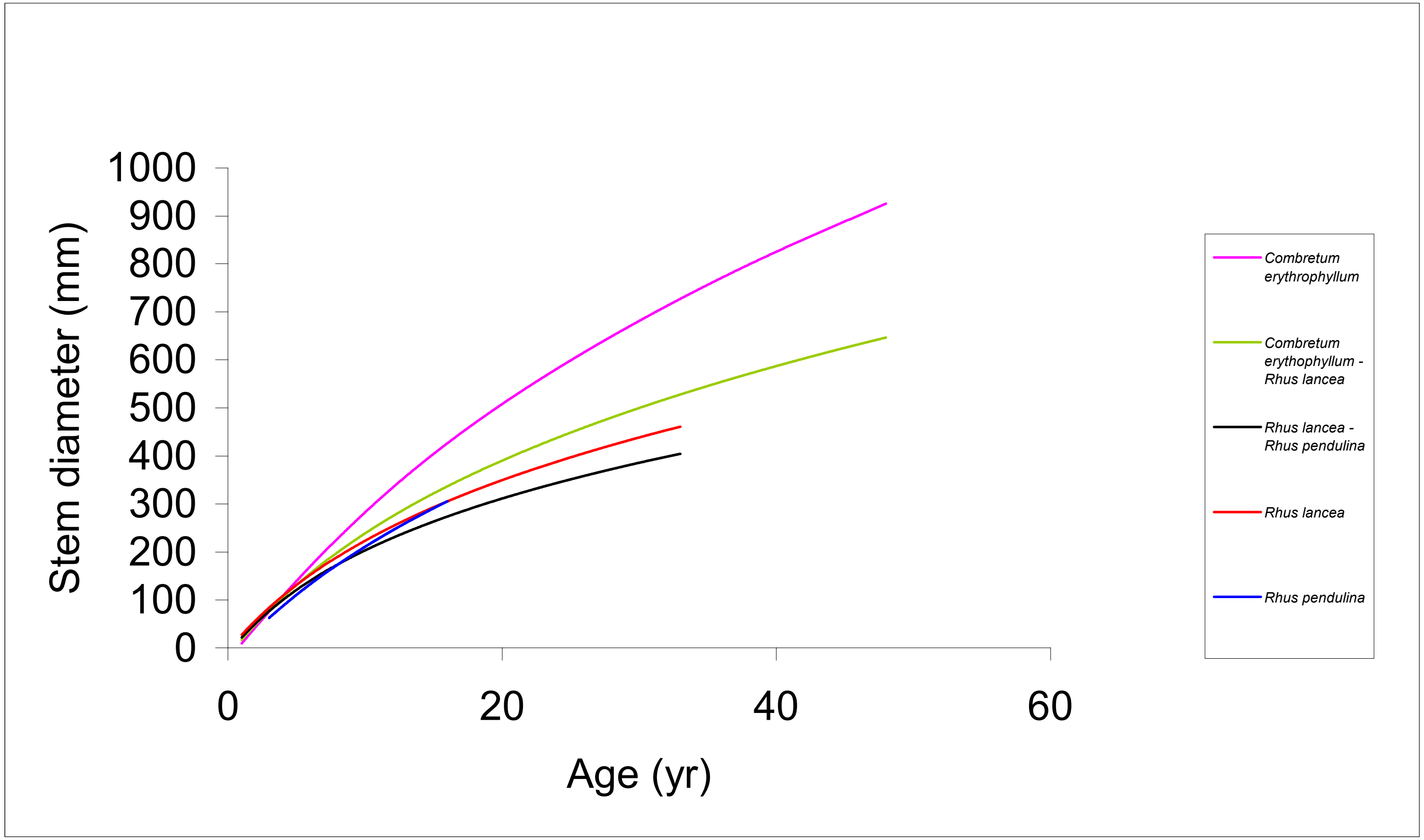


Figure 6.3. Stem diameter logarithmically regressed against tree age (years) for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* as well as the *Combretum erythrophyllum* - *Rhus lancea* and *Rhus lancea* - *Rhus pendulina* combined species regressions to enable growth rate comparisons between the species and the combined species regressions.

*Carbon sequestration*

The carbon sequestration results are presented in table format in Appendix A. Both circumference and stem diameter are provided for ease of use and to avoid conversion errors. Although tree age is the explanatory (independent) variable, stem diameter and circumference may also be used to determine carbon sequestration or tree age and *vice versa*.

Sequestration rates derived from the regressions show that the *Combretum erythrophyllum* and *Rhus lancea* combination sequestrates carbon at a faster rate (14 kg C $yr^{-1}$) than the *Rhus lancea* and *Rhus pendulina* combination (8 kg C $yr^{-1}$) but has a slower sequestration rate than *Combretum erythrophyllum* (29 kg C $yr^{-1}$) (Table 6.2). The *Rhus lancea* and *Rhus pendulina* combination sequestration rate is the same as that of *Rhus lancea* and *Rhus pendulina* respectively (8 kg C $yr^{-1}$).

The Municipality selected 12 indigenous species for the tree planting program, which forms part of its 2002 to 2008 urban forestry plan for the Townships (Table 6.2). *Combretum erythrophyllum* and *Ekebergia capensis* each represent 11 % of the total number of trees to be planted this program and *Combretum krausii* 8 %, and they sequestrate 20.1 %, 19.4 % and 14.5 % of the total amount of carbon respectively (Table 6.2). Thus they have relatively high sequestration percentages in relation to their proportional representation of the total number of trees. On the other hand *Rhus lancea*, *Rhus leptodictya*, *Rhus pendulina* and *Olea europaea* subsp. *africana* represent 16 %, 10 %, 12 %, and 16 % of the total population respectively. They in turn sequestrate 8.0 %, 5.1 %, 6.0 % and 14.6 % of the total amount of carbon respectively. Their sequestration proportion is less than their proportional representation of the total population. This can be attributed to the size of the mature trees and their growth rate (McPherson *et al.*, 1994; Nowak *et al.*, 2002a)

*Combretum erythrophyllum* is a relatively large tree in natural environments with a higher growth rate than *Rhus lancea* and *Rhus pendulina*, which are trees of medium size and of moderate growth rate that will therefore sequestrate less carbon and at a lower rate than the larger tree (*Combretum erythrophyllum*).One may therefore safely deduce that larger trees with higher growth rates will be more beneficial to ameliorate global warming since they sequestrate larger quantities of carbon faster.

Table 6.2. The species that are being planted and the regression equations used to calculate the estimated carbon sequestration The total number of trees planted per species by 2008, as well as the percentage (rounded) of each species represented in the total number of trees. The rate of carbon gain over a 30-year period and the total quantity of carbon sequestrated by 2032 as well as the percentage (rounded) carbon that each species sequestrates, are shown.

| Species planted | Regression equation used | Number of trees to be planted by 2008 | Percentage of total number of trees | Carbon sequestrated by 2032 (ton carbon) | Rate of carbon gain per individual tree (kg carbon $yr^{-1}$) | Percentage of total carbon |
|---|---|---|---|---|---|---|
| *Acacia caffra* | *Rhus* spp. combined | 5200 | 5 | 1189 | 8 | 2.2 |
| *Combretum erythrophyllum* | *Combretum erythrophyllum* | 12600 | 11 | 10984 | 29 | 20.1 |
| *Combretum krausii* | *Combretum erythrophyllum* | 9000 | 8 | 7932 | 29 | 14.5 |
| *Ekebergia capensis* | *Combretum erythrophyllum* | 12100 | 11 | 10589 | 29 | 19.4 |
| *Galpinia transvaalica* | *Combretum erythrophyllum- Rhus lancea* combined | 9500 | 8 | 4096 | 14 | 7.5 |
| *Heteropyxis natalensis* | *Rhus* spp. combined | 1200 | 1 | 279 | 8 | 0.5 |
| *Rhus lancea* | *Rhus lancea* | 18350 | 16 | 4363 | 8 | 8.0 |
| *Rhus leptodictya* | *Rhus* spp. combined | 11700 | 10 | 2764 | 8 | 5.1 |
| *Rhus pendulina* | *Rhus* spp. combined | 13600 | 12 | 3283 | 8 | 6.0 |
| *Olea europaea ssp africana* | *Combretum erythrophyllum- Rhus lancea* combined | 18950 | 16 | 7988 | 14 | 14.6 |
| *Vepris lanceolata* | *Rhus* spp. combined | 600 | 1 | 140 | 8 | 0.3 |
| *Warburgia salutaris* | *Combretum erythrophyllum- Rhus lancea* combined | 2400 | 2 | 1023 | 14 | 1.9 |
| Total | | 115200 | 101* | 54630 | | 100.1* |

*Total rounded percentages

When considering the threat of global warming, one may argue that it is best to revise the Municipality's planting schedule and plant all the streets with larger and faster growing trees. However, there is ecological safety in the use of a diversity of urban forestry species since it minimizes the risk of catastrophic loss resulting from insects, disease or other harmful agents (McPherson & Rowntree, 1987). An example of the destructive magnitude of pests is that of the urban forest of Brooklyn (New York, United States of America), where 51% of the tree population is infested with the Asian longhorn beetle. This infestation could lead to a US$390 million compensatory or replacement value loss in urban forest infrastructure (Nowak *et al.*, 2002b). A diversity of species also allows for the creation of a variety of habitats. As with natural forests, unique microclimates and environs are created by each individual tree species, which enables different understory plant compositions and arrangements. Furthermore, all the species are indigenous and will therefore enhance bird life (Joffe, 1993) in the Townships that should aid in transforming the aesthetic and environmental qualities of these biodiversity impoverished areas. From a landscape architectural point of view, diversity is also important for the creation of an aesthetically pleasing environment. Although planting a large diversity of fast growing large trees will address both the diversity and the carbon sequestration issues it will be inappropriate for urban environments which also necessitate the use of a diversity of tree sizes.

*Tshwane' s carbon sequestration*

Calculations show that by 2032 a quantity of 54 630 tonne carbon could be sequestrated by the 115 200 street trees. Often emission reductions are reported as the full molecular mass of $CO_2$ rather than the atomic mass of carbon. The molecular mass of $CO_2$ can be obtained by multiplying the atomic mass of carbon by 3.67 (McPherson & Simpson, 1999). In applying this conversion factor the abovementioned trees will result in an estimated 200 492 tonne $CO_2$ equivalent reduction. Assuming a market related price of US$10 tonne $CO_2$ (www.pointcarbon.com accessed 31 May 2005), the carbon dioxide could be valued US$2 004 920. This calculation does not include carbon dioxide costs due to tree propagation, tree planting and maintenance as well as tree mortalities.

This study only accounts for carbon sequestration as environmental benefit related to street trees. However, there are numerous other advantages that urban trees hold, amongst others storm water runoff reductions, pollution reduction and climate amelioration, (Akbari *et al.*, 2001; Akbari, 2002; Nowak *et al.*, 2002b; Maco & McPherson, 2003) (see Chapter 7). These and other benefits as well as costs involved with street tree maintenance (Nowak *et al.*, 2002a) for example, need to be considered when calculating the monetary benefit or cost of street trees (Nowak *et al.*, 2002b; McPherson, 2003).

## Conclusion

The aim of this study was to develop generic combined species growth rate regressions, to estimate the potential rate of carbon sequestration of three indigenous street tree species as well as that of the combined species' regressions and thirdly to determine the total quantity of carbon that could be sequestrated by future street tree planting over a 30 year period in the City of Tshwane.

*Combretum erythrophyllum* has the highest growth rate, thereafter the combined species regression of *Combretum erythrophyllum* - *Rhus lancea*, then *Rhus lancea*, *Rhus pendulina* and lastly that of the *Rhus lancea* - *Rhus pendulina* combined species regression.

*Combretum erythrophyllum* and *Rhus lancea* combination regression sequestrates carbon at a faster rate (14 kg C $yr^{-1}$) than the *Rhus lancea* and *Rhus pendulina* combination (8 kg C $yr^{-1}$). *Combretum erythrophyllum* and *Rhus lancea* combination regression has, however, a slower sequestration rate than *Combretum erythrophyllum* (29 kg C $yr^{-1}$) (Table 6.2). The *Rhus lancea* and *Rhus pendulina* individual species sequestration rates are the same as that of *Rhus lancea* and *Rhus pendulina* combination (8 kg C $yr^{-1}$).

Calculations show that by 2032 a quantity of 54 630 ton carbon could be sequestrated by the 115 200 street trees. This will result in an estimated 200 492 ton $CO_2$ equivalent reduction. Assuming a market related price of US$10 $ton^{-1}$ $CO_2$ the carbon dioxide could be valued at US$2 004 920. This calculation does not include carbon dioxide costs due to tree propagation, tree planting and maintenance as well as tree mortalities.

Although urban forests are smaller in scale than natural forest systems, they still offer carbon sequestration benefits. The Townships of South Africa render themselves as opportune environs for the establishment of new trees. These are zero carbon credit and debit baseline environs from which carbon sequestration can be calculated based on the growth of newly planted trees. Furthermore, carbon trade could provide valuable resources for the maintenance and establishment of such urban forests (personal communication with B. Dry, City of Tshwane Metropolitan Municipality, February 2003).

Limited research has been done on the growth rate and carbon sequestration rate of urban street trees and no literature could be found pertaining to the issues discussed for the species investigated in a South African context which renders additional significance to the research presented.

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## Appendix A

The tree age (years) and its correlated sequestrated carbon (kg), stem circumference (mm) and stem diameter (mm) is presented. Lower (L) and upper (U) confidence intervals at a level of 95% to the estimated means, are also provided. The following tables show the results for *Combretum erythrophyllum* (Table Appendix A 6.1a), *Rhus lancea* (Table Appendix A 6.1b), *Rhus pendulina* (Table Appendix A 6.1c), and the *Combretum erythrophyllum* - *Rhus lancea* (Table Appendix A 6.2), and *Rhus lancea* - *Rhus pendulina* (Table Appendix A 6.3) combined species regressions. The results show the predictions from age 1 year till the oldest tree measured by 0.25 year (3 month) intervals.

Table Appendix A 6.1a. Species: *Combretum erythrophyllum*

| ***Combretum erythrophyllum*** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Age** | **Sequestrated carbon (kg)** | | | **Stem circumference (mm)** | | | **Stem diameter (mm)** | | |
| **(years)** | **Mean** | **L** | **U** | **Mean** | **L** | **U** | **Mean** | **L** | **U** |
| 1.00 | 0.09 | 0.05 | 0.16 | 43 | 34 | 54 | 14 | 11 | 17 |
| 1.25 | 0.23 | 0.14 | 0.36 | 63 | 52 | 77 | 20 | 17 | 24 |
| 1.50 | 0.46 | 0.31 | 0.69 | 85 | 72 | 100 | 27 | 23 | 32 |
| 1.75 | 0.83 | 0.59 | 1.16 | 108 | 94 | 125 | 35 | 30 | 40 |
| 2.00 | 1.34 | 0.99 | 1.80 | 133 | 117 | 150 | 42 | 37 | 48 |
| 2.25 | 2.02 | 1.55 | 2.63 | 157 | 141 | 176 | 50 | 45 | 56 |
| 2.50 | 2.88 | 2.28 | 3.65 | 183 | 166 | 202 | 58 | 53 | 64 |
| 2.75 | 3.95 | 3.18 | 4.90 | 208 | 190 | 228 | 66 | 61 | 73 |
| 3.00 | 5.22 | 4.27 | 6.37 | 234 | 215 | 254 | 74 | 68 | 81 |
| 3.25 | 6.70 | 5.55 | 8.10 | 260 | 240 | 281 | 83 | 76 | 89 |
| 3.50 | 8.41 | 7.00 | 10.09 | 285 | 264 | 308 | 91 | 84 | 98 |
| 3.75 | 10.34 | 8.64 | 12.37 | 311 | 289 | 335 | 99 | 92 | 107 |
| 4.00 | 12.49 | 10.45 | 14.94 | 337 | 313 | 363 | 107 | 99 | 115 |
| 4.25 | 14.88 | 12.43 | 17.81 | 362 | 336 | 390 | 115 | 107 | 124 |
| 4.50 | 17.49 | 14.57 | 21.01 | 387 | 359 | 418 | 123 | 114 | 133 |
| 4.75 | 20.34 | 16.86 | 24.53 | 413 | 382 | 446 | 131 | 121 | 142 |
| 5.00 | 23.41 | 19.31 | 28.38 | 437 | 404 | 474 | 139 | 129 | 151 |
| 5.25 | 26.70 | 21.90 | 32.56 | 462 | 426 | 502 | 147 | 135 | 160 |
| 5.50 | 30.23 | 24.64 | 37.09 | 487 | 447 | 530 | 155 | 142 | 169 |
| 5.75 | 33.97 | 27.51 | 41.95 | 511 | 468 | 558 | 163 | 149 | 178 |
| 6.00 | 37.94 | 30.52 | 47.16 | 535 | 489 | 586 | 170 | 156 | 187 |
| 6.25 | 42.12 | 33.66 | 52.71 | 559 | 509 | 614 | 178 | 162 | 195 |
| 6.50 | 46.51 | 36.92 | 58.60 | 583 | 529 | 642 | 185 | 168 | 204 |

| *Combretum erythrophyllum* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Age** | **Sequestrated carbon (kg)** | | | **Stem circumference (mm)** | | | **Stem diameter (mm)** | | |
| **(years)** | **Mean** | **L** | **U** | **Mean** | **L** | **U** | **Mean** | **L** | **U** |
| 6.75 | 51.12 | 40.31 | 64.83 | 606 | 549 | 669 | 193 | 175 | 213 |
| 7.00 | 55.94 | 43.82 | 71.40 | 629 | 568 | 697 | 200 | 181 | 222 |
| 7.25 | 60.96 | 47.45 | 78.31 | 652 | 587 | 724 | 208 | 187 | 230 |
| 7.50 | 66.18 | 51.19 | 85.56 | 675 | 606 | 751 | 215 | 193 | 239 |
| 7.75 | 71.60 | 55.04 | 93.15 | 697 | 625 | 778 | 222 | 199 | 248 |
| 8.00 | 77.21 | 58.99 | 101.06 | 720 | 643 | 805 | 229 | 205 | 256 |
| 8.25 | 83.02 | 63.05 | 109.31 | 742 | 661 | 832 | 236 | 211 | 265 |
| 8.50 | 89.01 | 67.22 | 117.88 | 764 | 679 | 859 | 243 | 216 | 273 |
| 8.75 | 95.19 | 71.48 | 126.78 | 785 | 697 | 885 | 250 | 222 | 282 |
| 9.00 | 101.56 | 75.83 | 136.00 | 807 | 714 | 912 | 257 | 227 | 290 |
| 9.25 | 108.10 | 80.28 | 145.54 | 828 | 732 | 938 | 264 | 233 | 298 |
| 9.50 | 114.81 | 84.82 | 155.40 | 849 | 749 | 964 | 270 | 238 | 307 |
| 9.75 | 121.70 | 89.45 | 165.57 | 870 | 765 | 990 | 277 | 244 | 315 |
| 10.00 | 128.75 | 94.17 | 176.05 | 891 | 782 | 1015 | 284 | 249 | 323 |
| 10.25 | 135.98 | 98.96 | 186.83 | 911 | 798 | 1041 | 290 | 254 | 331 |
| 10.50 | 143.36 | 103.84 | 197.92 | 932 | 815 | 1066 | 297 | 259 | 339 |
| 10.75 | 150.91 | 108.80 | 209.30 | 952 | 831 | 1091 | 303 | 264 | 347 |
| 11.00 | 158.61 | 113.84 | 220.99 | 972 | 846 | 1116 | 309 | 269 | 355 |
| 11.25 | 166.47 | 118.95 | 232.96 | 992 | 862 | 1141 | 316 | 274 | 363 |
| 11.50 | 174.47 | 124.13 | 245.23 | 1011 | 877 | 1166 | 322 | 279 | 371 |
| 11.75 | 182.63 | 129.39 | 257.78 | 1031 | 893 | 1190 | 328 | 284 | 379 |
| 12.00 | 190.94 | 134.71 | 270.62 | 1050 | 908 | 1215 | 334 | 289 | 387 |
| 12.25 | 199.38 | 140.11 | 283.74 | 1069 | 923 | 1239 | 340 | 294 | 394 |
| 12.50 | 207.97 | 145.56 | 297.13 | 1088 | 938 | 1263 | 346 | 298 | 402 |
| 12.75 | 216.70 | 151.09 | 310.80 | 1107 | 952 | 1287 | 352 | 303 | 410 |
| 13.00 | 225.56 | 156.67 | 324.73 | 1126 | 967 | 1311 | 358 | 308 | 417 |
| 13.25 | 234.55 | 162.32 | 338.94 | 1144 | 981 | 1334 | 364 | 312 | 425 |
| 13.50 | 243.68 | 168.02 | 353.41 | 1163 | 996 | 1358 | 370 | 317 | 432 |
| 13.75 | 252.94 | 173.79 | 368.14 | 1181 | 1010 | 1381 | 376 | 321 | 440 |
| 14.00 | 262.32 | 179.61 | 383.12 | 1199 | 1024 | 1404 | 382 | 326 | 447 |
| 14.25 | 271.83 | 185.49 | 398.36 | 1217 | 1038 | 1427 | 387 | 330 | 454 |
| 14.50 | 281.46 | 191.42 | 413.86 | 1235 | 1051 | 1450 | 393 | 335 | 462 |
| 14.75 | 291.21 | 197.40 | 429.60 | 1252 | 1065 | 1473 | 399 | 339 | 469 |
| 15.00 | 301.08 | 203.43 | 445.59 | 1270 | 1078 | 1496 | 404 | 343 | 476 |
| 15.25 | 311.06 | 209.52 | 461.82 | 1287 | 1092 | 1518 | 410 | 347 | 483 |
| 15.50 | 321.16 | 215.65 | 478.29 | 1305 | 1105 | 1540 | 415 | 352 | 490 |
| 15.75 | 331.37 | 221.84 | 495.00 | 1322 | 1118 | 1563 | 421 | 356 | 497 |
| 16.00 | 341.70 | 228.06 | 511.94 | 1339 | 1131 | 1585 | 426 | 360 | 504 |
| 16.25 | 352.13 | 234.34 | 529.12 | 1356 | 1144 | 1607 | 432 | 364 | 511 |
| 16.50 | 362.66 | 240.66 | 546.52 | 1372 | 1157 | 1628 | 437 | 368 | 518 |
| 16.75 | 373.31 | 247.02 | 564.15 | 1389 | 1169 | 1650 | 442 | 372 | 525 |
| 17.00 | 384.05 | 253.43 | 582.01 | 1406 | 1182 | 1672 | 447 | 376 | 532 |
| 17.25 | 394.90 | 259.88 | 600.08 | 1422 | 1194 | 1693 | 453 | 380 | 539 |
| 17.50 | 405.85 | 266.36 | 618.37 | 1438 | 1207 | 1715 | 458 | 384 | 546 |
| 17.75 | 416.90 | 272.89 | 636.88 | 1455 | 1219 | 1736 | 463 | 388 | 553 |
| 18.00 | 428.04 | 279.46 | 655.61 | 1471 | 1231 | 1757 | 468 | 392 | 559 |
| 18.25 | 439.28 | 286.07 | 674.54 | 1487 | 1243 | 1778 | 473 | 396 | 566 |
| 18.50 | 450.61 | 292.71 | 693.68 | 1503 | 1255 | 1799 | 478 | 399 | 573 |
| 18.75 | 462.03 | 299.39 | 713.03 | 1518 | 1267 | 1820 | 483 | 403 | 579 |
| 19.00 | 473.55 | 306.11 | 732.59 | 1534 | 1279 | 1840 | 488 | 407 | 586 |
| 19.25 | 485.15 | 312.86 | 752.34 | 1550 | 1290 | 1861 | 493 | 411 | 592 |

| *Combretum erythrophyllum* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Age | Sequestrated carbon (kg) | | | Stem circumference (mm) | | | Stem diameter (mm) | | |
| (years) | Mean | L | U | Mean | L | U | Mean | L | U |
| 19.50 | 496.85 | 319.64 | 772.29 | 1565 | 1302 | 1881 | 498 | 414 | 599 |
| 19.75 | 508.63 | 326.46 | 792.44 | 1580 | 1313 | 1902 | 503 | 418 | 605 |
| 20.00 | 520.49 | 333.31 | 812.79 | 1596 | 1325 | 1922 | 508 | 422 | 612 |
| 20.25 | 532.44 | 340.20 | 833.33 | 1611 | 1336 | 1942 | 513 | 425 | 618 |
| 20.50 | 544.48 | 347.11 | 854.06 | 1626 | 1348 | 1962 | 518 | 429 | 624 |
| 20.75 | 556.59 | 354.06 | 874.97 | 1641 | 1359 | 1982 | 522 | 432 | 631 |
| 21.00 | 568.78 | 361.03 | 896.08 | 1656 | 1370 | 2002 | 527 | 436 | 637 |
| 21.25 | 581.06 | 368.04 | 917.36 | 1671 | 1381 | 2021 | 532 | 440 | 643 |
| 21.50 | 593.41 | 375.07 | 938.83 | 1685 | 1392 | 2041 | 536 | 443 | 650 |
| 21.75 | 605.84 | 382.14 | 960.48 | 1700 | 1403 | 2060 | 541 | 446 | 656 |
| 22.00 | 618.34 | 389.23 | 982.31 | 1715 | 1413 | 2080 | 546 | 450 | 662 |
| 22.25 | 630.92 | 396.35 | 1004.32 | 1729 | 1424 | 2099 | 550 | 453 | 668 |
| 22.50 | 643.57 | 403.49 | 1026.50 | 1743 | 1435 | 2118 | 555 | 457 | 674 |
| 22.75 | 656.29 | 410.66 | 1048.85 | 1758 | 1445 | 2137 | 559 | 460 | 680 |
| 23.00 | 669.09 | 417.86 | 1071.37 | 1772 | 1456 | 2156 | 564 | 463 | 686 |
| 23.25 | 681.96 | 425.08 | 1094.06 | 1786 | 1466 | 2175 | 569 | 467 | 692 |
| 23.50 | 694.89 | 432.33 | 1116.92 | 1800 | 1477 | 2194 | 573 | 470 | 698 |
| 23.75 | 707.89 | 439.60 | 1139.94 | 1814 | 1487 | 2213 | 577 | 473 | 704 |
| 24.00 | 720.97 | 446.89 | 1163.13 | 1828 | 1497 | 2232 | 582 | 477 | 710 |
| 24.25 | 734.10 | 454.21 | 1186.48 | 1842 | 1508 | 2250 | 586 | 480 | 716 |
| 24.50 | 747.31 | 461.55 | 1209.99 | 1856 | 1518 | 2269 | 591 | 483 | 722 |
| 24.75 | 760.57 | 468.91 | 1233.65 | 1869 | 1528 | 2287 | 595 | 486 | 728 |
| 25.00 | 773.91 | 476.29 | 1257.48 | 1883 | 1538 | 2305 | 599 | 489 | 734 |
| 25.25 | 787.30 | 483.70 | 1281.46 | 1896 | 1548 | 2324 | 604 | 493 | 740 |
| 25.50 | 800.76 | 491.13 | 1305.59 | 1910 | 1557 | 2342 | 608 | 496 | 745 |
| 25.75 | 814.27 | 498.57 | 1329.88 | 1923 | 1567 | 2360 | 612 | 499 | 751 |
| 26.00 | 827.85 | 506.04 | 1354.31 | 1937 | 1577 | 2378 | 616 | 502 | 757 |
| 26.25 | 841.49 | 513.53 | 1378.90 | 1950 | 1587 | 2396 | 621 | 505 | 763 |
| 26.50 | 855.18 | 521.03 | 1403.63 | 1963 | 1596 | 2414 | 625 | 508 | 768 |
| 26.75 | 868.94 | 528.56 | 1428.50 | 1976 | 1606 | 2431 | 629 | 511 | 774 |
| 27.00 | 882.75 | 536.10 | 1453.53 | 1989 | 1615 | 2449 | 633 | 514 | 780 |
| 27.25 | 896.61 | 543.67 | 1478.69 | 2002 | 1625 | 2467 | 637 | 517 | 785 |
| 27.50 | 910.54 | 551.25 | 1504.00 | 2015 | 1634 | 2484 | 641 | 520 | 791 |
| 27.75 | 924.51 | 558.84 | 1529.45 | 2028 | 1644 | 2502 | 645 | 523 | 796 |
| 28.00 | 938.54 | 566.46 | 1555.03 | 2041 | 1653 | 2519 | 650 | 526 | 802 |
| 28.25 | 952.63 | 574.09 | 1580.75 | 2053 | 1662 | 2536 | 654 | 529 | 807 |
| 28.50 | 966.77 | 581.74 | 1606.61 | 2066 | 1671 | 2554 | 658 | 532 | 813 |
| 28.75 | 980.95 | 589.41 | 1632.61 | 2079 | 1681 | 2571 | 662 | 535 | 818 |
| 29.00 | 995.20 | 597.09 | 1658.74 | 2091 | 1690 | 2588 | 666 | 538 | 824 |
| 29.25 | 1009.49 | 604.79 | 1684.99 | 2104 | 1699 | 2605 | 670 | 541 | 829 |
| 29.50 | 1023.83 | 612.50 | 1711.39 | 2116 | 1708 | 2622 | 674 | 544 | 835 |
| 29.75 | 1038.22 | 620.23 | 1737.91 | 2128 | 1717 | 2639 | 677 | 546 | 840 |
| 30.00 | 1052.66 | 627.97 | 1764.55 | 2141 | 1726 | 2655 | 681 | 549 | 845 |
| 30.25 | 1067.15 | 635.73 | 1791.33 | 2153 | 1735 | 2672 | 685 | 552 | 851 |
| 30.50 | 1081.68 | 643.50 | 1818.23 | 2165 | 1743 | 2689 | 689 | 555 | 856 |
| 30.75 | 1096.26 | 651.29 | 1845.26 | 2177 | 1752 | 2705 | 693 | 558 | 861 |
| 31.00 | 1110.89 | 659.09 | 1872.41 | 2189 | 1761 | 2722 | 697 | 560 | 866 |
| 31.25 | 1125.56 | 666.90 | 1899.68 | 2201 | 1769 | 2738 | 701 | 563 | 872 |
| 31.50 | 1140.28 | 674.73 | 1927.07 | 2213 | 1778 | 2755 | 705 | 566 | 877 |
| 31.75 | 1155.05 | 682.57 | 1954.58 | 2225 | 1787 | 2771 | 708 | 569 | 882 |
| 32.00 | 1169.86 | 690.42 | 1982.22 | 2237 | 1795 | 2788 | 712 | 571 | 887 |

| *Combretum erythrophyllum* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Age | Sequestrated carbon (kg) | | | Stem circumference (mm) | | | Stem diameter (mm) | | |
| (years) | Mean | L | U | Mean | L | U | Mean | L | U |
| 32.25 | 1184.71 | 698.28 | 2009.97 | 2249 | 1804 | 2804 | 716 | 574 | 892 |
| 32.50 | 1199.60 | 706.16 | 2037.83 | 2261 | 1812 | 2820 | 720 | 577 | 898 |
| 32.75 | 1214.54 | 714.05 | 2065.82 | 2272 | 1821 | 2836 | 723 | 580 | 903 |
| 33.00 | 1229.52 | 721.95 | 2093.91 | 2284 | 1829 | 2852 | 727 | 582 | 908 |
| 33.25 | 1244.54 | 729.87 | 2122.13 | 2296 | 1837 | 2868 | 731 | 585 | 913 |
| 33.50 | 1259.60 | 737.79 | 2150.45 | 2307 | 1846 | 2884 | 734 | 587 | 918 |
| 33.75 | 1274.70 | 745.73 | 2178.88 | 2319 | 1854 | 2900 | 738 | 590 | 923 |
| 34.00 | 1289.84 | 753.68 | 2207.43 | 2330 | 1862 | 2916 | 742 | 593 | 928 |
| 34.25 | 1305.02 | 761.64 | 2236.09 | 2341 | 1870 | 2931 | 745 | 595 | 933 |
| 34.50 | 1320.24 | 769.60 | 2264.85 | 2353 | 1878 | 2947 | 749 | 598 | 938 |
| 34.75 | 1335.50 | 777.58 | 2293.72 | 2364 | 1887 | 2963 | 753 | 601 | 943 |
| 35.00 | 1350.80 | 785.57 | 2322.70 | 2375 | 1895 | 2978 | 756 | 603 | 948 |
| 35.25 | 1366.13 | 793.57 | 2351.78 | 2387 | 1903 | 2994 | 760 | 606 | 953 |
| 35.50 | 1381.50 | 801.58 | 2380.97 | 2398 | 1911 | 3009 | 763 | 608 | 958 |
| 35.75 | 1396.91 | 809.60 | 2410.26 | 2409 | 1919 | 3024 | 767 | 611 | 963 |
| 36.00 | 1412.35 | 817.63 | 2439.66 | 2420 | 1927 | 3040 | 770 | 613 | 968 |
| 36.25 | 1427.83 | 825.67 | 2469.16 | 2431 | 1934 | 3055 | 774 | 616 | 972 |
| 36.50 | 1443.35 | 833.72 | 2498.75 | 2442 | 1942 | 3070 | 777 | 618 | 977 |
| 36.75 | 1458.90 | 841.77 | 2528.45 | 2453 | 1950 | 3085 | 781 | 621 | 982 |
| 37.00 | 1474.48 | 849.84 | 2558.25 | 2464 | 1958 | 3101 | 784 | 623 | 987 |
| 37.25 | 1490.10 | 857.92 | 2588.15 | 2475 | 1966 | 3116 | 788 | 626 | 992 |
| 37.50 | 1505.76 | 866.00 | 2618.14 | 2485 | 1973 | 3131 | 791 | 628 | 997 |
| 37.75 | 1521.44 | 874.09 | 2648.23 | 2496 | 1981 | 3146 | 795 | 631 | 1001 |
| 38.00 | 1537.16 | 882.19 | 2678.42 | 2507 | 1989 | 3160 | 798 | 633 | 1006 |
| 38.25 | 1552.92 | 890.30 | 2708.70 | 2518 | 1996 | 3175 | 801 | 635 | 1011 |
| 38.50 | 1568.70 | 898.41 | 2739.08 | 2528 | 2004 | 3190 | 805 | 638 | 1015 |
| 38.75 | 1584.52 | 906.54 | 2769.55 | 2539 | 2011 | 3205 | 808 | 640 | 1020 |
| 39.00 | 1600.37 | 914.67 | 2800.11 | 2549 | 2019 | 3220 | 812 | 643 | 1025 |
| 39.25 | 1616.25 | 922.81 | 2830.77 | 2560 | 2026 | 3234 | 815 | 645 | 1030 |
| 39.50 | 1632.16 | 930.95 | 2861.51 | 2570 | 2034 | 3249 | 818 | 647 | 1034 |
| 39.75 | 1648.10 | 939.11 | 2892.35 | 2581 | 2041 | 3263 | 822 | 650 | 1039 |
| 40.00 | 1664.07 | 947.27 | 2923.28 | 2591 | 2048 | 3278 | 825 | 652 | 1043 |
| 40.25 | 1680.07 | 955.43 | 2954.29 | 2602 | 2056 | 3292 | 828 | 654 | 1048 |
| 40.50 | 1696.10 | 963.61 | 2985.40 | 2612 | 2063 | 3307 | 831 | 657 | 1053 |
| 40.75 | 1712.16 | 971.79 | 3016.59 | 2622 | 2070 | 3321 | 835 | 659 | 1057 |
| 41.00 | 1728.25 | 979.98 | 3047.87 | 2633 | 2078 | 3336 | 838 | 661 | 1062 |
| 41.25 | 1744.37 | 988.17 | 3079.23 | 2643 | 2085 | 3350 | 841 | 664 | 1066 |
| 41.50 | 1760.51 | 996.37 | 3110.68 | 2653 | 2092 | 3364 | 844 | 666 | 1071 |
| 41.75 | 1776.68 | 1004.58 | 3142.22 | 2663 | 2099 | 3378 | 848 | 668 | 1075 |
| 42.00 | 1792.89 | 1012.79 | 3173.83 | 2673 | 2106 | 3392 | 851 | 671 | 1080 |
| 42.25 | 1809.11 | 1021.01 | 3205.54 | 2683 | 2114 | 3406 | 854 | 673 | 1084 |
| 42.50 | 1825.37 | 1029.24 | 3237.32 | 2693 | 2121 | 3421 | 857 | 675 | 1089 |
| 42.75 | 1841.65 | 1037.47 | 3269.19 | 2703 | 2128 | 3435 | 860 | 677 | 1093 |
| 43.00 | 1857.96 | 1045.70 | 3301.14 | 2713 | 2135 | 3448 | 864 | 680 | 1098 |
| 43.25 | 1874.29 | 1053.95 | 3333.16 | 2723 | 2142 | 3462 | 867 | 682 | 1102 |
| 43.50 | 1890.65 | 1062.19 | 3365.27 | 2733 | 2149 | 3476 | 870 | 684 | 1107 |
| 43.75 | 1907.04 | 1070.45 | 3397.46 | 2743 | 2156 | 3490 | 873 | 686 | 1111 |
| 44.00 | 1923.45 | 1078.71 | 3429.73 | 2753 | 2163 | 3504 | 876 | 688 | 1115 |
| 44.25 | 1939.89 | 1086.97 | 3462.07 | 2763 | 2169 | 3518 | 879 | 691 | 1120 |
| 44.50 | 1956.35 | 1095.24 | 3494.49 | 2772 | 2176 | 3531 | 882 | 693 | 1124 |
| 44.75 | 1972.83 | 1103.51 | 3526.99 | 2782 | 2183 | 3545 | 886 | 695 | 1128 |

| *Combretum erythrophyllum* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Age** | **Sequestrated carbon (kg)** | | | **Stem circumference (mm)** | | | **Stem diameter (mm)** | | |
| **(years)** | **Mean** | **L** | **U** | **Mean** | **L** | **U** | **Mean** | **L** | **U** |
| 45.00 | 1989.34 | 1111.79 | 3559.57 | 2792 | 2190 | 3559 | 889 | 697 | 1133 |
| 45.25 | 2005.88 | 1120.07 | 3592.22 | 2801 | 2197 | 3572 | 892 | 699 | 1137 |
| 45.50 | 2022.43 | 1128.36 | 3624.95 | 2811 | 2204 | 3586 | 895 | 701 | 1141 |
| 45.75 | 2039.02 | 1136.65 | 3657.75 | 2821 | 2210 | 3599 | 898 | 704 | 1146 |
| 46.00 | 2055.62 | 1144.95 | 3690.62 | 2830 | 2217 | 3613 | 901 | 706 | 1150 |
| 46.25 | 2072.25 | 1153.25 | 3723.57 | 2840 | 2224 | 3626 | 904 | 708 | 1154 |
| 46.50 | 2088.90 | 1161.55 | 3756.59 | 2849 | 2230 | 3640 | 907 | 710 | 1159 |
| 46.75 | 2105.57 | 1169.86 | 3789.69 | 2859 | 2237 | 3653 | 910 | 712 | 1163 |
| 47.00 | 2122.26 | 1178.18 | 3822.85 | 2868 | 2244 | 3666 | 913 | 714 | 1167 |
| 47.25 | 2138.98 | 1186.50 | 3856.09 | 2877 | 2250 | 3679 | 916 | 716 | 1171 |
| 47.50 | 2155.72 | 1194.82 | 3889.40 | 2887 | 2257 | 3693 | 919 | 718 | 1175 |

# Table Appendix A 6.1b. Species: *Rhus lancea*

| ***Rhus lancea*** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Age** | **Sequestrated carbon (kg)** | | | **Stem circumference (mm)** | | | **Stem diameter (mm)** | | |
| **(years)** | **Mean** | **L** | **U** | **Mean** | **L** | **U** | **Mean** | **L** | **U** |
| 1.00 | 0.34 | 0.25 | 0.47 | 75 | 65 | 86 | 24 | 21 | 27 |
| 1.25 | 0.65 | 0.50 | 0.86 | 98 | 88 | 110 | 31 | 28 | 35 |
| 1.50 | 1.09 | 0.87 | 1.38 | 122 | 111 | 134 | 39 | 35 | 43 |
| 1.75 | 1.65 | 1.35 | 2.02 | 145 | 133 | 158 | 46 | 42 | 50 |
| 2.00 | 2.33 | 1.95 | 2.79 | 167 | 155 | 180 | 53 | 49 | 57 |
| 2.25 | 3.13 | 2.67 | 3.68 | 189 | 177 | 202 | 60 | 56 | 64 |
| 2.50 | 4.05 | 3.50 | 4.68 | 210 | 198 | 224 | 67 | 63 | 71 |
| 2.75 | 5.07 | 4.43 | 5.79 | 231 | 218 | 244 | 74 | 70 | 78 |
| 3.00 | 6.18 | 5.46 | 7.01 | 251 | 238 | 265 | 80 | 76 | 84 |
| 3.25 | 7.40 | 6.57 | 8.33 | 271 | 257 | 284 | 86 | 82 | 91 |
| 3.50 | 8.70 | 7.76 | 9.76 | 290 | 276 | 304 | 92 | 88 | 97 |
| 3.75 | 10.09 | 9.02 | 11.28 | 308 | 294 | 323 | 98 | 94 | 103 |
| 4.00 | 11.56 | 10.35 | 12.91 | 326 | 311 | 341 | 104 | 99 | 109 |
| 4.25 | 13.10 | 11.73 | 14.62 | 343 | 328 | 360 | 109 | 104 | 114 |
| 4.50 | 14.71 | 13.16 | 16.43 | 360 | 344 | 377 | 115 | 110 | 120 |
| 4.75 | 16.38 | 14.64 | 18.33 | 377 | 360 | 395 | 120 | 114 | 126 |
| 5.00 | 18.12 | 16.16 | 20.31 | 393 | 375 | 412 | 125 | 119 | 131 |
| 5.25 | 19.91 | 17.72 | 22.37 | 409 | 390 | 429 | 130 | 124 | 137 |
| 5.50 | 21.76 | 19.31 | 24.51 | 424 | 404 | 446 | 135 | 129 | 142 |
| 5.75 | 23.65 | 20.94 | 26.72 | 439 | 418 | 462 | 140 | 133 | 147 |
| 6.00 | 25.60 | 22.59 | 29.01 | 454 | 431 | 478 | 145 | 137 | 152 |
| 6.25 | 27.59 | 24.27 | 31.36 | 469 | 444 | 494 | 149 | 141 | 157 |
| 6.50 | 29.62 | 25.98 | 33.77 | 483 | 457 | 510 | 154 | 145 | 162 |
| 6.75 | 31.69 | 27.71 | 36.25 | 496 | 469 | 525 | 158 | 149 | 167 |
| 7.00 | 33.80 | 29.46 | 38.79 | 510 | 482 | 540 | 162 | 153 | 172 |
| 7.25 | 35.95 | 31.23 | 41.38 | 523 | 493 | 555 | 167 | 157 | 177 |
| 7.50 | 38.13 | 33.02 | 44.02 | 536 | 505 | 569 | 171 | 161 | 181 |
| 7.75 | 40.34 | 34.83 | 46.72 | 549 | 516 | 584 | 175 | 164 | 186 |
| 8.00 | 42.58 | 36.65 | 49.46 | 562 | 527 | 598 | 179 | 168 | 190 |
| 8.25 | 44.85 | 38.49 | 52.25 | 574 | 538 | 612 | 183 | 171 | 195 |
| 8.50 | 47.14 | 40.34 | 55.09 | 586 | 549 | 625 | 186 | 175 | 199 |
| 8.75 | 49.46 | 42.21 | 57.97 | 598 | 559 | 639 | 190 | 178 | 203 |
| 9.00 | 51.81 | 44.08 | 60.89 | 609 | 570 | 652 | 194 | 181 | 207 |
| 9.25 | 54.18 | 45.97 | 63.84 | 621 | 580 | 665 | 198 | 185 | 212 |
| 9.50 | 56.56 | 47.87 | 66.84 | 632 | 590 | 678 | 201 | 188 | 216 |
| 9.75 | 58.97 | 49.78 | 69.87 | 643 | 599 | 690 | 205 | 191 | 220 |
| 10.00 | 61.40 | 51.69 | 72.93 | 654 | 609 | 703 | 208 | 194 | 224 |
| 10.25 | 63.85 | 53.62 | 76.03 | 665 | 618 | 715 | 212 | 197 | 228 |
| 10.50 | 66.31 | 55.55 | 79.16 | 676 | 627 | 727 | 215 | 200 | 232 |
| 10.75 | 68.79 | 57.49 | 82.32 | 686 | 636 | 739 | 218 | 203 | 235 |
| 11.00 | 71.29 | 59.43 | 85.51 | 696 | 645 | 751 | 222 | 205 | 239 |
| 11.25 | 73.80 | 61.38 | 88.73 | 706 | 654 | 763 | 225 | 208 | 243 |
| 11.50 | 76.33 | 63.34 | 91.97 | 716 | 663 | 774 | 228 | 211 | 246 |
| 11.75 | 78.86 | 65.30 | 95.24 | 726 | 671 | 786 | 231 | 214 | 250 |
| 12.00 | 81.41 | 67.27 | 98.54 | 736 | 680 | 797 | 234 | 216 | 254 |
| 12.25 | 83.98 | 69.24 | 101.85 | 745 | 688 | 808 | 237 | 219 | 257 |
| 12.50 | 86.55 | 71.21 | 105.19 | 755 | 696 | 819 | 240 | 222 | 261 |
| 12.75 | 89.14 | 73.19 | 108.56 | 764 | 704 | 830 | 243 | 224 | 264 |

*Rhus lancea*

| Age | Sequestrated carbon (kg) | | | Stem circumference (mm) | | | Stem diameter (mm) | | |
|---|---|---|---|---|---|---|---|---|---|
| (years) | Mean | L | U | Mean | L | U | Mean | L | U |
| 13.00 | 91.73 | 75.17 | 111.94 | 773 | 712 | 840 | 246 | 227 | 268 |
| 13.25 | 94.34 | 77.16 | 115.34 | 783 | 720 | 851 | 249 | 229 | 271 |
| 13.50 | 96.95 | 79.14 | 118.77 | 792 | 727 | 861 | 252 | 231 | 274 |
| 13.75 | 99.57 | 81.13 | 122.21 | 800 | 735 | 872 | 255 | 234 | 277 |
| 14.00 | 102.20 | 83.12 | 125.67 | 809 | 742 | 882 | 258 | 236 | 281 |
| 14.25 | 104.84 | 85.11 | 129.15 | 818 | 750 | 892 | 260 | 239 | 284 |
| 14.50 | 107.49 | 87.11 | 132.64 | 826 | 757 | 902 | 263 | 241 | 287 |
| 14.75 | 110.14 | 89.10 | 136.15 | 835 | 764 | 912 | 266 | 243 | 290 |
| 15.00 | 112.80 | 91.10 | 139.68 | 843 | 771 | 922 | 268 | 245 | 293 |
| 15.25 | 115.47 | 93.09 | 143.22 | 851 | 778 | 931 | 271 | 248 | 296 |
| 15.50 | 118.14 | 95.09 | 146.78 | 860 | 785 | 941 | 274 | 250 | 300 |
| 15.75 | 120.82 | 97.09 | 150.35 | 868 | 792 | 950 | 276 | 252 | 303 |
| 16.00 | 123.50 | 99.09 | 153.93 | 876 | 799 | 960 | 279 | 254 | 306 |
| 16.25 | 126.19 | 101.09 | 157.53 | 883 | 805 | 969 | 281 | 256 | 308 |
| 16.50 | 128.88 | 103.08 | 161.13 | 891 | 812 | 978 | 284 | 258 | 311 |
| 16.75 | 131.58 | 105.08 | 164.75 | 899 | 819 | 987 | 286 | 261 | 314 |
| 17.00 | 134.28 | 107.08 | 168.39 | 907 | 825 | 996 | 289 | 263 | 317 |
| 17.25 | 136.98 | 109.08 | 172.03 | 914 | 831 | 1005 | 291 | 265 | 320 |
| 17.50 | 139.69 | 111.08 | 175.68 | 922 | 838 | 1014 | 293 | 267 | 323 |
| 17.75 | 142.40 | 113.07 | 179.34 | 929 | 844 | 1023 | 296 | 269 | 326 |
| 18.00 | 145.12 | 115.07 | 183.02 | 937 | 850 | 1032 | 298 | 271 | 328 |
| 18.25 | 147.84 | 117.06 | 186.70 | 944 | 856 | 1040 | 300 | 273 | 331 |
| 18.50 | 150.56 | 119.06 | 190.39 | 951 | 862 | 1049 | 303 | 274 | 334 |
| 18.75 | 153.28 | 121.05 | 194.09 | 958 | 868 | 1057 | 305 | 276 | 337 |
| 19.00 | 156.01 | 123.04 | 197.80 | 965 | 874 | 1066 | 307 | 278 | 339 |
| 19.25 | 158.73 | 125.03 | 201.52 | 972 | 880 | 1074 | 309 | 280 | 342 |
| 19.50 | 161.46 | 127.02 | 205.25 | 979 | 886 | 1082 | 312 | 282 | 344 |
| 19.75 | 164.20 | 129.01 | 208.98 | 986 | 892 | 1090 | 314 | 284 | 347 |
| 20.00 | 166.93 | 131.00 | 212.72 | 993 | 897 | 1099 | 316 | 286 | 350 |
| 20.25 | 169.67 | 132.98 | 216.47 | 1000 | 903 | 1107 | 318 | 287 | 352 |
| 20.50 | 172.40 | 134.96 | 220.22 | 1006 | 909 | 1115 | 320 | 289 | 355 |
| 20.75 | 175.14 | 136.95 | 223.98 | 1013 | 914 | 1122 | 322 | 291 | 357 |
| 21.00 | 177.88 | 138.93 | 227.75 | 1020 | 920 | 1130 | 325 | 293 | 360 |
| 21.25 | 180.62 | 140.90 | 231.52 | 1026 | 925 | 1138 | 327 | 294 | 362 |
| 21.50 | 183.36 | 142.88 | 235.30 | 1033 | 930 | 1146 | 329 | 296 | 365 |
| 21.75 | 186.10 | 144.86 | 239.09 | 1039 | 936 | 1153 | 331 | 298 | 367 |
| 22.00 | 188.84 | 146.83 | 242.88 | 1045 | 941 | 1161 | 333 | 300 | 370 |
| 22.25 | 191.58 | 148.80 | 246.67 | 1052 | 946 | 1169 | 335 | 301 | 372 |
| 22.50 | 194.33 | 150.77 | 250.47 | 1058 | 952 | 1176 | 337 | 303 | 374 |
| 22.75 | 197.07 | 152.74 | 254.28 | 1064 | 957 | 1183 | 339 | 305 | 377 |
| 23.00 | 199.81 | 154.70 | 258.08 | 1070 | 962 | 1191 | 341 | 306 | 379 |
| 23.25 | 202.56 | 156.66 | 261.90 | 1076 | 967 | 1198 | 343 | 308 | 381 |
| 23.50 | 205.30 | 158.62 | 265.72 | 1082 | 972 | 1205 | 345 | 309 | 384 |
| 23.75 | 208.04 | 160.58 | 269.54 | 1088 | 977 | 1213 | 346 | 311 | 386 |
| 24.00 | 210.79 | 162.54 | 273.36 | 1094 | 982 | 1220 | 348 | 313 | 388 |
| 24.25 | 213.53 | 164.49 | 277.19 | 1100 | 987 | 1227 | 350 | 314 | 391 |
| 24.50 | 216.27 | 166.44 | 281.02 | 1106 | 992 | 1234 | 352 | 316 | 393 |
| 24.75 | 219.02 | 168.39 | 284.86 | 1112 | 997 | 1241 | 354 | 317 | 395 |
| 25.00 | 221.76 | 170.34 | 288.70 | 1118 | 1001 | 1248 | 356 | 319 | 397 |
| 25.25 | 224.50 | 172.28 | 292.54 | 1124 | 1006 | 1255 | 358 | 320 | 399 |
| 25.50 | 227.24 | 174.23 | 296.39 | 1129 | 1011 | 1262 | 359 | 322 | 402 |

| *Rhus lancea* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Age** | **Sequestrated carbon (kg)** | | | **Stem circumference (mm)** | | | **Stem diameter (mm)** | | |
| **(years)** | **Mean** | **L** | **U** | **Mean** | **L** | **U** | **Mean** | **L** | **U** |
| 25.75 | 229.98 | 176.17 | 300.23 | 1135 | 1015 | 1268 | 361 | 323 | 404 |
| 26.00 | 232.72 | 178.10 | 304.08 | 1141 | 1020 | 1275 | 363 | 325 | 406 |
| 26.25 | 235.46 | 180.04 | 307.94 | 1146 | 1025 | 1282 | 365 | 326 | 408 |
| 26.50 | 238.19 | 181.97 | 311.79 | 1152 | 1029 | 1289 | 367 | 328 | 410 |
| 26.75 | 240.93 | 183.90 | 315.65 | 1157 | 1034 | 1295 | 368 | 329 | 412 |
| 27.00 | 243.67 | 185.83 | 319.51 | 1163 | 1038 | 1302 | 370 | 331 | 414 |
| 27.25 | 246.40 | 187.75 | 323.37 | 1168 | 1043 | 1308 | 372 | 332 | 416 |
| 27.50 | 249.13 | 189.68 | 327.23 | 1173 | 1047 | 1315 | 374 | 333 | 419 |
| 27.75 | 251.87 | 191.60 | 331.10 | 1179 | 1052 | 1321 | 375 | 335 | 421 |
| 28.00 | 254.60 | 193.51 | 334.96 | 1184 | 1056 | 1328 | 377 | 336 | 423 |
| 28.25 | 257.33 | 195.43 | 338.83 | 1189 | 1060 | 1334 | 379 | 338 | 425 |
| 28.50 | 260.06 | 197.34 | 342.70 | 1195 | 1065 | 1340 | 380 | 339 | 427 |
| 28.75 | 262.78 | 199.25 | 346.57 | 1200 | 1069 | 1347 | 382 | 340 | 429 |
| 29.00 | 265.51 | 201.16 | 350.45 | 1205 | 1073 | 1353 | 384 | 342 | 431 |
| 29.25 | 268.23 | 203.06 | 354.32 | 1210 | 1077 | 1359 | 385 | 343 | 433 |
| 29.50 | 270.96 | 204.96 | 358.19 | 1215 | 1082 | 1365 | 387 | 344 | 435 |
| 29.75 | 273.68 | 206.86 | 362.07 | 1220 | 1086 | 1371 | 388 | 346 | 437 |
| 30.00 | 276.40 | 208.76 | 365.95 | 1225 | 1090 | 1378 | 390 | 347 | 438 |
| 30.25 | 279.12 | 210.66 | 369.82 | 1230 | 1094 | 1384 | 392 | 348 | 440 |
| 30.50 | 281.83 | 212.55 | 373.70 | 1235 | 1098 | 1390 | 393 | 350 | 442 |
| 30.75 | 284.55 | 214.44 | 377.58 | 1240 | 1102 | 1396 | 395 | 351 | 444 |
| 31.00 | 287.26 | 216.32 | 381.46 | 1245 | 1106 | 1402 | 396 | 352 | 446 |
| 31.25 | 289.97 | 218.21 | 385.34 | 1250 | 1110 | 1408 | 398 | 353 | 448 |
| 31.50 | 292.68 | 220.09 | 389.22 | 1255 | 1114 | 1413 | 399 | 355 | 450 |
| 31.75 | 295.39 | 221.97 | 393.10 | 1260 | 1118 | 1419 | 401 | 356 | 452 |
| 32.00 | 298.10 | 223.84 | 396.98 | 1265 | 1122 | 1425 | 403 | 357 | 454 |
| 32.25 | 300.80 | 225.72 | 400.87 | 1269 | 1126 | 1431 | 404 | 358 | 455 |
| 32.50 | 303.50 | 227.59 | 404.75 | 1274 | 1130 | 1437 | 406 | 360 | 457 |

## Table Appendix A 6.1c. Species: *Rhus pendulina*

| *Rhus pendulina* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Age** | **Carbon sequestrated (kg)** | | | **Stem circumference (mm)** | | | **Stem diameter (mm)** | | |
| **(years)** | **Mean** | **L** | **U** | **Mean** | **L** | **U** | **Mean** | **L** | **U** |
| 1.00 | 0.09 | 0.04 | 0.19 | 42 | 31 | 58 | 14 | 10 | 19 |
| 1.25 | 0.20 | 0.11 | 0.39 | 60 | 46 | 79 | 19 | 15 | 25 |
| 1.50 | 0.38 | 0.22 | 0.67 | 79 | 62 | 100 | 25 | 20 | 32 |
| 1.75 | 0.65 | 0.40 | 1.06 | 98 | 80 | 120 | 31 | 25 | 38 |
| 2.00 | 1.01 | 0.65 | 1.55 | 118 | 98 | 141 | 37 | 31 | 45 |
| 2.25 | 1.46 | 1.00 | 2.15 | 138 | 117 | 162 | 44 | 37 | 51 |
| 2.50 | 2.02 | 1.44 | 2.85 | 158 | 137 | 182 | 50 | 43 | 58 |
| 2.75 | 2.69 | 1.98 | 3.65 | 177 | 156 | 202 | 56 | 50 | 64 |
| 3.00 | 3.46 | 2.63 | 4.56 | 197 | 176 | 221 | 63 | 56 | 70 |
| 3.25 | 4.35 | 3.39 | 5.57 | 217 | 195 | 240 | 69 | 62 | 76 |
| 3.50 | 5.34 | 4.27 | 6.68 | 236 | 215 | 259 | 75 | 68 | 83 |
| 3.75 | 6.44 | 5.26 | 7.89 | 255 | 235 | 278 | 81 | 75 | 88 |
| 4.00 | 7.65 | 6.35 | 9.21 | 274 | 254 | 296 | 87 | 81 | 94 |
| 4.25 | 8.96 | 7.56 | 10.63 | 293 | 273 | 315 | 93 | 87 | 100 |
| 4.50 | 10.38 | 8.86 | 12.16 | 312 | 292 | 333 | 99 | 93 | 106 |
| 4.75 | 11.90 | 10.26 | 13.81 | 330 | 310 | 351 | 105 | 99 | 112 |
| 5.00 | 13.52 | 11.75 | 15.57 | 348 | 328 | 369 | 111 | 104 | 117 |
| 5.25 | 15.24 | 13.31 | 17.45 | 366 | 346 | 387 | 116 | 110 | 123 |
| 5.50 | 17.06 | 14.95 | 19.46 | 383 | 363 | 405 | 122 | 115 | 129 |
| 5.75 | 18.96 | 16.65 | 21.61 | 401 | 379 | 423 | 128 | 121 | 135 |
| 6.00 | 20.96 | 18.40 | 23.88 | 418 | 396 | 441 | 133 | 126 | 140 |
| 6.25 | 23.05 | 20.20 | 26.30 | 435 | 411 | 459 | 138 | 131 | 146 |
| 6.50 | 25.22 | 22.05 | 28.85 | 451 | 427 | 477 | 144 | 136 | 152 |
| 6.75 | 27.48 | 23.94 | 31.54 | 468 | 442 | 495 | 149 | 141 | 158 |
| 7.00 | 29.82 | 25.88 | 34.36 | 484 | 456 | 513 | 154 | 145 | 163 |
| 7.25 | 32.24 | 27.85 | 37.32 | 500 | 470 | 531 | 159 | 150 | 169 |
| 7.50 | 34.74 | 29.85 | 40.42 | 516 | 484 | 549 | 164 | 154 | 175 |
| 7.75 | 37.31 | 31.90 | 43.64 | 531 | 498 | 567 | 169 | 158 | 181 |
| 8.00 | 39.95 | 33.97 | 46.99 | 547 | 511 | 585 | 174 | 163 | 186 |
| 8.25 | 42.67 | 36.08 | 50.47 | 562 | 524 | 603 | 179 | 167 | 192 |
| 8.50 | 45.46 | 38.22 | 54.07 | 577 | 537 | 620 | 184 | 171 | 197 |
| 8.75 | 48.31 | 40.39 | 57.79 | 592 | 549 | 638 | 188 | 175 | 203 |
| 9.00 | 51.24 | 42.59 | 61.64 | 607 | 562 | 655 | 193 | 179 | 209 |
| 9.25 | 54.22 | 44.82 | 65.60 | 621 | 574 | 672 | 198 | 183 | 214 |
| 9.50 | 57.27 | 47.07 | 69.68 | 635 | 586 | 690 | 202 | 186 | 220 |
| 9.75 | 60.38 | 49.35 | 73.87 | 650 | 597 | 707 | 207 | 190 | 225 |
| 10.00 | 63.55 | 51.66 | 78.17 | 664 | 609 | 724 | 211 | 194 | 230 |
| 10.25 | 66.78 | 53.99 | 82.58 | 677 | 620 | 740 | 216 | 197 | 236 |
| 10.50 | 70.06 | 56.35 | 87.10 | 691 | 631 | 757 | 220 | 201 | 241 |
| 10.75 | 73.40 | 58.73 | 91.73 | 705 | 642 | 773 | 224 | 204 | 246 |
| 11.00 | 76.79 | 61.13 | 96.46 | 718 | 653 | 790 | 229 | 208 | 251 |
| 11.25 | 80.23 | 63.55 | 101.30 | 731 | 664 | 806 | 233 | 211 | 257 |
| 11.50 | 83.73 | 65.99 | 106.23 | 745 | 674 | 822 | 237 | 215 | 262 |
| 11.75 | 87.28 | 68.46 | 111.27 | 758 | 685 | 838 | 241 | 218 | 267 |
| 12.00 | 90.87 | 70.94 | 116.40 | 770 | 695 | 854 | 245 | 221 | 272 |
| 12.25 | 94.51 | 73.44 | 121.63 | 783 | 705 | 870 | 249 | 224 | 277 |
| 12.50 | 98.20 | 75.96 | 126.95 | 796 | 715 | 886 | 253 | 228 | 282 |
| 12.75 | 101.93 | 78.49 | 132.36 | 808 | 725 | 901 | 257 | 231 | 287 |
| 13.00 | 105.71 | 81.05 | 137.87 | 821 | 734 | 917 | 261 | 234 | 292 |

| *Rhus pendulina* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Age** | **Carbon sequestrated (kg)** | | | **Stem circumference (mm)** | | | **Stem diameter (mm)** | | |
| **(years)** | **Mean** | **L** | **U** | **Mean** | **L** | **U** | **Mean** | **L** | **U** |
| 13.25 | 109.53 | 83.61 | 143.47 | 833 | 744 | 932 | 265 | 237 | 297 |
| 13.50 | 113.39 | 86.20 | 149.15 | 845 | 754 | 947 | 269 | 240 | 302 |
| 13.75 | 117.29 | 88.80 | 154.93 | 857 | 763 | 962 | 273 | 243 | 306 |
| 14.00 | 121.23 | 91.41 | 160.78 | 869 | 772 | 977 | 277 | 246 | 311 |
| 14.25 | 125.21 | 94.04 | 166.73 | 881 | 781 | 992 | 280 | 249 | 316 |
| 14.50 | 129.23 | 96.68 | 172.75 | 892 | 791 | 1007 | 284 | 252 | 321 |
| 14.75 | 133.29 | 99.33 | 178.86 | 904 | 800 | 1022 | 288 | 255 | 325 |
| 15.00 | 137.38 | 102.00 | 185.05 | 915 | 808 | 1037 | 291 | 257 | 330 |
| 15.25 | 141.51 | 104.67 | 191.32 | 927 | 817 | 1051 | 295 | 260 | 335 |
| 15.50 | 145.68 | 107.36 | 197.66 | 938 | 826 | 1065 | 299 | 263 | 339 |

Table Appendix A 6.2. *Combretum erythrophyllum* - *Rhus lancea* combination

| ***Combretum erythrophyllum* and *Rhus lancea* combination** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Age** | **Sequestrated carbon (kg)** | | | **Stem circumference (mm)** | | | **Stem diameter (mm)** | | |
| **(years)** | **Mean** | **L** | **U** | **Mean** | **L** | **U** | **Mean** | **L** | **U** |
| 1.00 | 0.19 | 0.14 | 0.26 | 59 | 51 | 67 | 19 | 16 | 21 |
| 1.25 | 0.41 | 0.31 | 0.54 | 81 | 72 | 91 | 26 | 23 | 29 |
| 1.50 | 0.75 | 0.59 | 0.95 | 104 | 95 | 115 | 33 | 30 | 37 |
| 1.75 | 1.22 | 1.00 | 1.50 | 128 | 117 | 139 | 41 | 37 | 44 |
| 2.00 | 1.84 | 1.54 | 2.19 | 151 | 140 | 163 | 48 | 45 | 52 |
| 2.25 | 2.59 | 2.21 | 3.04 | 175 | 164 | 187 | 56 | 52 | 59 |
| 2.50 | 3.50 | 3.03 | 4.04 | 198 | 187 | 210 | 63 | 59 | 67 |
| 2.75 | 4.56 | 4.00 | 5.20 | 221 | 209 | 234 | 70 | 67 | 74 |
| 3.00 | 5.77 | 5.10 | 6.52 | 244 | 232 | 257 | 78 | 74 | 82 |
| 3.25 | 7.12 | 6.34 | 8.00 | 266 | 254 | 279 | 85 | 81 | 89 |
| 3.50 | 8.61 | 7.70 | 9.64 | 288 | 275 | 302 | 92 | 88 | 96 |
| 3.75 | 10.25 | 9.19 | 11.44 | 310 | 296 | 324 | 99 | 94 | 103 |
| 4.00 | 12.02 | 10.78 | 13.40 | 331 | 317 | 347 | 105 | 101 | 110 |
| 4.25 | 13.92 | 12.49 | 15.53 | 352 | 337 | 369 | 112 | 107 | 117 |
| 4.50 | 15.96 | 14.29 | 17.81 | 373 | 356 | 390 | 119 | 113 | 124 |
| 4.75 | 18.11 | 16.19 | 20.26 | 393 | 375 | 412 | 125 | 119 | 131 |
| 5.00 | 20.39 | 18.18 | 22.86 | 413 | 394 | 433 | 131 | 125 | 138 |
| 5.25 | 22.78 | 20.25 | 25.61 | 433 | 412 | 454 | 138 | 131 | 145 |
| 5.50 | 25.28 | 22.41 | 28.51 | 452 | 430 | 475 | 144 | 137 | 151 |
| 5.75 | 27.89 | 24.64 | 31.56 | 471 | 447 | 496 | 150 | 142 | 158 |
| 6.00 | 30.60 | 26.95 | 34.75 | 489 | 464 | 516 | 156 | 148 | 164 |
| 6.25 | 33.42 | 29.32 | 38.08 | 508 | 481 | 536 | 162 | 153 | 171 |
| 6.50 | 36.33 | 31.76 | 41.54 | 526 | 497 | 556 | 167 | 158 | 177 |
| 6.75 | 39.33 | 34.27 | 45.14 | 543 | 513 | 575 | 173 | 163 | 183 |
| 7.00 | 42.42 | 36.83 | 48.86 | 561 | 529 | 595 | 178 | 168 | 189 |
| 7.25 | 45.60 | 39.46 | 52.71 | 578 | 544 | 614 | 184 | 173 | 195 |
| 7.50 | 48.87 | 42.14 | 56.67 | 595 | 559 | 633 | 189 | 178 | 201 |
| 7.75 | 52.22 | 44.87 | 60.76 | 611 | 574 | 651 | 195 | 183 | 207 |
| 8.00 | 55.64 | 47.66 | 64.96 | 628 | 589 | 670 | 200 | 187 | 213 |
| 8.25 | 59.14 | 50.49 | 69.27 | 644 | 603 | 688 | 205 | 192 | 219 |
| 8.50 | 62.71 | 53.37 | 73.68 | 660 | 617 | 706 | 210 | 196 | 225 |
| 8.75 | 66.35 | 56.30 | 78.21 | 676 | 631 | 724 | 215 | 201 | 230 |
| 9.00 | 70.06 | 59.26 | 82.83 | 691 | 645 | 741 | 220 | 205 | 236 |
| 9.25 | 73.84 | 62.27 | 87.56 | 707 | 658 | 759 | 225 | 209 | 241 |
| 9.50 | 77.68 | 65.32 | 92.38 | 722 | 671 | 776 | 230 | 214 | 247 |
| 9.75 | 81.58 | 68.41 | 97.29 | 737 | 684 | 793 | 234 | 218 | 252 |
| 10.00 | 85.55 | 71.53 | 102.30 | 751 | 697 | 809 | 239 | 222 | 258 |
| 10.25 | 89.56 | 74.69 | 107.40 | 766 | 710 | 826 | 244 | 226 | 263 |
| 10.50 | 93.64 | 77.88 | 112.58 | 780 | 722 | 842 | 248 | 230 | 268 |
| 10.75 | 97.77 | 81.11 | 117.85 | 794 | 735 | 859 | 253 | 234 | 273 |
| 11.00 | 101.95 | 84.36 | 123.20 | 808 | 747 | 875 | 257 | 238 | 278 |
| 11.25 | 106.18 | 87.65 | 128.63 | 822 | 759 | 891 | 262 | 242 | 283 |
| 11.50 | 110.46 | 90.96 | 134.14 | 836 | 771 | 906 | 266 | 245 | 288 |
| 11.75 | 114.79 | 94.30 | 139.73 | 849 | 782 | 922 | 270 | 249 | 293 |
| 12.00 | 119.17 | 97.67 | 145.39 | 863 | 794 | 937 | 275 | 253 | 298 |

***Combretum erythrophyllum*** **and** ***Rhus lancea*** **combination**

| Age | Sequestrated carbon (kg) | | | Stem circumference (mm) | | | Stem diameter (mm) | | |
|---|---|---|---|---|---|---|---|---|---|
| (years) | Mean | L | U | Mean | L | U | Mean | L | U |
| 12.25 | 123.59 | 101.07 | 151.12 | 876 | 805 | 953 | 279 | 256 | 303 |
| 12.50 | 128.05 | 104.49 | 156.93 | 889 | 817 | 968 | 283 | 260 | 308 |
| 12.75 | 132.55 | 107.93 | 162.80 | 902 | 828 | 983 | 287 | 263 | 313 |
| 13.00 | 137.10 | 111.39 | 168.74 | 915 | 839 | 997 | 291 | 267 | 317 |
| 13.25 | 141.69 | 114.88 | 174.75 | 927 | 850 | 1012 | 295 | 270 | 322 |
| 13.50 | 146.31 | 118.39 | 180.82 | 940 | 860 | 1027 | 299 | 274 | 327 |
| 13.75 | 150.97 | 121.92 | 186.95 | 952 | 871 | 1041 | 303 | 277 | 331 |
| 14.00 | 155.67 | 125.47 | 193.14 | 964 | 881 | 1055 | 307 | 281 | 336 |
| 14.25 | 160.40 | 129.03 | 199.40 | 977 | 892 | 1069 | 311 | 284 | 340 |
| 14.50 | 165.17 | 132.62 | 205.71 | 989 | 902 | 1083 | 315 | 287 | 345 |
| 14.75 | 169.97 | 136.22 | 212.08 | 1000 | 912 | 1097 | 318 | 290 | 349 |
| 15.00 | 174.80 | 139.84 | 218.50 | 1012 | 922 | 1111 | 322 | 294 | 354 |
| 15.25 | 179.67 | 143.48 | 224.98 | 1024 | 932 | 1125 | 326 | 297 | 358 |
| 15.50 | 184.56 | 147.13 | 231.51 | 1035 | 942 | 1138 | 330 | 300 | 362 |
| 15.75 | 189.49 | 150.80 | 238.10 | 1047 | 952 | 1151 | 333 | 303 | 367 |
| 16.00 | 194.44 | 154.48 | 244.73 | 1058 | 961 | 1165 | 337 | 306 | 371 |
| 16.25 | 199.42 | 158.18 | 251.42 | 1069 | 971 | 1178 | 340 | 309 | 375 |
| 16.50 | 204.43 | 161.89 | 258.15 | 1080 | 980 | 1191 | 344 | 312 | 379 |
| 16.75 | 209.47 | 165.61 | 264.93 | 1092 | 990 | 1204 | 347 | 315 | 383 |
| 17.00 | 214.53 | 169.35 | 271.75 | 1102 | 999 | 1217 | 351 | 318 | 387 |
| 17.25 | 219.61 | 173.10 | 278.63 | 1113 | 1008 | 1229 | 354 | 321 | 391 |
| 17.50 | 224.72 | 176.86 | 285.54 | 1124 | 1017 | 1242 | 358 | 324 | 395 |
| 17.75 | 229.86 | 180.63 | 292.50 | 1135 | 1026 | 1255 | 361 | 327 | 399 |
| 18.00 | 235.02 | 184.41 | 299.50 | 1145 | 1035 | 1267 | 365 | 329 | 403 |
| 18.25 | 240.20 | 188.21 | 306.55 | 1156 | 1044 | 1279 | 368 | 332 | 407 |
| 18.50 | 245.40 | 192.01 | 313.63 | 1166 | 1053 | 1292 | 371 | 335 | 411 |
| 18.75 | 250.62 | 195.82 | 320.75 | 1176 | 1061 | 1304 | 374 | 338 | 415 |
| 19.00 | 255.87 | 199.65 | 327.92 | 1187 | 1070 | 1316 | 378 | 341 | 419 |
| 19.25 | 261.13 | 203.48 | 335.12 | 1197 | 1078 | 1328 | 381 | 343 | 423 |
| 19.50 | 266.42 | 207.32 | 342.35 | 1207 | 1087 | 1340 | 384 | 346 | 426 |
| 19.75 | 271.72 | 211.17 | 349.63 | 1217 | 1095 | 1352 | 387 | 349 | 430 |
| 20.00 | 277.04 | 215.03 | 356.94 | 1227 | 1104 | 1363 | 390 | 351 | 434 |
| 20.25 | 282.38 | 218.90 | 364.28 | 1236 | 1112 | 1375 | 394 | 354 | 438 |
| 20.50 | 287.74 | 222.77 | 371.66 | 1246 | 1120 | 1387 | 397 | 356 | 441 |
| 20.75 | 293.12 | 226.65 | 379.08 | 1256 | 1128 | 1398 | 400 | 359 | 445 |
| 21.00 | 298.51 | 230.54 | 386.52 | 1265 | 1136 | 1409 | 403 | 362 | 449 |
| 21.25 | 303.92 | 234.44 | 394.00 | 1275 | 1144 | 1421 | 406 | 364 | 452 |
| 21.50 | 309.35 | 238.34 | 401.51 | 1284 | 1152 | 1432 | 409 | 367 | 456 |
| 21.75 | 314.79 | 242.25 | 409.05 | 1294 | 1160 | 1443 | 412 | 369 | 459 |
| 22.00 | 320.25 | 246.16 | 416.63 | 1303 | 1168 | 1454 | 415 | 372 | 463 |
| 22.25 | 325.72 | 250.08 | 424.23 | 1312 | 1175 | 1465 | 418 | 374 | 466 |
| 22.50 | 331.20 | 254.01 | 431.86 | 1321 | 1183 | 1476 | 421 | 377 | 470 |
| 22.75 | 336.70 | 257.94 | 439.52 | 1331 | 1191 | 1487 | 424 | 379 | 473 |
| 23.00 | 342.22 | 261.88 | 447.21 | 1340 | 1198 | 1498 | 426 | 381 | 477 |
| 23.25 | 347.75 | 265.82 | 454.92 | 1349 | 1206 | 1508 | 429 | 384 | 480 |
| 23.50 | 353.29 | 269.77 | 462.66 | 1357 | 1213 | 1519 | 432 | 386 | 484 |
| 23.75 | 358.84 | 273.72 | 470.43 | 1366 | 1220 | 1530 | 435 | 388 | 487 |
| 24.00 | 364.41 | 277.67 | 478.23 | 1375 | 1228 | 1540 | 438 | 391 | 490 |

***Combretum erythrophyllum*** **and** ***Rhus lancea*** **combination**

| Age | Sequestrated carbon (kg) | | | Stem circumference (mm) | | | Stem diameter (mm) | | |
|---|---|---|---|---|---|---|---|---|---|
| (years) | Mean | L | U | Mean | L | U | Mean | L | U |
| 24.25 | 369.98 | 281.63 | 486.05 | 1384 | 1235 | 1551 | 441 | 393 | 494 |
| 24.50 | 375.57 | 285.60 | 493.89 | 1393 | 1242 | 1561 | 443 | 395 | 497 |
| 24.75 | 381.17 | 289.57 | 501.76 | 1401 | 1249 | 1571 | 446 | 398 | 500 |
| 25.00 | 386.79 | 293.54 | 509.66 | 1410 | 1257 | 1582 | 449 | 400 | 503 |
| 25.25 | 392.41 | 297.52 | 517.58 | 1418 | 1264 | 1592 | 451 | 402 | 507 |
| 25.50 | 398.05 | 301.50 | 525.52 | 1427 | 1271 | 1602 | 454 | 404 | 510 |
| 25.75 | 403.69 | 305.48 | 533.48 | 1435 | 1278 | 1612 | 457 | 407 | 513 |
| 26.00 | 409.35 | 309.46 | 541.47 | 1444 | 1285 | 1622 | 459 | 409 | 516 |
| 26.25 | 415.01 | 313.45 | 549.47 | 1452 | 1291 | 1632 | 462 | 411 | 520 |
| 26.50 | 420.69 | 317.45 | 557.50 | 1460 | 1298 | 1642 | 465 | 413 | 523 |
| 26.75 | 426.37 | 321.44 | 565.55 | 1468 | 1305 | 1652 | 467 | 415 | 526 |
| 27.00 | 432.06 | 325.44 | 573.62 | 1476 | 1312 | 1662 | 470 | 418 | 529 |
| 27.25 | 437.77 | 329.44 | 581.72 | 1485 | 1318 | 1671 | 473 | 420 | 532 |
| 27.50 | 443.48 | 333.44 | 589.83 | 1493 | 1325 | 1681 | 475 | 422 | 535 |
| 27.75 | 449.20 | 337.45 | 597.96 | 1501 | 1332 | 1691 | 478 | 424 | 538 |
| 28.00 | 454.93 | 341.46 | 606.11 | 1509 | 1338 | 1700 | 480 | 426 | 541 |
| 28.25 | 460.66 | 345.47 | 614.28 | 1516 | 1345 | 1710 | 483 | 428 | 544 |
| 28.50 | 466.41 | 349.48 | 622.46 | 1524 | 1351 | 1719 | 485 | 430 | 547 |
| 28.75 | 472.16 | 353.49 | 630.67 | 1532 | 1358 | 1729 | 488 | 432 | 550 |
| 29.00 | 477.92 | 357.51 | 638.89 | 1540 | 1364 | 1738 | 490 | 434 | 553 |
| 29.25 | 483.69 | 361.52 | 647.13 | 1548 | 1371 | 1747 | 493 | 436 | 556 |
| 29.50 | 489.46 | 365.54 | 655.39 | 1555 | 1377 | 1757 | 495 | 438 | 559 |
| 29.75 | 495.24 | 369.56 | 663.67 | 1563 | 1383 | 1766 | 497 | 440 | 562 |
| 30.00 | 501.03 | 373.58 | 671.96 | 1570 | 1389 | 1775 | 500 | 442 | 565 |
| 30.25 | 506.83 | 377.60 | 680.27 | 1578 | 1396 | 1784 | 502 | 444 | 568 |
| 30.50 | 512.63 | 381.63 | 688.59 | 1586 | 1402 | 1793 | 505 | 446 | 571 |
| 30.75 | 518.43 | 385.65 | 696.93 | 1593 | 1408 | 1802 | 507 | 448 | 574 |
| 31.00 | 524.25 | 389.68 | 705.29 | 1600 | 1414 | 1811 | 509 | 450 | 577 |
| 31.25 | 530.07 | 393.70 | 713.66 | 1608 | 1420 | 1820 | 512 | 452 | 579 |
| 31.50 | 535.89 | 397.73 | 722.04 | 1615 | 1426 | 1829 | 514 | 454 | 582 |
| 31.75 | 541.72 | 401.76 | 730.44 | 1622 | 1432 | 1838 | 516 | 456 | 585 |
| 32.00 | 547.56 | 405.79 | 738.86 | 1630 | 1438 | 1847 | 519 | 458 | 588 |
| 32.25 | 553.40 | 409.82 | 747.29 | 1637 | 1444 | 1856 | 521 | 460 | 591 |
| 32.50 | 559.25 | 413.85 | 755.73 | 1644 | 1450 | 1864 | 523 | 462 | 593 |
| 32.75 | 565.10 | 417.88 | 764.19 | 1651 | 1456 | 1873 | 526 | 463 | 596 |
| 33.00 | 570.96 | 421.91 | 772.66 | 1658 | 1462 | 1882 | 528 | 465 | 599 |
| 33.25 | 576.82 | 425.94 | 781.14 | 1666 | 1468 | 1890 | 530 | 467 | 602 |
| 33.50 | 582.69 | 429.98 | 789.64 | 1673 | 1473 | 1899 | 532 | 469 | 604 |
| 33.75 | 588.56 | 434.01 | 798.14 | 1680 | 1479 | 1907 | 535 | 471 | 607 |
| 34.00 | 594.43 | 438.04 | 806.66 | 1687 | 1485 | 1916 | 537 | 473 | 610 |
| 34.25 | 600.32 | 442.07 | 815.20 | 1694 | 1491 | 1924 | 539 | 474 | 612 |
| 34.50 | 606.20 | 446.11 | 823.74 | 1700 | 1496 | 1932 | 541 | 476 | 615 |
| 34.75 | 612.09 | 450.14 | 832.30 | 1707 | 1502 | 1941 | 543 | 478 | 618 |
| 35.00 | 617.98 | 454.17 | 840.87 | 1714 | 1507 | 1949 | 546 | 480 | 620 |
| 35.25 | 623.88 | 458.20 | 849.45 | 1721 | 1513 | 1957 | 548 | 482 | 623 |
| 35.50 | 629.78 | 462.24 | 858.04 | 1728 | 1519 | 1966 | 550 | 483 | 626 |
| 35.75 | 635.68 | 466.27 | 866.64 | 1734 | 1524 | 1974 | 552 | 485 | 628 |
| 36.00 | 641.59 | 470.30 | 875.26 | 1741 | 1530 | 1982 | 554 | 487 | 631 |

***Combretum erythrophyllum* and *Rhus lancea* combination**

| Age | Sequestrated carbon (kg) | | | Stem circumference (mm) | | | Stem diameter (mm) | | |
|---|---|---|---|---|---|---|---|---|---|
| (years) | Mean | L | U | Mean | L | U | Mean | L | U |
| 36.25 | 647.50 | 474.33 | 883.88 | 1748 | 1535 | 1990 | 556 | 489 | 633 |
| 36.50 | 653.41 | 478.36 | 892.52 | 1754 | 1540 | 1998 | 558 | 490 | 636 |
| 36.75 | 659.33 | 482.39 | 901.16 | 1761 | 1546 | 2006 | 561 | 492 | 639 |
| 37.00 | 665.25 | 486.42 | 909.82 | 1768 | 1551 | 2014 | 563 | 494 | 641 |
| 37.25 | 671.17 | 490.45 | 918.48 | 1774 | 1557 | 2022 | 565 | 495 | 644 |
| 37.50 | 677.10 | 494.48 | 927.16 | 1781 | 1562 | 2030 | 567 | 497 | 646 |
| 37.75 | 683.03 | 498.51 | 935.84 | 1787 | 1567 | 2038 | 569 | 499 | 649 |
| 38.00 | 688.96 | 502.54 | 944.54 | 1794 | 1572 | 2046 | 571 | 501 | 651 |
| 38.25 | 694.90 | 506.57 | 953.24 | 1800 | 1578 | 2054 | 573 | 502 | 654 |
| 38.50 | 700.83 | 510.60 | 961.95 | 1807 | 1583 | 2062 | 575 | 504 | 656 |
| 38.75 | 706.77 | 514.62 | 970.67 | 1813 | 1588 | 2069 | 577 | 506 | 659 |
| 39.00 | 712.72 | 518.65 | 979.40 | 1819 | 1593 | 2077 | 579 | 507 | 661 |
| 39.25 | 718.66 | 522.67 | 988.14 | 1826 | 1598 | 2085 | 581 | 509 | 664 |
| 39.50 | 724.61 | 526.69 | 996.89 | 1832 | 1604 | 2093 | 583 | 510 | 666 |
| 39.75 | 730.56 | 530.72 | 1005.64 | 1838 | 1609 | 2100 | 585 | 512 | 669 |
| 40.00 | 736.51 | 534.74 | 1014.41 | 1844 | 1614 | 2108 | 587 | 514 | 671 |
| 40.25 | 742.46 | 538.76 | 1023.18 | 1851 | 1619 | 2115 | 589 | 515 | 673 |
| 40.50 | 748.42 | 542.78 | 1031.96 | 1857 | 1624 | 2123 | 591 | 517 | 676 |
| 40.75 | 754.37 | 546.80 | 1040.75 | 1863 | 1629 | 2131 | 593 | 518 | 678 |
| 41.00 | 760.33 | 550.82 | 1049.54 | 1869 | 1634 | 2138 | 595 | 520 | 681 |
| 41.25 | 766.29 | 554.83 | 1058.34 | 1875 | 1639 | 2145 | 597 | 522 | 683 |
| 41.50 | 772.25 | 558.85 | 1067.15 | 1881 | 1644 | 2153 | 599 | 523 | 685 |
| 41.75 | 778.22 | 562.86 | 1075.97 | 1887 | 1649 | 2160 | 601 | 525 | 688 |
| 42.00 | 784.18 | 566.88 | 1084.80 | 1893 | 1654 | 2168 | 603 | 526 | 690 |
| 42.25 | 790.15 | 570.89 | 1093.63 | 1899 | 1658 | 2175 | 605 | 528 | 692 |
| 42.50 | 796.12 | 574.90 | 1102.46 | 1905 | 1663 | 2182 | 606 | 529 | 695 |
| 42.75 | 802.09 | 578.91 | 1111.31 | 1911 | 1668 | 2190 | 608 | 531 | 697 |
| 43.00 | 808.06 | 582.92 | 1120.16 | 1917 | 1673 | 2197 | 610 | 532 | 699 |
| 43.25 | 814.03 | 586.92 | 1129.02 | 1923 | 1678 | 2204 | 612 | 534 | 702 |
| 43.50 | 820.01 | 590.93 | 1137.88 | 1929 | 1682 | 2211 | 614 | 536 | 704 |
| 43.75 | 825.98 | 594.93 | 1146.75 | 1935 | 1687 | 2219 | 616 | 537 | 706 |
| 44.00 | 831.96 | 598.94 | 1155.63 | 1941 | 1692 | 2226 | 618 | 539 | 708 |
| 44.25 | 837.93 | 602.94 | 1164.51 | 1946 | 1697 | 2233 | 620 | 540 | 711 |
| 44.50 | 843.91 | 606.94 | 1173.40 | 1952 | 1701 | 2240 | 621 | 542 | 713 |
| 44.75 | 849.89 | 610.94 | 1182.30 | 1958 | 1706 | 2247 | 623 | 543 | 715 |
| 45.00 | 855.87 | 614.94 | 1191.20 | 1964 | 1711 | 2254 | 625 | 545 | 717 |
| 45.25 | 861.85 | 618.93 | 1200.10 | 1969 | 1715 | 2261 | 627 | 546 | 720 |
| 45.50 | 867.83 | 622.93 | 1209.02 | 1975 | 1720 | 2268 | 629 | 547 | 722 |
| 45.75 | 873.81 | 626.92 | 1217.93 | 1981 | 1724 | 2275 | 630 | 549 | 724 |
| 46.00 | 879.79 | 630.91 | 1226.85 | 1986 | 1729 | 2282 | 632 | 550 | 726 |
| 46.25 | 885.78 | 634.90 | 1235.78 | 1992 | 1734 | 2289 | 634 | 552 | 729 |
| 46.50 | 891.76 | 638.89 | 1244.71 | 1998 | 1738 | 2296 | 636 | 553 | 731 |
| 46.75 | 897.74 | 642.88 | 1253.65 | 2003 | 1743 | 2303 | 638 | 555 | 733 |
| 47.00 | 903.73 | 646.86 | 1262.59 | 2009 | 1747 | 2309 | 639 | 556 | 735 |
| 47.25 | 909.71 | 650.84 | 1271.54 | 2014 | 1752 | 2316 | 641 | 558 | 737 |
| 47.50 | 915.70 | 654.83 | 1280.49 | 2020 | 1756 | 2323 | 643 | 559 | 739 |

Table Appendix A 6.3. *Rhus lancea* - *Rhus pendulina* combination

| *Rhus lancea* and *Rhus pendulina* combination | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Age** | **Sequestrated carbon (kg)** | | | **Stem circumference (mm)** | | | **Stem diameter (mm)** | | |
| **(years)** | **Mean** | **L** | **U** | **Mean** | **L** | **U** | **Mean** | **L** | **U** |
| 1.00 | 0.29 | 0.22 | 0.39 | 70 | 62 | 80 | 22 | 20 | 25 |
| 1.25 | 0.57 | 0.44 | 0.73 | 93 | 84 | 103 | 30 | 27 | 33 |
| 1.50 | 0.96 | 0.77 | 1.19 | 115 | 105 | 126 | 37 | 34 | 40 |
| 1.75 | 1.46 | 1.21 | 1.77 | 138 | 127 | 149 | 44 | 40 | 47 |
| 2.00 | 2.08 | 1.76 | 2.46 | 159 | 149 | 171 | 51 | 47 | 54 |
| 2.25 | 2.81 | 2.42 | 3.26 | 181 | 170 | 192 | 57 | 54 | 61 |
| 2.50 | 3.64 | 3.18 | 4.17 | 201 | 190 | 213 | 64 | 61 | 68 |
| 2.75 | 4.58 | 4.05 | 5.18 | 221 | 210 | 233 | 70 | 67 | 74 |
| 3.00 | 5.61 | 5.01 | 6.28 | 241 | 230 | 253 | 77 | 73 | 80 |
| 3.25 | 6.74 | 6.07 | 7.48 | 260 | 249 | 272 | 83 | 79 | 87 |
| 3.50 | 7.95 | 7.20 | 8.77 | 279 | 268 | 290 | 89 | 85 | 92 |
| 3.75 | 9.24 | 8.41 | 10.15 | 297 | 285 | 309 | 94 | 91 | 98 |
| 4.00 | 10.61 | 9.69 | 11.61 | 314 | 303 | 327 | 100 | 96 | 104 |
| 4.25 | 12.05 | 11.04 | 13.16 | 332 | 320 | 344 | 106 | 102 | 110 |
| 4.50 | 13.56 | 12.43 | 14.79 | 348 | 336 | 361 | 111 | 107 | 115 |
| 4.75 | 15.14 | 13.88 | 16.50 | 365 | 352 | 378 | 116 | 112 | 120 |
| 5.00 | 16.77 | 15.38 | 18.29 | 381 | 367 | 395 | 121 | 117 | 126 |
| 5.25 | 18.47 | 16.92 | 20.16 | 396 | 382 | 411 | 126 | 122 | 131 |
| 5.50 | 20.21 | 18.49 | 22.09 | 411 | 397 | 427 | 131 | 126 | 136 |
| 5.75 | 22.01 | 20.10 | 24.09 | 426 | 411 | 443 | 136 | 131 | 141 |
| 6.00 | 23.85 | 21.75 | 26.16 | 441 | 424 | 458 | 140 | 135 | 146 |
| 6.25 | 25.74 | 23.42 | 28.30 | 455 | 438 | 474 | 145 | 139 | 151 |
| 6.50 | 27.68 | 25.13 | 30.49 | 469 | 451 | 488 | 149 | 143 | 155 |
| 6.75 | 29.65 | 26.86 | 32.74 | 483 | 463 | 503 | 154 | 147 | 160 |
| 7.00 | 31.66 | 28.61 | 35.05 | 496 | 476 | 518 | 158 | 151 | 165 |
| 7.25 | 33.71 | 30.38 | 37.41 | 509 | 488 | 532 | 162 | 155 | 169 |
| 7.50 | 35.80 | 32.18 | 39.82 | 522 | 500 | 546 | 166 | 159 | 174 |
| 7.75 | 37.91 | 34.00 | 42.27 | 535 | 511 | 560 | 170 | 163 | 178 |
| 8.00 | 40.06 | 35.84 | 44.78 | 547 | 523 | 573 | 174 | 166 | 183 |
| 8.25 | 42.23 | 37.69 | 47.33 | 560 | 534 | 587 | 178 | 170 | 187 |
| 8.50 | 44.44 | 39.56 | 49.92 | 572 | 545 | 600 | 182 | 173 | 191 |
| 8.75 | 46.67 | 41.45 | 52.55 | 583 | 555 | 613 | 186 | 177 | 195 |
| 9.00 | 48.92 | 43.35 | 55.22 | 595 | 566 | 626 | 189 | 180 | 199 |
| 9.25 | 51.20 | 45.26 | 57.92 | 606 | 576 | 638 | 193 | 183 | 203 |
| 9.50 | 53.50 | 47.18 | 60.67 | 618 | 586 | 651 | 197 | 187 | 207 |
| 9.75 | 55.82 | 49.12 | 63.44 | 629 | 596 | 663 | 200 | 190 | 211 |
| 10.00 | 58.17 | 51.07 | 66.25 | 640 | 606 | 675 | 204 | 193 | 215 |
| 10.25 | 60.53 | 53.03 | 69.09 | 650 | 615 | 687 | 207 | 196 | 219 |
| 10.50 | 62.91 | 55.00 | 71.96 | 661 | 625 | 699 | 210 | 199 | 222 |
| 10.75 | 65.31 | 56.98 | 74.86 | 671 | 634 | 711 | 214 | 202 | 226 |
| 11.00 | 67.73 | 58.96 | 77.79 | 681 | 643 | 722 | 217 | 205 | 230 |
| 11.25 | 70.16 | 60.96 | 80.74 | 692 | 652 | 733 | 220 | 208 | 233 |
| 11.50 | 72.60 | 62.96 | 83.72 | 702 | 661 | 745 | 223 | 210 | 237 |
| 11.75 | 75.06 | 64.97 | 86.73 | 711 | 670 | 756 | 226 | 213 | 240 |
| 12.00 | 77.54 | 66.98 | 89.76 | 721 | 678 | 766 | 230 | 216 | 244 |

***Rhus lancea*** **and** ***Rhus pendulina*** **combination**

| Age | Sequestrated carbon (kg) | | | Stem circumference (mm) | | | Stem diameter (mm) | | |
|---|---|---|---|---|---|---|---|---|---|
| (years) | Mean | L | U | Mean | L | U | Mean | L | U |
| 12.25 | 80.02 | 69.00 | 92.81 | 731 | 687 | 777 | 233 | 219 | 247 |
| 12.50 | 82.52 | 71.03 | 95.88 | 740 | 695 | 788 | 236 | 221 | 251 |
| 12.75 | 85.04 | 73.06 | 98.98 | 749 | 703 | 798 | 239 | 224 | 254 |
| 13.00 | 87.56 | 75.10 | 102.09 | 759 | 711 | 809 | 241 | 226 | 257 |
| 13.25 | 90.09 | 77.14 | 105.23 | 768 | 719 | 819 | 244 | 229 | 261 |
| 13.50 | 92.64 | 79.18 | 108.38 | 777 | 727 | 829 | 247 | 232 | 264 |
| 13.75 | 95.19 | 81.23 | 111.55 | 785 | 735 | 839 | 250 | 234 | 267 |
| 14.00 | 97.75 | 83.28 | 114.74 | 794 | 743 | 849 | 253 | 236 | 270 |
| 14.25 | 100.33 | 85.34 | 117.95 | 803 | 750 | 859 | 256 | 239 | 273 |
| 14.50 | 102.91 | 87.40 | 121.17 | 811 | 758 | 869 | 258 | 241 | 277 |
| 14.75 | 105.50 | 89.46 | 124.41 | 820 | 765 | 878 | 261 | 244 | 280 |
| 15.00 | 108.09 | 91.52 | 127.66 | 828 | 773 | 888 | 264 | 246 | 283 |
| 15.25 | 110.69 | 93.59 | 130.93 | 837 | 780 | 897 | 266 | 248 | 286 |
| 15.50 | 113.31 | 95.66 | 134.21 | 845 | 787 | 907 | 269 | 251 | 289 |
| 15.75 | 115.92 | 97.73 | 137.50 | 853 | 794 | 916 | 271 | 253 | 291 |
| 16.00 | 118.54 | 99.80 | 140.81 | 861 | 801 | 925 | 274 | 255 | 294 |
| 16.25 | 121.17 | 101.87 | 144.13 | 869 | 808 | 934 | 277 | 257 | 297 |
| 16.50 | 123.81 | 103.95 | 147.47 | 877 | 815 | 943 | 279 | 259 | 300 |
| 16.75 | 126.45 | 106.02 | 150.81 | 884 | 822 | 952 | 281 | 262 | 303 |
| 17.00 | 129.09 | 108.10 | 154.17 | 892 | 828 | 960 | 284 | 264 | 306 |
| 17.25 | 131.74 | 110.17 | 157.54 | 900 | 835 | 969 | 286 | 266 | 308 |
| 17.50 | 134.40 | 112.25 | 160.91 | 907 | 841 | 978 | 289 | 268 | 311 |
| 17.75 | 137.06 | 114.33 | 164.30 | 914 | 848 | 986 | 291 | 270 | 314 |
| 18.00 | 139.72 | 116.41 | 167.70 | 922 | 854 | 995 | 293 | 272 | 317 |
| 18.25 | 142.39 | 118.49 | 171.11 | 929 | 861 | 1003 | 296 | 274 | 319 |
| 18.50 | 145.06 | 120.56 | 174.52 | 936 | 867 | 1011 | 298 | 276 | 322 |
| 18.75 | 147.73 | 122.64 | 177.95 | 944 | 873 | 1020 | 300 | 278 | 325 |
| 19.00 | 150.41 | 124.72 | 181.38 | 951 | 879 | 1028 | 303 | 280 | 327 |
| 19.25 | 153.09 | 126.80 | 184.82 | 958 | 885 | 1036 | 305 | 282 | 330 |
| 19.50 | 155.77 | 128.88 | 188.27 | 965 | 891 | 1044 | 307 | 284 | 332 |
| 19.75 | 158.45 | 130.95 | 191.73 | 972 | 897 | 1052 | 309 | 286 | 335 |
| 20.00 | 161.14 | 133.03 | 195.19 | 978 | 903 | 1060 | 311 | 287 | 337 |
| 20.25 | 163.83 | 135.11 | 198.66 | 985 | 909 | 1068 | 314 | 289 | 340 |
| 20.50 | 166.53 | 137.18 | 202.14 | 992 | 915 | 1075 | 316 | 291 | 342 |
| 20.75 | 169.22 | 139.26 | 205.63 | 999 | 921 | 1083 | 318 | 293 | 345 |
| 21.00 | 171.92 | 141.33 | 209.12 | 1005 | 926 | 1091 | 320 | 295 | 347 |
| 21.25 | 174.61 | 143.40 | 212.62 | 1012 | 932 | 1098 | 322 | 297 | 350 |
| 21.50 | 177.31 | 145.48 | 216.12 | 1018 | 938 | 1106 | 324 | 298 | 352 |
| 21.75 | 180.02 | 147.55 | 219.63 | 1025 | 943 | 1113 | 326 | 300 | 354 |
| 22.00 | 182.72 | 149.62 | 223.14 | 1031 | 949 | 1121 | 328 | 302 | 357 |
| 22.25 | 185.42 | 151.68 | 226.66 | 1037 | 954 | 1128 | 330 | 304 | 359 |
| 22.50 | 188.13 | 153.75 | 230.19 | 1044 | 959 | 1135 | 332 | 305 | 361 |
| 22.75 | 190.83 | 155.82 | 233.72 | 1050 | 965 | 1143 | 334 | 307 | 364 |
| 23.00 | 193.54 | 157.88 | 237.25 | 1056 | 970 | 1150 | 336 | 309 | 366 |
| 23.25 | 196.25 | 159.94 | 240.79 | 1062 | 975 | 1157 | 338 | 310 | 368 |
| 23.50 | 198.96 | 162.01 | 244.33 | 1068 | 981 | 1164 | 340 | 312 | 370 |
| 23.75 | 201.67 | 164.07 | 247.88 | 1074 | 986 | 1171 | 342 | 314 | 373 |
| 24.00 | 204.37 | 166.12 | 251.43 | 1080 | 991 | 1178 | 344 | 315 | 375 |

| *Rhus lancea* and *Rhus pendulina* combination | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Age | Sequestrated carbon (kg) | | | Stem circumference (mm) | | | Stem diameter (mm) | | |
| (years) | Mean | L | U | Mean | L | U | Mean | L | U |
| 24.25 | 207.08 | 168.18 | 254.99 | 1086 | 996 | 1185 | 346 | 317 | 377 |
| 24.50 | 209.79 | 170.24 | 258.55 | 1092 | 1001 | 1192 | 348 | 319 | 379 |
| 24.75 | 212.51 | 172.29 | 262.11 | 1098 | 1006 | 1199 | 350 | 320 | 382 |
| 25.00 | 215.22 | 174.34 | 265.67 | 1104 | 1011 | 1205 | 351 | 322 | 384 |
| 25.25 | 217.93 | 176.39 | 269.24 | 1110 | 1016 | 1212 | 353 | 323 | 386 |
| 25.50 | 220.64 | 178.44 | 272.81 | 1115 | 1021 | 1219 | 355 | 325 | 388 |
| 25.75 | 223.35 | 180.49 | 276.39 | 1121 | 1026 | 1225 | 357 | 327 | 390 |
| 26.00 | 226.06 | 182.53 | 279.97 | 1127 | 1031 | 1232 | 359 | 328 | 392 |
| 26.25 | 228.77 | 184.57 | 283.55 | 1132 | 1035 | 1238 | 360 | 330 | 394 |
| 26.50 | 231.48 | 186.61 | 287.13 | 1138 | 1040 | 1245 | 362 | 331 | 396 |
| 26.75 | 234.19 | 188.65 | 290.72 | 1144 | 1045 | 1251 | 364 | 333 | 398 |
| 27.00 | 236.90 | 190.69 | 294.31 | 1149 | 1050 | 1258 | 366 | 334 | 400 |
| 27.25 | 239.61 | 192.72 | 297.90 | 1154 | 1054 | 1264 | 367 | 336 | 402 |
| 27.50 | 242.32 | 194.76 | 301.49 | 1160 | 1059 | 1271 | 369 | 337 | 404 |
| 27.75 | 245.02 | 196.79 | 305.08 | 1165 | 1063 | 1277 | 371 | 339 | 406 |
| 28.00 | 247.73 | 198.82 | 308.68 | 1171 | 1068 | 1283 | 373 | 340 | 408 |
| 28.25 | 250.44 | 200.84 | 312.28 | 1176 | 1073 | 1289 | 374 | 341 | 410 |
| 28.50 | 253.14 | 202.87 | 315.88 | 1181 | 1077 | 1296 | 376 | 343 | 412 |
| 28.75 | 255.85 | 204.89 | 319.48 | 1186 | 1081 | 1302 | 378 | 344 | 414 |
| 29.00 | 258.55 | 206.91 | 323.08 | 1192 | 1086 | 1308 | 379 | 346 | 416 |
| 29.25 | 261.25 | 208.93 | 326.69 | 1197 | 1090 | 1314 | 381 | 347 | 418 |
| 29.50 | 263.96 | 210.94 | 330.29 | 1202 | 1095 | 1320 | 383 | 348 | 420 |
| 29.75 | 266.66 | 212.96 | 333.90 | 1207 | 1099 | 1326 | 384 | 350 | 422 |
| 30.00 | 269.36 | 214.97 | 337.51 | 1212 | 1103 | 1332 | 386 | 351 | 424 |
| 30.25 | 272.06 | 216.98 | 341.12 | 1217 | 1108 | 1338 | 387 | 353 | 426 |
| 30.50 | 274.75 | 218.98 | 344.73 | 1222 | 1112 | 1344 | 389 | 354 | 428 |
| 30.75 | 277.45 | 220.99 | 348.34 | 1227 | 1116 | 1350 | 391 | 355 | 430 |
| 31.00 | 280.15 | 222.99 | 351.95 | 1232 | 1120 | 1355 | 392 | 357 | 431 |
| 31.25 | 282.84 | 224.99 | 355.57 | 1237 | 1125 | 1361 | 394 | 358 | 433 |
| 31.50 | 285.54 | 226.99 | 359.18 | 1242 | 1129 | 1367 | 395 | 359 | 435 |
| 31.75 | 288.23 | 228.99 | 362.80 | 1247 | 1133 | 1373 | 397 | 361 | 437 |
| 32.00 | 290.92 | 230.98 | 366.41 | 1252 | 1137 | 1378 | 398 | 362 | 439 |
| 32.25 | 293.61 | 232.97 | 370.03 | 1257 | 1141 | 1384 | 400 | 363 | 441 |
| 32.50 | 296.30 | 234.96 | 373.64 | 1261 | 1145 | 1390 | 402 | 364 | 442 |

# Chapter 7

## Estimates of carbon sequestrated by the *Jacaranda mimosifolia* street trees in the City of Tshwane, South Africa

### Abstract

In 2003 approximately 17% of the City of Tshwane's urban street tree forests (195 789 trees) were populated with Jacaranda trees (33 630 trees). However, the National Department of Agriculture declared *Jacaranda mimosifolia* as a Category 3 alien invader and consequently Jacaranda street trees may not be replaced. This will eventually result in the total loss of the Jacaranda population of the City of Tshwane.

The City of Tshwane Metropolitan Municipality requested that monetary values be determined for the trees with the aim of determining the value of the Jacaranda urban street tree forest to the City of Tshwane. The aim of this report was therefore to calculate the estimated quantity of carbon contained in the Jacaranda street tree population and its related monetary value. It is hoped that this quantifiable environmental benefit in terms of carbon that has been sequestrated and its associated monetary value will provide some motivation for the preservation of the Jacaranda urban forest.

Stem circumference measurements were taken from 1525 Jacaranda street trees in 73 suburbs. Tree volume was determined from the measurements and tree volumes were converted to biomass and thence into carbon and from there into $CO_2$. A per tree mean of 0.378 tonne carbon (t C) was estimated for all the suburbs in which trees were measured. The calculated percentage error in this per tree mean carbon quantity for all of the Jacaranda street trees in Tshwane was 3.59%. Mean carbon per suburb, standard deviation and total carbon in each suburb were determined. The total quantity of carbon in all the suburbs of Tshwane (114 suburbs) that have Jacaranda street trees is estimated at 12 709.241 t C. It is suggested due to discrepancies of approximately 10% between the numbers of trees observed during fieldwork and municipal tree census data, that an adjusted carbon quantity be assumed. An adjustment of -10% is therefore suggested, yielding a total estimated carbon quantity for Tshwane's Jacaranda street trees of 11 438.317 t C. A per tree mean of 1.387 t $CO_2$ equivalent ($CO_2$eq) was estimated for all the measured suburbs, and an adjusted total of 41 978.625 t $CO_2$eq was estimated for the Jacaranda street trees in Tshwane. Assuming a hypothetical market related price of US$10 tonne$^{-1}$ $CO_2$, the total value of all the Jacaranda street trees in Tshwane based on the suggested adjusted carbon value could be estimated at US$419 786 and has an estimated value of R2 766 391 (R6.59 = US$1.00; 17/08/2004).

The carbon captured by the trees cannot be traded. The above carbon quantities and monetary values provide preliminary estimates. More robust estimates will be obtainable once a locally derived allometric biomass equation has been developed.

The carbon sequestration value of Jacarandas is but a portion of the total environmental, social and economical contribution made by the Jacaranda street trees of Tshwane's urban forest. The Jacaranda urban forest has been a part of the city's natural, cultural, and historical heritage for more than a century and it should thus be appreciated that such an asset outweighs monetary benefits and values.

**Keywords**: carbon sequestration, carbon trade, *Jacaranda mimosifolia*, street trees, urban forest

## Introduction

The first two *Jacaranda mimosifolia* trees arrived in Pretoria (currently the City of Tshwane) in 1888 from Rio de Janeiro and were planted by a Cape botanist, Mr Templeman, in the garden of Myrtle Lodge owned by Mr J.D. Celliers. These trees are currently on the Sunnyside school campus. The first official Jacaranda street trees were planted in 1906 in the current Bosman and Arcadia Streets when Mr James Clark donated a number of these trees to the Municipality of Pretoria. Mr Clark kept a nursery in the suburb of Groenkloof for the Transvaal Colony government. The seeds for these trees had been imported from Australia (Department of Environment Planning and Energy, 1980).

Since 1906 the Municipality of Pretoria planted Jacarandas to such an extent that in 2003 approximately 17% of the City of Tshwane's urban street tree forests were populated with Jacaranda trees (Mr Bertie Dry, Deputy Manager: Urban Forestry, Nursery and Training of the City of Tshwane Metropolitan Municipality, personal communication, 27/10/2003). Due to the fact that the street trees were planted from early in the twentieth century there is a strong association between the Jacaranda trees and the City's history. In spring and early summer Jacarandas create such a display of colour and splendour throughout the city that the City of Tshwane has become known as the Jacaranda City of South Africa. Many of the Jacaranda trees are older than architectural and public infrastructure in the city. These trees have become synonymous with the city and could be viewed as an integral part of the city's cultural, natural and historical heritage.

The City of Tshwane Metropolitan Municipality is however concerned about the future of the Jacaranda population. In 2001 the National Department of Agriculture declared *Jacaranda mimosifolia* as a Category 3 alien invader according to the amended regulation 15 of the Conservation of Agricultural Resources Act (No 43 of 1983) (Urban Green File, 2002). Category 3 invaders may not be propagated or established in any part of South Africa except for the biological control reserves. As a consequence the Jacaranda street trees may not be replaced where these trees have to be removed due to for example disease or other unavoidable circumstances. This will eventually result in the total loss of the Jacaranda population of the City of Tshwane.

In a quest to preserve the Jacaranda population, the City of Tshwane Metropolitan Municipality requested that monetary values be determined for the trees. Because the Jacarandas store carbon they ameliorate global warming and the greenhouse effect. A part of the Jacaranda's value to society can be determined by calculating its carbon storage and converting that to a monetary value. The aim of this report was therefore to calculate the estimated quantity of carbon contained by the street tree population and its related monetary value. It is hoped that the quantifiable environmental benefit in terms of carbon that has been sequestrated and its associated monetary value will provide further motivation for the preservation of the Jacaranda urban forest.

## Methodology

The Deputy Manager of Urban Forestry, Nursery and Training of the City of Tshwane Metropolitan Municipality (hereafter referred to as Municipality), Mr B. Dry, provided data (27/10/2003) containing suburb and street names with the number of *Jacaranda mimosifolia* trees in each street. (This was the only data provided by the Municipality.) This database was compiled from a census conducted in the late 1990s as well as from a tree-planting database initiated in 1995.

A total of 73 suburbs of the 114 suburbs that have Jacarandas planted as street trees in the Pretoria area of the City of Tshwane, were measured for stem circumference. Overbark stem circumference was taken at breast height i.e. at 1.37 m above ground level. The stem circumferences were measured in February and early March of 2004. A total of 116 streets were investigated and 1525 trees were measured in total. Forty-one suburbs that had less than 50 trees were not measured (Table 7.1).

To determine the mean stem circumferences of the Jacaranda street tree population in each suburb, a test sample was conducted to establish the number of trees that had to be measured per suburb. The stem circumferences of 20 trees per suburb for 13 different suburbs were measured. The low percentage error as calculated from the aforementioned 13 suburbs (see Results and Discussion sections below) showed that 20 trees per suburb provided a statistically representative sample of the mean stem circumference of *Jacaranda mimosifolia* trees in a suburb.

Table 7.1. Total number (n) of *Jacaranda mimosifolia* trees in descending numerical order growing in each suburb in the City of Tshwane. The total number of trees includes the various extensions of the different suburbs. The data were obtained from the City of Tshwane Metropolitan Municipality (27/10/2003)

| **Suburb** | **n** |
|---|---|
| Pretoria Central | 2853 |
| Brooklyn | 2535 |
| Arcadia | 1929 |
| Sunnyside | 1836 |
| Waterkloof Ridge | 1509 |
| Waterkloof | 1412 |
| Villeria | 1207 |
| Rietfontein | 1028 |
| Hatfield | 977 |
| Proclamation Hill | 896 |
| Pretoria North | 840 |
| Pretoria West | 702 |
| West Park | 622 |
| Muckleneuk | 559 |
| Lisdogan Park | 531 |
| Lynnwood | 514 |
| Eastwood | 499 |
| Annlin | 492 |
| Riviera | 465 |
| Rietondale | 454 |
| Garsfontein | 449 |
| Valhalla | 447 |
| Eersterust | 442 |
| Ashlea Gardens | 409 |
| Pretoria Industrial | 396 |
| Constantia Park | 393 |
| Menlo Park | 378 |
| Moreletta Park x 1 | 348 |
| Claremont | 344 |
| Lukasrand | 323 |
| Kwaggasrand | 310 |
| Colbyn | 308 |
| Mamelodi | 304 |
| Nieuw Muckleneuk | 284 |
| Laudium | 281 |
| Atteridgeville | 268 |
| Waltloo | 248 |
| Kilner Park | 235 |
| Meyers Park | 235 |
| Erasmusrand | 227 |
| Wonderboom South | 227 |

| Suburb | n |
|---|---|
| Faerie Glen | 223 |
| Queenswood | 215 |
| Saulsville | 208 |
| Waterkloof Park | 189 |
| Florauna | 168 |
| Silverton | 166 |
| Elardus Park | 159 |
| Eloffsdal | 159 |
| Hillcrest | 155 |
| Waterkloof Glen | 155 |
| Mountain View | 153 |
| Capital Park | 144 |
| Pretoria Gardens | 132 |
| Trevenna | 128 |
| Lynnwood Ridge | 108 |
| Dorandia | 103 |
| Lynnwood Glen | 102 |
| Alphen Park | 96 |
| Samkor Park | 95 |
| Montana | 93 |
| Wingate Park | 92 |
| Salvokop* | 87 |
| Deerness** | 82 |
| Sinoville | 82 |
| Hazelwood | 77 |
| Erasmuskloof | 70 |
| Asiatic Bazaar | 67 |
| Clydesdale* | 67 |
| Danville | 67 |
| Jan Niemand Park | 61 |
| Newlands | 60 |
| La Montagne | 59 |
| Menlyn x 4 | 58 |
| Philip Nel Park | 56 |
| Monument Park | 54 |
| Maroelana | 50 |
| Gezina | 48 |
| Prinshof | 48 |
| Die Wilgers | 45 |
| Koedoespoort | 45 |
| Lyttleton Manor | 42 |
| Mayville | 42 |
| Murrayfield | 42 |
| Weavind Park | 42 |
| Pierre van Ryneveld | 41 |
| Groenkloof | 40 |
| Ekklesia | 39 |
| Pretoria | 38 |
| Hermanstad | 37 |

| Suburb | n |
|---|---|
| Eastclyffe | 33 |
| Bailey's Muckleneuk | 32 |
| Erasmia | 28 |
| East Lynne | 22 |
| Brummeria x 2 | 20 |
| Lydiana | 18 |
| Nellmapius x 3 | 17 |
| Bellevue | 16 |
| Hennopspark | 13 |
| Les Marais | 12 |
| Zwartkop | 12 |
| Maroelana x 3 | 10 |
| Doringkloof | 9 |
| Eldoraigne | 9 |
| The Reeds | 9 |
| Lynnwood Manor | 8 |
| Rooihuiskraal | 8 |
| Waverley | 8 |
| Booysens | 6 |
| Bryntirion | 6 |
| Heuweloord | 6 |
| Irene | 5 |
| Val-De-Grace | 5 |
| Moregloed | 4 |
| Waterkloof Heights | 4 |
| Highveld | 2 |
| Die Hoewes | 1 |
| Salieshoek | 1 |
| Wierda Park | 1 |
| **Total** | **33630** |

* Not indicated on Figure 7.1, Figure 7.2, and Figure 7.3.
** Not taken into account in calculating the mean stem circumference.

Not all streets had 20 trees that could be measured and in such instances additional trees in other streets in the same suburb were measured to obtain the required 20 circumference values. In some suburbs less than 20 trees were available for measurement (Table 7.1). In some streets, the number of trees encountered differed from the data provided by the municipality. Where possible, these discrepancies were noted. It was, however, not part of the study to conduct a tree census and therefore these differences were not rigorously observed, but were rather noted in passing.

To determine the possible effect of local environmental conditions on the variation in stem circumference two transects, of varying length, were surveyed in the same street. For this statistical test two sets of 20 large trees were measured at opposite ends of Milner Street in the suburb Waterkloof. In the first set the trees at the western end of the street were measured consecutively and for the second set, every second tree was measured at the eastern end of the street. When measuring the trees consecutively, measurements were taken on both sides of the street in a zigzag manner in order to minimise the transect length (approximately 150 m long). In the second case, every alternate tree only on the northern side of the street was measured, in order to maximise the transect length. In this particular case there were a number of damaged trees that were not measured and the transect length was approximately 1 km.

Apart from the above *intra*-street stem circumference variation, *inter*-street variation in stem circumference within a suburb was also analysed. This was done to determine whether larger stem circumference distributions would be found in different streets of the same suburb rather than in only one street of that suburb. If this were the case more than one street would need to be measured in each suburb. The *inter*-street analysis was done by measuring 20 trees in each of two streets in Brooklyn, Hatfield and Sunnyside and showed that taking measurements in one street per suburb is sufficient for obtaining statistically satisfactory representative measurements.

Anticipating an urban to rural gradient in this study, Church Square was used as the focal point because Church Square was the location of the first settlements in the Pretoria region of the City of Tshwane from which the city developed in all directions. Church Square is currently in the Pretoria Central suburb. At any given location where tree measurements were taken, the trees in the street were measured starting from the point closest to Church Square and working further away from it. In all instances where the street runs in an east west direction the trees were measured on the northern side of the street or the side closest to the north. When a street runs in a north south direction, the trees on the eastern side of the street were measured. However if these selected sides did not have 20 trees available for measurement trees were measured on both sides of the street. In these instances trees on both sides of the street were measured starting from the tree closest to Church Square in that particular street.

The measurement methodology had to be adapted under specific conditions depending on the physical conditions in the street. It must be emphasized, though, that these were the exceptions to the norm and were enforced by practical considerations:

- In some instances where there were very few trees in a street, the trees were measured on both sides parallel to the centre line of the road – starting in one direction and coming back in the opposite.
- In some instances where there were very few trees, the first 20 trees from a designated point were measured regardless of which side of the street it stood.
- In Government Avenue in Eastwood and Lisdogan Park there were two rows of trees on either side of the street. Here both rows on only one side of the street were measured. These trees were measured in a zigzag method starting with the northernmost tree closest to Church Square of the particular street block.

Longitude and latitude were recorded with a global positioning system (Garmin, eTrex, Venture GPS) at the start and end of each transect in a street. The reading was taken as close as possible to the tree stem without jeopardising accuracy of the reading. Often this resulted in the reading being taken on the street corner, to avoid interference with satellite reception by the canopy. The name of the closest street that crosses the street in which the first tree was measured, as well as that of the closest street crossing it after the last tree measured, were noted for future reference (Table 7.2).

Table 7.2. Suburb names, streets in which measurements were made, direction in which the trees were measured in the street, closest cross street to first and last trees measured and GPS co-ordinates for first and last trees in each street (trees in more than one street were measured in some suburbs (see Methodology)) for the Jacaranda street trees that were measured for stem circumference in February and March 2004 in the City of Tshwane. The suburb and street names in which Jacarandas grow were obtained from the City of Tshwane Metropolitan Municipality (27/102003)

| No | Suburb | Street name | Direction | Closest cross street to first tree | Closest cross street to last tree | Start GPS South | | | Start GPS East | | | End GPS South | | | End GPS East | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Degree | Minute | Second | Degree | Minute | Second | Degree | Minute | Second | Degree | Minute | Second |
| 1 | Alphen Park | Dely | SE | Nuwe Hoop | Club | 25 | 47 | 4.164 | 28 | 15 | 37.008 | 25 | 42 | 23.976 | 28 | 15 | 41.616 |
| 2 | Alphen Park | Garsfontein | E | Selati | Nuwe Hoop | 25 | 46 | 57.504 | 28 | 15 | 49.680 | 25 | 46 | 58.116 | 28 | 15 | 42.084 |
| 3 | Annlin | Zambesi | E | Veldkornet | Parsley / Elizabeth | 25 | 40 | 36.984 | 28 | 11 | 49.956 | 25 | 40 | 41.088 | 28 | 12 | 9.252 |
| 4 | Arcadia | Schoeman | E | Beckett | Eastwood | 25 | 44 | 50.388 | 28 | 13 | 35.400 | 25 | 44 | 48.768 | 28 | 13 | 19.560 |
| 5 | Ashlea Gardens | Garsfontein | W | Matroosberg | Selati | 25 | 47 | 4.812 | 28 | 16 | 0.876 | 25 | 46 | 57.504 | 28 | 15 | 49.680 |
| 6 | Ashlea Gardens | Matroosberg | NE | Dely | Garsfontein | 25 | 47 | 23.208 | 28 | 15 | 53.136 | 25 | 47 | 4.812 | 28 | 16 | 0.876 |
| 7 | Asiatic Bazaar | Boom | W | 7th Street | DF Malan | 25 | 44 | 24.252 | 28 | 10 | 35.976 | 25 | 44 | 26.988 | 28 | 10 | 22.584 |
| 8 | Atteridgeville | Maunde | W | Khoza | Monoa | 25 | 46 | 29.028 | 28 | 5 | 22.344 | 25 | 46 | 31.980 | 28 | 4 | 59.664 |
| 9 | Brooklyn | Brooks | E | Hay | Duncan | 25 | 45 | 31.104 | 28 | 14 | 8.160 | 25 | 45 | 34.596 | 28 | 14 | 14.784 |
| 10 | Brooklyn | Mackenzie | E | Duncan | Pienaar | 25 | 45 | 50.472 | 28 | 14 | 13.524 | 25 | 45 | 54.504 | 28 | 14 | 28.860 |
| 11 | Claremont | Diamond | N | Dead end of st | Weir | 25 | 43 | 37.956 | 28 | 7 | 55.632 | 25 | 43 | 21.792 | 28 | 7 | 58.260 |
| 12 | Clydesdale | Kirkness | S | Park | Jorrison | 25 | 45 | 3.672 | 28 | 13 | 19.704 | 25 | 45 | 18.432 | 28 | 13 | 17.760 |
| 13 | Colbyn | Amos | E | Douglas | Glyn | 25 | 44 | 21.372 | 28 | 14 | 14.460 | 25 | 44 | 21.876 | 28 | 14 | 32.784 |
| 14 | Constantia Park | Anton van Wouw | NW | Beethoven | Langenhoven | 25 | 47 | 57.012 | 28 | 17 | 5.460 | 25 | 48 | 5.904 | 28 | 17 | 12.372 |
| 15 | Danville | Wrentmore | W | Paul Roos | Ferdie Berg | 25 | 44 | 9.996 | 28 | 8 | 9.204 | 25 | 44 | 7.440 | 28 | 7 | 58.98 |
| 16 | Eastwood | Government | E | Becket | Herbert | 25 | 44 | 24.468 | 28 | 13 | 1.380 | 25 | 44 | 24.072 | 28 | 13 | 7.428 |
| 17 | Eersterust | Hans Coverdale North | E | Spitfire | Neon | 25 | 42 | 8.244 | 28 | 18 | 0.468 | 25 | 42 | 1.332 | 28 | 18 | 20.520 |
| 18 | Elardus Park | Boeing | S | Hans Strijdom | Allandale/ Ebenhaezer | 25 | 49 | 20.964 | 28 | 15 | 20.268 | 25 | 49 | 52.500 | 28 | 15 | 19.440 |
| 19 | Eloffsdal | Franzina | E | Mansfield | Avril | 25 | 42 | 46.116 | 28 | 11 | 12.444 | 25 | 42 | 47.412 | 28 | 11 | 26.556 |

| No | Suburb | Street name | Direction | Closest cross street to first tree | Closest cross street to last tree | Start GPS South | | | Start GPS East | | | End GPS South | | | End GPS East | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Degree | Minute | Second | Degree | Minute | Second | Degree | Minute | Second | Degree | Minute | Second |
| 20 | Erasmuskloof | Lois | S, SW | Peak (Place) | Hans Strijdom | 25 | 48 | 32.760 | 28 | 16 | 13.188 | 25 | 49 | 9.192 | 28 | 16 | 18.588 |
| 21 | Erasmusrand | Rigel | S,E | Neptune | Buffelsdrift | 25 | 48 | 27.720 | 28 | 14 | 54.312 | 25 | 48 | 29.340 | 28 | 15 | 19.584 |
| 22 | Faerie Glen | Olympus | SE | Skukuza | Kromdraai | 25 | 47 | 23.460 | 28 | 19 | 46.164 | 25 | 47 | 45.780 | 28 | 19 | 50.088 |
| 23 | Garsfontein | Serene | E | Beatrix Mare | Isie Smuts | 25 | 47 | 17.988 | 28 | 17 | 3.948 | 25 | 47 | 48.840 | 28 | 17 | 36.960 |
| 24 | Hatfield | Park | E | Hilda | Grosvenor | 25 | 44 | 56.724 | 28 | 14 | 6.252 | 25 | 44 | 56.040 | 28 | 14 | 17.232 |
| 25 | Hatfield | Prospect | E | Hilda | Duncan | 25 | 45 | 7.452 | 28 | 14 | 7.620 | 25 | 45 | 6.084 | 28 | 14 | 23.352 |
| 26 | Hazelwood | Dely | SE | Albert | Highlands | 25 | 16 | 40.080 | 28 | 15 | 20.844 | 25 | 46 | 49.224 | 28 | 15 | 26.712 |
| 27 | Hestea Park | Daan de Wet Nel Dr | NW | President Steyn | Waterbok | 25 | 40 | 24.204 | 28 | 9 | 51.588 | 25 | 40 | 12.000 | 28 | 9 | 29.196 |
| 28 | Hillcrest | Duxbury | W | Duncan | - | 25 | 45 | 20.124 | 28 | 14 | 21.192 | 25 | 45 | 17.820 | 28 | 14 | 11.616 |
| 29 | Jan Niemand Park | Uil | E | Meeu | Voetpadnek | 25 | 42 | 7.920 | 28 | 17 | 7.008 | 25 | 42 | 11.304 | 28 | 17 | 33.396 |
| 30 | Kilner Park | C.R. Swart | N | Soutpansberg | Webb | 25 | 43 | 55.452 | 28 | 15 | 32.220 | 25 | 43 | 40.620 | 28 | 15 | 31.428 |
| 31 | Kwaggasrand | Reier | NW | Waterbok | Digteby | 25 | 45 | 44.424 | 28 | 7 | 6.096 | 25 | 45 | 39.420 | 28 | 6 | 57.204 |
| 32 | La Montagne | Catharina | E | Trevor | Margarita | 25 | 44 | 46.644 | 28 | 18 | 29.124 | 25 | 44 | 46.500 | 28 | 18 | 33.516 |
| 33 | La Montagne | Kandelaar | E | Shirley Ave East | Waggellaan | 25 | 45 | 4.320 | 28 | 18 | 49.104 | 25 | 45 | 4.500 | 28 | 19 | 8.976 |
| 34 | Laudium | Emerald | W | 6th Street | 13th Street | 25 | 47 | 8.232 | 28 | 6 | 20.916 | 25 | 47 | 8.736 | 28 | 6 | 7.848 |
| 35 | Lisdogan Park | Government | W | Dumbarton | Balmoral | 25 | 44 | 25.080 | 28 | 13 | 28.488 | 25 | 44 | 26.448 | 28 | 13 | 25.248 |
| 36 | Lukasrand | Sibelius | E | Arnoldi | Lingbeek | 25 | 45 | 58.392 | 28 | 12 | 35.784 | 25 | 45 | 55.548 | 28 | 12 | 59.040 |
| 37 | Lynnwood | Elizabeth Grove South | S | Kings Highway | Dead end of street | 25 | 45 | 35.316 | 28 | 15 | 47.592 | 25 | 45 | 43.884 | 28 | 15 | 45.108 |
| 38 | Lynnwood Glen | Glenwood | S, SE | Alcade | - | 25 | 46 | 3.144 | 28 | 16 | 46.128 | 25 | 46 | 21.432 | 28 | 16 | 51.636 |
| 39 | Lynnwood Ridge | Freesia | E | Insignis | Hibiscus | 25 | 46 | 0.840 | 28 | 17 | 23.496 | 25 | 46 | 0.480 | 28 | 18 | 1.836 |
| 40 | Mamelodi | Denneboom | E | Dobolwane | Dumsa | 25 | 43 | 5.592 | 28 | 20 | 42.432 | 25 | 43 | 5.808 | 28 | 20 | 54.204 |
| 41 | Mamelodi | Tsamaja | E | Kgomo | Hinterland | 25 | 43 | 9.192 | 28 | 21 | 36.756 | 25 | 42 | 50.976 | 28 | 22 | 28.380 |
| 42 | Maroelana | Maroelana | S | Hazelwood | Elandslaagte | 25 | 46 | 36.444 | 28 | 15 | 42.840 | 25 | 46 | 47.064 | 28 | 15 | 35.712 |
| 43 | Maroelana | Nuwe Hoop | S | Koelman | Roeline | 25 | 46 | 48.720 | 28 | 15 | 47.988 | 25 | 46 | 52.752 | 28 | 15 | 44.496 |
| 44 | Mayville | Mansfield | N | Fred Nicolson | Van Rensburg | 25 | 42 | 26.784 | 28 | 11 | 12.840 | 25 | 42 | 5.472 | 28 | 11 | 15.576 |
| 45 | Menlo Park | Brooklyn | S | Bariton | 6th Street | 25 | 45 | 42.228 | 28 | 14 | 45.168 | 25 | 46 | 0.156 | 28 | 14 | 56.976 |
| 46 | Meyers Park | Pretoria | E | Waltloo | Battery | 25 | 44 | 5.100 | 28 | 18 | 59.076 | 25 | 44 | 8.160 | 28 | 19 | 13.224 |
| 47 | Montana | Zambesi | E | - | - | 25 | 40 | 51.744 | 28 | 13 | 57.972 | 25 | 40 | 43.716 | 28 | 14 | 50.352 |
| 48 | Moreleta Park | Rubenstein | W | Stander | Helios | 25 | 49 | 8.580 | 28 | 17 | 32.640 | 25 | 49 | 10.560 | 28 | 16 | 51.888 |

| No | Suburb | Street name | Direction | Closest cross street to first tree | Closest cross street to last tree | Start GPS South | | | Start GPS East | | | End GPS South | | | End GPS East | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Degree | Minute | Second | Degree | Minute | Second | Degree | Minute | Second | Degree | Minute | Second |
| 49 | Mountain View | Daniel | N | Ivor | Daphne | 25 | 42 | 6.876 | 28 | 9 | 22.212 | 25 | 41 | 58.308 | 28 | 9 | 24.552 |
| 50 | Muckleneuk | Bourke | S | Walker | Berea | 25 | 45 | 32.616 | 28 | 12 | 25.308 | 25 | 45 | 41.688 | 28 | 12 | 23.544 |
| 51 | Newlands | Dely | SE | Lois | Matroosberg | 25 | 47 | 43.584 | 28 | 16 | 9.732 | 25 | 47 | 25.116 | 28 | 15 | 51.732 |
| 52 | Nieuw Muckleneuk | Dey | S | Nixon / Cameron | Middel | 25 | 46 | 16.968 | 28 | 13 | 50.088 | 25 | 46 | 4.008 | 28 | 13 | 44.616 |
| 53 | Philip Nel Park | Staatsartillerie | W | Technikon oord | Rebecca | 25 | 44 | 19.284 | 28 | 9 | 32.652 | 25 | 44 | 20.220 | 28 | 9 | 25.344 |
| 54 | Pretoria Central | Bloed | E | Bosman | Andries | 25 | 44 | 26.448 | 28 | 11 | 6.828 | 25 | 44 | 25.404 | 28 | 11 | 22.308 |
| 55 | Pretoria Central | Visagie | W | Paul Kruger | Andries | 25 | 45 | 8.136 | 28 | 11 | 19.140 | 25 | 45 | 7.668 | 28 | 11 | 31.092 |
| 56 | Pretoria West | Servaas | W | Zeiler | Rosetta | 25 | 45 | 6.012 | 28 | 9 | 26.856 | 25 | 45 | 7.056 | 28 | 9 | 9.468 |
| 57 | Pretoria Gardens | Bornman | N | Willies Hill | Hanny | 25 | 43 | 35.148 | 28 | 8 | 32.964 | 25 | 43 | 12.900 | 28 | 8 | 36.276 |
| 58 | Pretoria Industrial | Staal | NE | Bessemer | Industrial | 25 | 45 | 57.096 | 28 | 7 | 44.580 | 25 | 45 | 45.972 | 28 | 7 | 57.792 |
| 59 | Pretoria-North | Brits | W | Koos de la Rey | Danie Theron | 25 | 40 | 50.664 | 28 | 10 | 47.424 | 25 | 40 | 49.044 | 28 | 10 | 27.876 |
| 60 | Proclamation Hill | Acacia | W | Tungsten | Mica | 25 | 45 | 4.608 | 28 | 8 | 38.760 | 25 | 45 | 5.868 | 28 | 8 | 17.304 |
| 61 | Queenswood | Soutpansberg | E | Gordon | Kilnerton | 25 | 43 | 57.720 | 28 | 14 | 47.472 | 25 | 43 | 56.532 | 28 | 15 | 17.568 |
| 62 | Rietfontein | 19th Avenue | N | Swemmer | Haarhof | 25 | 42 | 50.796 | 28 | 13 | 10.452 | 25 | 42 | 37.404 | 28 | 13 | 8.076 |
| 63 | Rietondale | Nuffield | N | Soutpansberg | - | 25 | 43 | 58.872 | 28 | 13 | 11.244 | 25 | 43 | 49.620 | 28 | 13 | 10.092 |
| 64 | Riviera | Annie Botha | E | Union | Blacke | 25 | 43 | 58.548 | 28 | 12 | 30.420 | 25 | 43 | 58.188 | 28 | 12 | 42.372 |
| 65 | Salvokop | Skietpoort | W | Koch | Potgieter | 25 | 45 | 35.388 | 28 | 11 | 12.120 | 25 | 45 | 36.072 | 28 | 10 | 59.484 |
| 66 | Samcor Park | Simon Vermooten | N | Alwyn | Waltloo | 25 | 43 | 42.564 | 28 | 19 | 56.856 | 25 | 43 | 21.072 | 28 | 19 | 57.900 |
| 67 | Saulsville | Makaza | NW | Maunde | Mngomezulu | 25 | 46 | 48.036 | 28 | 3 | 12.348 | 25 | 46 | 41.952 | 28 | 3 | 4.752 |
| 68 | Saulsville | Masopha | N | Makaza | Mesa | 25 | 46 | 39.972 | 28 | 3 | 5.148 | 25 | 46 | 32.196 | 28 | 3 | 5.184 |
| 69 | Silverton | Fakkel | S | Jasmyn | Joseph Bosman | 25 | 43 | 54.192 | 28 | 17 | 46.608 | 25 | 44 | 10.464 | 28 | 17 | 45.096 |
| 70 | Sinoville | Zambesi | E | Miriana | Aldo | 25 | 40 | 42.456 | 28 | 12 | 15.732 | 25 | 40 | 46.956 | 28 | 12 | 43.812 |
| 71 | Sunnyside | Bourke | S | Water | De Kock | 25 | 45 | 7.596 | 28 | 12 | 37.620 | 25 | 45 | 19.584 | 28 | 12 | 31.536 |
| 72 | Sunnyside | Jorrison | E | Troye | Vos | 25 | 45 | 16.740 | 28 | 12 | 13.788 | 25 | 45 | 24.372 | 28 | 12 | 39.348 |
| 73 | Trevena | Meintjie | N | Kotze | Esselen | 25 | 45 | 7.416 | 28 | 12 | 2.196 | 25 | 45 | 4.824 | 28 | 12 | 2.088 |
| 74 | Valhalla | Fjord | S | Paul Kruger | Angvick | 25 | 47 | 45.960 | 28 | 9 | 32.796 | 25 | 47 | 58.200 | 28 | 9 | 27.468 |
| 75 | Villiera | Pierneef | E | 29th Avenue | 31th Avenue | 25 | 43 | 19.056 | 28 | 14 | 5.280 | 25 | 43 | 19.128 | 28 | 14 | 17.952 |
| 76 | Waterkloof | Milner (both sides) | E | Kloof | Rautenbach | 25 | 46 | 46.100 | 28 | 13 | 51.000 | 25 | 46 | 18.800 | 28 | 14 | 16.400 |
| 77 | Waterkloof | Milner (one side) | W | Heloma | Crown | 25 | 46 | 36.400 | 28 | 15 | 4.500 | 25 | 46 | 40.100 | 28 | 14 | 36.200 |

| No | Suburb | Street name | Direction | Closest cross street to first tree | Closest cross street to last tree | Start GPS South | | | Start GPS East | | | End GPS South | | | End GPS East | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Degree | Minute | Second | Degree | Minute | Second | Degree | Minute | Second | Degree | Minute | Second |
| 78 | Waterkloof Glen | Anton van Wouw | SE | Beethoven | Mendelsohn | 25 | 47 | 57.012 | 28 | 17 | 5.460 | 25 | 47 | 45.168 | 28 | 16 | 59.808 |
| 79 | Waterkloof Park | Drakensberg | S | Outeniqua | Matroosberg | 25 | 47 | 21.732 | 28 | 15 | 37.152 | 25 | 47 | 33.180 | 28 | 15 | 42.516 |
| 80 | Waterkloof Park | Matroosberg | E | Outeniqua | Dely | 25 | 47 | 29.688 | 28 | 15 | 43.416 | 25 | 47 | 25.872 | 28 | 15 | 49.320 |
| 81 | Waterkloof Ridge | Delphinus | NE | Rigel | Dorado | 25 | 47 | 36.816 | 28 | 14 | 23.964 | 25 | 47 | 21.012 | 28 | 14 | 32.100 |
| 82 | Watloo | Mundt | E | Dead end of st | Watloo | 25 | 43 | 18.588 | 28 | 19 | 9.192 | 25 | 43 | 19.344 | 28 | 19 | 25.428 |
| 83 | Wes Park | Iscor | SW | Cordelfos | Bosbok | 25 | 45 | 6.480 | 28 | 7 | 50.304 | 25 | 45 | 20.880 | 28 | 7 | 39.936 |
| 84 | Wingate Park | Delmas | S | Barnard | Hans Strijdom | 25 | 49 | 35.040 | 28 | 15 | 40.104 | 25 | 49 | 17.652 | 28 | 15 | 37.620 |
| 85 | Wonderboom South | De Beer | E | 9th Street | 12th Street | 25 | 41 | 54.996 | 28 | 12 | 4.824 | 25 | 41 | 53.340 | 28 | 12 | 17.496 |

When there were sufficient trees in a street, trees on the street corners were not measured. Trees with scars at breast height that could influence the stem circumference measurement were discarded, nor were trees measured that branched at or below 1.37 m. However, if there were no other suitable trees that could be measured, these trees were measured at an appropriate level with respect to the scar or just below the branch swelling. If forking occurred at or just above breast height, the tree was not measured. However, if the tree had to be included due to a shortage of trees in the street, the measurement was taken below the fork swelling. If a tree had an indentation on the one side, steps were taken to avoid skewing the measurement. The measurements were taken perpendicularly to the central vertical axis of the tree stem. If a tree was leaning sideways, the measurement was taken on the portion where the side of the tree stem that had the acute angle to the ground was at a vertical height of 1.37 m from the ground.

Trees that were overgrown with ivy (*Hedera sp.*) were not measured since the ivy could not be removed to obtain an accurate stem circumference. In some suburbs this caused a substantial number of trees to be skipped, resulting in longer transects.

If a tree obviously differed in size from the majority of the trees in the street, it was not measured. Often these trees were smaller than the other trees in the street, indicating that they were possibly replacements for trees that had died. When a continuous variation in tree stem circumference sizes was encountered, a representative sample was taken, ensuring that most of the different sizes were represented in the sample. In some instances discontinuous size classes were obvious and identifiable, in which case the trees were randomly measured in informal visually identified, size classes. The method involved visually judging tree stem circumferences when first moving along the street. Size classes were then identified from these visual observations. Sampling was stratified by measuring trees within each of the identified size classes. For example, if four classes were identified, measurements would be taken of five trees in each class to amount to 20 trees in that street. In cases where there were many trees with a large variation in stem circumference size, no stratification and size class subdivision were done and the trees were measured, as was the norm for the other streets.

Trees that had been damaged by fire at the base of the stem, by people presumably making fire for cooking or for heating, were not measured. In Laudium some trees had termite or ant nests at their base. These trees were still measured because there was no indication that the growth of these trees had been affected. Where trees were dead, showed signs of dieback or re-growth, they were excluded from measurement.

The statistical methodology and analysis in this report was conducted under the instruction and guidance of Professor F. Steffens (Statistician) formerly from the University of South Africa. The data were captured and analysed in Microsoft® Excel. The mean circumference and the standard deviation of the stem circumferences were calculated for each suburb (Table 7.3). The following equation (Pillsbury *et al.*, 1998) was used to estimate the volume of each tree:

$$V(cf) = 0.036147(dbh)^{2.486248} \tag{1}$$

where $V(cf)$ is the volume of the aboveground woody parts (excluding leaf volume) of the tree in cubic feet, and $dbh$ is the stem diameter at breast height in inches. Following from the above, equation (1) was converted to metric units as follows:

$$V(m^3) = 3.29118\ .\ 10^{-7}(dbh(mm))^{2.486248} \tag{2}$$

where $V(m^3)$ is the volume of the aboveground woody parts in cubic metres and $dbh(mm)$ is the stem diameter in millimetres at breast height. Because the stem circumference of the trees were measured, the circumferences were converted to diameters for application in equation (2). After the volume of each tree was calculated its biomass was determined as:

$$Biomass = density\ .\ V(m^3) \tag{3}$$

where $Biomass$ is calculated in kilograms (kg) and $density$ is a given value. In this report the density of 520 kg/m$^3$ was used which was determined from sampling stem wood derived from a *Jacaranda mimosifolia* tree that grew on the University of Pretoria campus. The wood was oven dried to a constant mass and the density was calculated.

Fifty percent of the dry biomass per tree is allocated to carbon (McPherson *et al.*, 1994; McPherson & Simpson, 1999; Gifford, 2000; McPherson *et al.*, 2001; IPCC, 2003) and this value was converted to metric tonnes. The mean aboveground carbon quantity per suburb as well as the standard deviation of aboveground carbon per suburb were calculated. The standard error was calculated for the aboveground carbon of each suburb in the following manner:

$$SE = \frac{SD}{\sqrt{(n)}} \tag{4}$$

where $SE$ is the standard error, $SD$ is the standard deviation and $n$ is the sample size. The standards deviation ($SD$) is a measure of the variability of individual trees within the suburb. The standard error ($SE$) is a measure of the accuracy of the estimated mean for the suburb. A correction factor was applied to the standard error and was derived from the following equation:

$$c = \sqrt{\frac{W_i - n}{W_i - 1}} \tag{5}$$

where $c$ is the correction factor, $W_i$ is the total number of trees in the suburb and $n$ is the sample size in the particular suburb.

The correction factor was applied to the $SE$ as follows:

$$SE(c) = SE \ . \ c \tag{6}$$

where $SE(c)$ is the corrected standard error. The mean quantity of aboveground carbon per Jacaranda tree in Tshwane can be calculated as:

$$X = \frac{\Sigma(W_i \ . \ X_i)}{\Sigma W_i} \tag{7}$$

where $X$ is the mean quantity of aboveground carbon per Jacaranda tree in Tshwane, $W_i$ is the total number of trees in each suburb and $X_i$ is the mean aboveground carbon per tree for each suburb. The total quantity of aboveground carbon that has been sequestrated by all the Jacaranda trees in Tshwane ($C_{agt}$) can be calculated as:

$$C_{agt} = X \ . \ N \tag{8}$$

where $N$ is the total number of Jacaranda trees in Tshwane.

The carbon standard error per tree $(SE_{pertree})$ was calculated as follows:

$$SE_{pertree} = \sqrt{\frac{\Sigma W_i^{\,2} SE(c)_i^{\,2}}{(\Sigma W_i)^2}} \tag{9}$$

From equation (9) the standard error for the aboveground carbon of the total quantity of trees follows:

$$SE_{total} = N * SE_{pertree} \tag{10}$$

where $SE_{total}$ is the standard error of the aboveground carbon for the total quantity of trees. The percentage error ($\%Err$) follows as:

$$\%Err = \frac{SE_{total}}{C_{agt}} \ . \ 100 \ . \ 2 \tag{11}$$

To determine the belowground biomass of the Jacarandas a root : shoot ratio of 22:78 was used (McPherson *et al.*, 2001) and Equations (4) to (11) were repeated to determine the total carbon quantities that include the root carbon. The percentage carbon of the root was also taken as 50% of total biomass (McPherson *et al.*, 2001; IPCC, 2003).

## Results

The total number of trees on which the calculations were based, were 33 630 according to the data provided by the municipality. The difference between the number of trees per street as provided by the municipality and that obtained from informal field observations indicated that there were approximately 10% fewer trees in the streets in which stem circumferences were measured than was indicated by the municipality's data. Figure 7.1 gives an indication as to the numbers of trees found in various suburbs as per the data provided by the municipality (27/10/2003). Pretoria Central, Brooklyn, Arcadia, Sunnyside, Waterkloof Ridge, Waterkloof, Villeria and Rietfontein (darkest colour) have between 1001 and 2853 Jacaranda street trees.

A 2.17% error was obtained from the test sample conducted by measuring stem circumferences of 20 trees per suburb for 13 different suburbs to establish the number of trees that had to be measured per suburb. This low percentage error suggested that 20 trees per suburb provided a sufficiently acceptable statistically representative sample of the mean stem circumference of Jacaranda trees in a suburb. The percentage error calculated for all of the Jacaranda trees in Tshwane was 3.59%.

Table 7.3. Suburbs with mean stem circumferences (mm) of trees in descending order of magnitude as well as the standard deviation (mm) in stem circumference for each suburb. Mean circumference and standard deviation are based on measurements that were taken of Jacaranda street trees in February and March 2004 in the Pretoria region of the City of Tshwane

| No | Suburb | Mean circumference (mm) | Standard deviation (mm) |
|---|---|---|---|
| 1 | Asiatic Bazaar | 1687 | 320 |
| 2 | Laudium | 1671 | 245 |
| 3 | Claremont | 1644 | 316 |
| 4 | Colbyn | 1616 | 263 |
| 5 | Mountain View | 1587 | 298 |
| 6 | Wonderboom South | 1552 | 297 |
| 7 | Waterkloof | 1538 | 288 |
| 8 | Sinoville | 1532 | 251 |
| 9 | Riviera | 1497 | 206 |
| 10 | Pretoria Gardens | 1471 | 297 |
| 11 | Muckleneuk | 1467 | 341 |
| 12 | Brooklyn | 1446 | 187 |
| 13 | Rietfontein | 1430 | 196 |
| 14 | Pretoria Central | 1420 | 342 |
| 15 | Villiera | 1410 | 271 |
| 16 | Eloffsdal | 1403 | 402 |
| 17 | Rietondale | 1400 | 340 |
| 18 | Menlo Park | 1400 | 311 |
| 19 | Lynnwood | 1395 | 486 |
| 20 | Salvokop | 1392 | 342 |
| 21 | Pretoria-North | 1389 | 277 |
| 22 | Sunnyside | 1383 | 227 |
| 23 | Pretoria West | 1381 | 205 |
| 24 | Nieuw Muckleneuk | 1347 | 250 |
| 25 | Proclamation Hill | 1345 | 170 |
| 26 | Hatfield | 1332 | 171 |
| 27 | Lisdogan Park | 1331 | 338 |
| 28 | Trevena | 1312 | 385 |
| 29 | Arcadia | 1302 | 199 |
| 30 | Kwaggasrand | 1286 | 166 |
| 31 | Samcor Park | 1272 | 361 |
| 32 | Valhalla | 1256 | 270 |
| 33 | Silverton | 1233 | 261 |
| 34 | Annlin | 1218 | 417 |
| 35 | Clydesdale | 1216 | 236 |

| No | Suburb | Mean circumference (mm) | Standard deviation (mm) |
|---|---|---|---|
| 36 | Pretoria Industrial | 1193 | 193 |
| 37 | Wes Park | 1159 | 196 |
| 38 | Danville | 1129 | 254 |
| 39 | Lynnwood Glen | 1108 | 187 |
| 40 | Waterkloof Ridge | 1102 | 176 |
| 41 | Eastwood | 1098 | 288 |
| 42 | Lukasrand | 1089 | 252 |
| 43 | Watloo | 1063 | 215 |
| 44 | Ashlea Gardens | 1060 | 389 |
| 45 | Eersterust | 1049 | 257 |
| 46 | Queenswood | 1039 | 404 |
| 47 | Hillcrest | 1027 | 264 |
| 48 | Meyers Park | 1021 | 219 |
| 49 | Alphen Park | 913 | 258 |
| 50 | La Montagne | 898 | 310 |
| 51 | Constantia Park | 848 | 175 |
| 52 | Maroelana | 843 | 158 |
| 53 | Waterkloof Park | 824 | 224 |
| 54 | Garsfontein | 818 | 191 |
| 55 | Atteridgeville | 814 | 119 |
| 56 | Kilner Park | 810 | 207 |
| 57 | Waterkloof Glen | 805 | 170 |
| 58 | Erasmusrand | 773 | 204 |
| 59 | Mamelodi | 736 | 174 |
| 60 | Jan Niemand Park | 669 | 273 |
| 61 | Lynnwood Ridge | 626 | 156 |
| 62 | Moreleta Park | 624 | 173 |
| 63 | Hazelwood | 523 | 347 |
| 64 | Faerie Glen | 522 | 124 |
| 65 | Montana | 522 | 200 |
| 66 | Philip Nel Park | 520 | 112 |
| 67 | Mayville | 419 | 176 |
| 68 | Erasmuskloof | 390 | 162 |
| 69 | Saulsville | 340 | 85 |
| 70 | Elardus Park | 323 | 91 |
| 71 | Hestea Park | 278 | 85 |
| 72 | Newlands | 213 | 110 |
| 73 | Wingate Park | 195 | 64 |

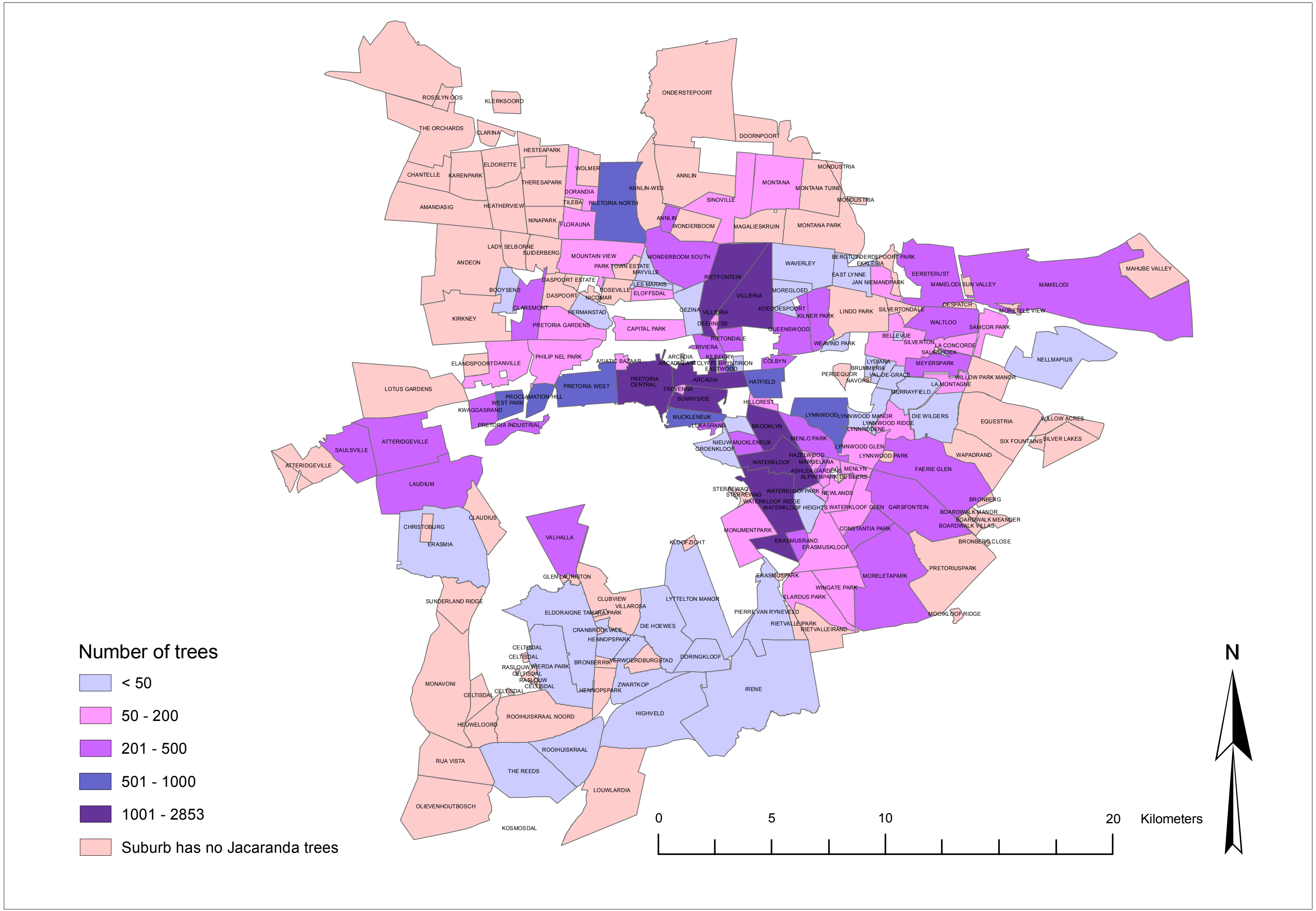

Figure 7.1. The number of Jacaranda street trees in Tshwane on 27 October 2003 based on the data provided by the City of Tshwane Metropolitan Municipality. The darker colours represent suburbs with larger numbers of trees.

An *intra*-street variation test conducted in the suburb of Waterkloof showed no significant difference between a long and short transect (ANOVA, Alpha = 0.05, p = 0.362). *Inter*-street variation showed no significant difference for trees measured in two different streets in the same suburb (ANOVA, Alpha = 0.05, Brooklyn p = 0.164; Hatfield, p = 0.394; Sunnyside p = 0.884).

After the statistical test sample analysis was conducted, it became clear that there was no definite urban to rural gradient in stem circumference size. Suburbs with their associated mean stem circumferences as well as the standard deviation for the circumferences are shown in Table 7.3. Figure 7.2 illustrates the stem diameter distribution in the different suburbs of the City of Tshwane as measured in this study. The trees with larger stem diameters tend to occur in the older suburbs. However, a clear urban to rural gradient is not deducible, which may be due to the city's morphological development since establishment in 1855 in combination with the planting regime of the Urban Forestry division of the municipality.

Suburb names, number of Jacaranda street trees per suburb, mean carbon per tree per suburb, standard deviation and total carbon in each suburb are shown in Table 7.4. The carbon calculations were based on the total number of trees in the suburbs in which trees were measured (73 suburbs) and amounted to 32 302 trees. The highest mean carbon quantities per tree occurred in Asiatic Bazaar, Laudium and Claremont with an estimated 0.713 tonne carbon (t C), 0.680 t C and 0.670 t C per street tree respectively (Table 7.4). The lowest mean carbon quantities per street tree occurred in Hestea Park, Newlands and Wingate Park with an estimated 0.009 t C, 0.006 t C and 0.004 t C per tree respectively (Table 7.4). Figure 7.3 shows the Jacaranda street tree carbon quantities for each suburb. The darkest rendered areas on the map indicate those areas with large carbon quantities. When calculating the sum of the total amount of carbon that the areas rendered in the darkest two colours contain it amounts to 5 425.980 t C, which indicates that 44.448% of the total quantity of carbon that is stored in the Jacaranda street tree population occurs in these suburbs (Pretoria Central, Brooklyn, Waterkloof, Sunnyside, Arcadia and Villieria).

Pretoria Central, Brooklyn, and Waterkloof had the highest total quantity of carbon with an estimated 1 379.037 t C (11.297% of the total quantity of carbon), 1 195.351 t C (9.792% of the total quantity of carbon), and 801.359 t C (6.565% of the total quantity of carbon) respectively. Hestea Park, Newlands and Wingate Park had the lowest total carbon quantities with an estimated 0.913 t C (0.007% of the total quantity of carbon), 0.346 t C (0.003% of the total quantity of carbon), and 0.344 t C (0.003% of the total quantity of carbon) respectively.

The total carbon quantity of all the street trees of all the suburbs in which trees were measured (73 suburbs) and on which the calculations are based, is estimated at 12 207.372 t C. A per tree mean of 0.378 t C was estimated for all the suburbs in which trees were measured. The total quantity of carbon for all the street trees in all the suburbs of Tshwane (114 suburbs) is estimated at 12 709.241 t C. Due to discrepancies observed in the quantity of trees it is suggested that an adjusted carbon quantity be assumed. Based on the aforementioned observations an adjustment of -10% is suggested and results in a total estimated carbon quantity for Tshwane's Jacaranda street trees of 11 438.317 t C.

Emission reductions are often reported as the full molecular mass of $CO_2$ rather than the atomic mass of carbon. The molecular mass of $CO_2$ can be obtained by multiplying the atomic mass of carbon by 3.67 (McPherson & Simpson, 1999). When applying this conversion factor the abovementioned trees will result in a per tree mean of 1.387 t $CO_2$ equivalent ($CO_2$eq) for all the measured suburbs, an estimated total of 46 642.916 t $CO_2$eq and an adjusted total of 41 978.625 t $CO_2$eq for all the Jacaranda street trees in Tshwane. Assuming a hypothetical market related price of US$10 tonne$^{-1}$ $CO_2$eq (www.pointcarbon.com accessed 31 May 2005), the total value of all the Jacaranda street trees in Tshwane based on the suggested adjusted carbon value could be estimated at US$ 419 786. At the time of writing the carbon dioxide value of all the Jacaranda street trees in the City of Tshwane could thus be estimated at R2 766 391 (exchange rate of US$1.00 = R6.59 (http://www.finance24.co.za/Finance/Sake/Home/, accessed 17/08/2004)).

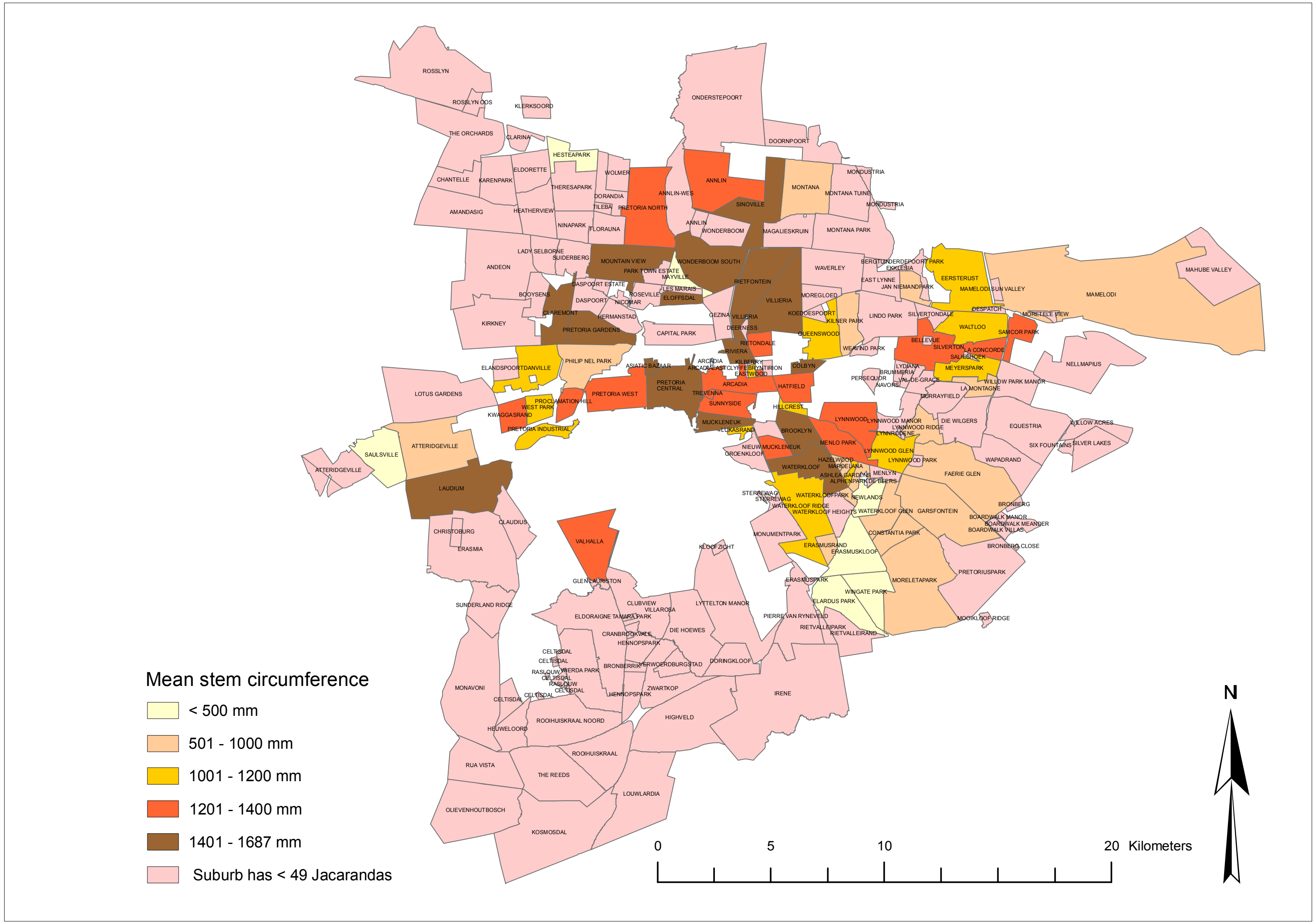

Figure 7.2. The mean stem circumference of Jacaranda street trees in the City of Tshwane as measured in February and March 2004. The darker colours represent suburbs with larger trees.

Table 7.4. Suburb names, number of Jacaranda trees per suburb (n), mean carbon (tonne) per tree per suburb in descending order, standard deviation (t C) and total carbon (tonne) in each suburb as well as the percentage of total carbon per suburb. The calculations are based on stem circumference measurements taken of Jacaranda street trees in February and March 2004 in the Pretoria region in the City of Tshwane

| No | Suburb | n | Mean t C per tree | Standard deviation t C | Total t C | % |
|---|---|---|---|---|---|---|
| 1 | Asiatic Bazaar | 67 | 0.713 | 0.286 | 47.791 | 0.391 |
| 2 | Laudium | 281 | 0.680 | 0.237 | 191.184 | 1.566 |
| 3 | Claremont | 344 | 0.670 | 0.304 | 230.642 | 1.889 |
| 4 | Colbyn | 308 | 0.631 | 0.243 | 194.436 | 1.593 |
| 5 | Mountain View | 153 | 0.612 | 0.250 | 93.645 | 0.767 |
| 6 | Wonderboom South | 227 | 0.582 | 0.279 | 132.014 | 1.081 |
| 7 | Waterkloof | 1412 | 0.568 | 0.265 | 801.359 | 6.565 |
| 8 | Sinoville | 82 | 0.553 | 0.211 | 45.358 | 0.372 |
| 9 | Muckleneuk | 559 | 0.520 | 0.301 | 290.647 | 2.381 |
| 10 | Riviera | 465 | 0.516 | 0.170 | 239.763 | 1.964 |
| 11 | Pretoria Gardens | 132 | 0.511 | 0.226 | 67.445 | 0.552 |
| 12 | Lynnwood | 514 | 0.508 | 0.406 | 261.110 | 2.139 |
| 13 | Eloffsdal | 159 | 0.487 | 0.336 | 77.396 | 0.634 |
| 14 | Pretoria Central | 2853 | 0.483 | 0.277 | 1379.037 | 11.297 |
| 15 | Brooklyn | 2535 | 0.472 | 0.150 | 1195.351 | 9.792 |
| 16 | Rietondale | 454 | 0.467 | 0.273 | 211.941 | 1.736 |
| 17 | Salvokop | 87 | 0.462 | 0.287 | 40.159 | 0.329 |
| 18 | Rietfontein | 1028 | 0.460 | 0.156 | 473.021 | 3.875 |
| 19 | Menlo Park | 378 | 0.458 | 0.235 | 173.310 | 1.420 |
| 20 | Villiera | 1207 | 0.458 | 0.225 | 552.806 | 4.528 |
| 21 | Pretoria-North | 840 | 0.443 | 0.227 | 372.497 | 3.051 |
| 22 | Sunnyside | 1836 | 0.430 | 0.177 | 788.651 | 6.460 |
| 23 | Pretoria West | 702 | 0.424 | 0.148 | 297.842 | 2.440 |
| 24 | Lisdogan Park | 531 | 0.415 | 0.255 | 220.387 | 1.805 |
| 25 | Trevena | 128 | 0.415 | 0.324 | 53.111 | 0.435 |
| 26 | Nieuw Muckleneuk | 284 | 0.407 | 0.196 | 115.723 | 0.948 |
| 27 | Proclamation Hill | 896 | 0.393 | 0.118 | 352.157 | 2.885 |
| 28 | Hatfield | 977 | 0.385 | 0.129 | 375.986 | 3.080 |
| 29 | Samcor Park | 95 | 0.381 | 0.278 | 36.223 | 0.297 |
| 30 | Arcadia | 1929 | 0.367 | 0.139 | 708.776 | 5.806 |
| 31 | Annlin | 492 | 0.359 | 0.251 | 176.627 | 1.447 |
| 32 | Kwaggasrand | 310 | 0.352 | 0.105 | 109.051 | 0.893 |

| No | Suburb | n | Mean t C per tree | Standard deviation t C | Total t C | % |
|---|---|---|---|---|---|---|
| 33 | Valhalla | 447 | 0.348 | 0.171 | 155.683 | 1.275 |
| 34 | Silverton | 166 | 0.332 | 0.157 | 55.080 | 0.451 |
| 35 | Clydesdale | 67 | 0.317 | 0.148 | 21.265 | 0.174 |
| 36 | Pretoria Industrial | 396 | 0.297 | 0.119 | 117.623 | 0.964 |
| 37 | Wes Park | 622 | 0.277 | 0.116 | 172.483 | 1.413 |
| 38 | Danville | 67 | 0.269 | 0.148 | 18.051 | 0.148 |
| 39 | Ashlea Gardens | 409 | 0.263 | 0.224 | 107.491 | 0.881 |
| 40 | Eastwood | 499 | 0.259 | 0.154 | 129.201 | 1.058 |
| 41 | Queenswood | 215 | 0.253 | 0.183 | 54.314 | 0.445 |
| 42 | Lynnwood Glen | 102 | 0.248 | 0.096 | 25.311 | 0.207 |
| 43 | Lukasrand | 323 | 0.248 | 0.150 | 80.042 | 0.656 |
| 44 | Waterkloof Ridge | 1509 | 0.243 | 0.095 | 367.287 | 3.009 |
| 45 | Watloo | 248 | 0.229 | 0.119 | 56.683 | 0.464 |
| 46 | Eersterust | 442 | 0.228 | 0.126 | 100.602 | 0.824 |
| 47 | Hillcrest | 155 | 0.218 | 0.134 | 33.859 | 0.277 |
| 48 | Meyers Park | 235 | 0.208 | 0.103 | 48.855 | 0.400 |
| 49 | La Montagne | 59 | 0.170 | 0.148 | 10.047 | 0.082 |
| 50 | Alphen Park | 96 | 0.165 | 0.085 | 15.823 | 0.130 |
| 51 | Constantia Park | 393 | 0.131 | 0.068 | 51.386 | 0.421 |
| 52 | Waterkloof Park | 189 | 0.127 | 0.082 | 24.096 | 0.197 |
| 53 | Maroelana | 60 | 0.127 | 0.059 | 7.619 | 0.062 |
| 54 | Garsfontein | 449 | 0.122 | 0.072 | 54.670 | 0.448 |
| 55 | Kilner Park | 235 | 0.121 | 0.073 | 28.406 | 0.233 |
| 56 | Waterkloof Glen | 155 | 0.115 | 0.057 | 17.824 | 0.146 |
| 57 | Atteridgeville | 268 | 0.114 | 0.041 | 30.545 | 0.250 |
| 58 | Erasmusrand | 227 | 0.109 | 0.078 | 24.692 | 0.202 |
| 59 | Mamelodi | 304 | 0.094 | 0.056 | 28.549 | 0.234 |
| 60 | Jan Niemand Park | 61 | 0.088 | 0.093 | 5.375 | 0.044 |
| 61 | Hazelwood | 77 | 0.067 | 0.109 | 5.197 | 0.043 |
| 62 | Moreleta Park | 348 | 0.065 | 0.049 | 22.452 | 0.184 |
| 63 | Lynnwood Ridge | 108 | 0.063 | 0.038 | 6.856 | 0.056 |
| 64 | Montana | 93 | 0.045 | 0.031 | 4.195 | 0.034 |
| 65 | Faerie Glen | 223 | 0.040 | 0.022 | 8.889 | 0.073 |
| 66 | Philip Nel Park | 56 | 0.039 | 0.021 | 2.182 | 0.018 |
| 67 | Mayville | 42 | 0.028 | 0.023 | 1.156 | 0.009 |
| 68 | Erasmuskloof | 70 | 0.023 | 0.025 | 1.625 | 0.013 |
| 69 | Saulsville | 208 | 0.014 | 0.009 | 2.900 | 0.024 |
| 70 | Elardus Park | 159 | 0.013 | 0.009 | 2.007 | 0.016 |
| 71 | Hestea Park | 103 | 0.009 | 0.007 | 0.913 | 0.007 |
| 72 | Newlands | 60 | 0.006 | 0.007 | 0.346 | 0.003 |
| 73 | Wingate Park | 92 | 0.004 | 0.003 | 0.344 | 0.003 |

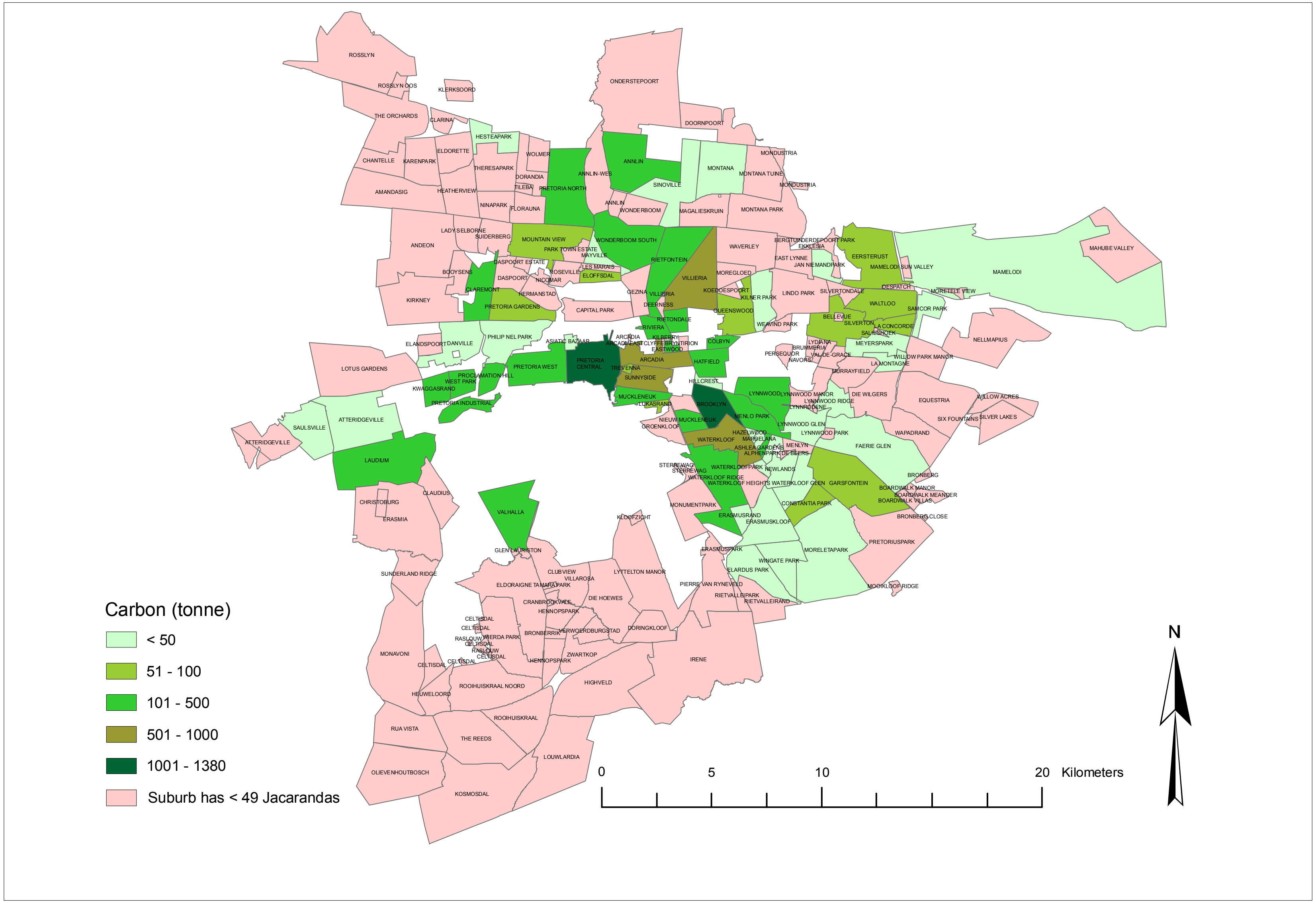

Figure 7.3. The estimated carbon quantities in each suburb for Jacaranda street trees in the City of Tshwane as determined in 2004. The darker colours represent suburbs with larger quantities of carbon.

Mean carbon per tree in a suburb, mean $CO_2$ per tree and the associated monetary values of the carbon dioxide equivalent in US dollars and Rand are shown in Table 7.5. The estimated mean value of a Jacaranda tree in the City of Tshwane is US$13.87 or R91.40. The estimated carbon dioxide equivalent ($CO_2$eq) stored in the above and belowground biomass of a mean tree in Asiatic Bazaar, Laudium, Claremont and Colbyn are 2.618 t $CO_2$eq, 2.497 t $CO_2$eq, 2.461 t $CO_2$eq, 2.317 t $CO_2$eq respectively and is worth an estimated R172.51, R164.55, R162.16 and R152.68 respectively (Table 7.5).

Total carbon per suburb, total $CO_2$ equivalent per suburb and the associated monetary values of the carbon dioxide equivalent in US dollars and Rand per suburb are shown in Table 7.6. The largest estimated total quantities of carbon dioxide equivalent that have been sequestrated at the time of measurements by all the Jacaranda street trees in a suburb are 5 061.067 t $CO_2$eq, 4 386.939 t $CO_2$eq, 2 940.988 t $CO_2$eq and 2 894.349 t $CO_2$eq and are of the suburbs Pretoria Central, Brooklyn, Waterkloof and Sunnyside respectively. The estimated monetary value of all the Jacaranda street trees in these suburbs is R333 524.29 (11.297% of the total value), R289 099.26 (9.792% of the total value), R193 811.08 (6.565% of the total value) and R190 737.60 (6.460% of the total value) respectively (Table 7.6).

Table 7.5. Suburb names, mean carbon (tonne) per Jacaranda tree in descending order, mean $CO_2$ eq (tonne) per Jacaranda tree and the associated monetary values of $CO_2$ eq in US$ and Rand per tree, based on trade value of US$10.00 per tonne $CO_2$ eq and an exchange rate of US$1.00 = R6.59 (http://www.finance24.co.za/Finance/Sake/Home/, accessed 17/08/2004). The calculations are based on stem circumference measurements taken of Jacaranda street trees in February and March 2004 in the Pretoria region in the City of Tshwane

| No | Suburb | Mean t C / tree | Mean t $CO_2$eq / tree | US$ | Rand |
|---|---|---|---|---|---|
| 1 | Asiatic Bazaar | 0.713 | 2.618 | 26.18 | 172.51 |
| 2 | Laudium | 0.680 | 2.497 | 24.97 | 164.55 |
| 3 | Claremont | 0.670 | 2.461 | 24.61 | 162.16 |
| 4 | Colbyn | 0.631 | 2.317 | 23.17 | 152.68 |
| 5 | Mountain View | 0.612 | 2.246 | 22.46 | 148.03 |
| 6 | Wonderboom South | 0.582 | 2.134 | 21.34 | 140.65 |
| 7 | Waterkloof | 0.568 | 2.083 | 20.83 | 137.26 |
| 8 | Sinoville | 0.553 | 2.030 | 20.30 | 133.78 |
| 9 | Muckleneuk | 0.520 | 1.908 | 19.08 | 125.75 |
| 10 | Riviera | 0.516 | 1.892 | 18.92 | 124.70 |
| 11 | Pretoria Gardens | 0.511 | 1.875 | 18.75 | 123.57 |
| 12 | Lynnwood | 0.508 | 1.864 | 18.64 | 122.86 |
| 13 | Eloffsdal | 0.487 | 1.786 | 17.86 | 117.73 |
| 14 | Pretoria Central | 0.483 | 1.774 | 17.74 | 116.90 |
| 15 | Brooklyn | 0.472 | 1.731 | 17.31 | 114.04 |
| 16 | Rietondale | 0.467 | 1.713 | 17.13 | 112.90 |
| 17 | Salvokop | 0.462 | 1.694 | 16.94 | 111.64 |
| 18 | Rietfontein | 0.460 | 1.689 | 16.89 | 111.29 |
| 19 | Menlo Park | 0.458 | 1.683 | 16.83 | 110.89 |
| 20 | Villiera | 0.458 | 1.681 | 16.81 | 110.77 |
| 21 | Pretoria-North | 0.443 | 1.627 | 16.27 | 107.25 |
| 22 | Sunnyside | 0.430 | 1.576 | 15.76 | 103.89 |
| 23 | Pretoria West | 0.424 | 1.557 | 15.57 | 102.61 |
| 24 | Lisdogan Park | 0.415 | 1.523 | 15.23 | 100.38 |
| 25 | Trevena | 0.415 | 1.523 | 15.23 | 100.35 |
| 26 | Nieuw Muckleneuk | 0.407 | 1.495 | 14.95 | 98.55 |
| 27 | Proclamation Hill | 0.393 | 1.442 | 14.42 | 95.06 |
| 28 | Hatfield | 0.385 | 1.412 | 14.12 | 93.07 |
| 29 | Samcor Park | 0.381 | 1.399 | 13.99 | 92.22 |

| No | Suburb | Mean t C / tree | Mean t $CO_2$eq / tree | US$ | Rand |
|---|---|---|---|---|---|
| 30 | Arcadia | 0.367 | 1.348 | 13.48 | 88.86 |
| 31 | Annlin | 0.359 | 1.318 | 13.18 | 86.82 |
| 32 | Kwaggasrand | 0.352 | 1.291 | 12.91 | 85.08 |
| 33 | Valhalla | 0.348 | 1.278 | 12.78 | 84.23 |
| 34 | Silverton | 0.332 | 1.218 | 12.18 | 80.25 |
| 35 | Clydesdale | 0.317 | 1.165 | 11.65 | 76.76 |
| 36 | Pretoria Industrial | 0.297 | 1.090 | 10.90 | 71.84 |
| 37 | Wes Park | 0.277 | 1.018 | 10.18 | 67.07 |
| 38 | Danville | 0.269 | 0.989 | 9.89 | 65.16 |
| 39 | Ashlea Gardens | 0.263 | 0.965 | 9.65 | 63.56 |
| 40 | Eastwood | 0.259 | 0.950 | 9.50 | 62.62 |
| 41 | Queenswood | 0.253 | 0.927 | 9.27 | 61.10 |
| 42 | Lynnwood Glen | 0.248 | 0.911 | 9.11 | 60.02 |
| 43 | Lukasrand | 0.248 | 0.909 | 9.09 | 59.93 |
| 44 | Waterkloof Ridge | 0.243 | 0.893 | 8.93 | 58.87 |
| 45 | Watloo | 0.229 | 0.839 | 8.39 | 55.28 |
| 46 | Eersterust | 0.228 | 0.835 | 8.35 | 55.05 |
| 47 | Hillcrest | 0.218 | 0.802 | 8.02 | 52.83 |
| 48 | Meyers Park | 0.208 | 0.763 | 7.63 | 50.28 |
| 49 | La Montagne | 0.170 | 0.625 | 6.25 | 41.19 |
| 50 | Alphen Park | 0.165 | 0.605 | 6.05 | 39.86 |
| 51 | Constantia Park | 0.131 | 0.480 | 4.80 | 31.62 |
| 52 | Waterkloof Park | 0.127 | 0.468 | 4.68 | 30.83 |
| 53 | Maroelana | 0.127 | 0.466 | 4.66 | 30.71 |
| 54 | Garsfontein | 0.122 | 0.447 | 4.47 | 29.45 |
| 55 | Kilner Park | 0.121 | 0.444 | 4.44 | 29.23 |
| 56 | Waterkloof Glen | 0.115 | 0.422 | 4.22 | 27.81 |
| 57 | Atteridgeville | 0.114 | 0.418 | 4.18 | 27.56 |
| 58 | Erasmusrand | 0.109 | 0.399 | 3.99 | 26.31 |
| 59 | Mamelodi | 0.094 | 0.345 | 3.45 | 22.71 |
| 60 | Jan Niemand Park | 0.088 | 0.323 | 3.23 | 21.31 |
| 61 | Hazelwood | 0.067 | 0.248 | 2.48 | 16.32 |
| 62 | Moreleta Park | 0.065 | 0.237 | 2.37 | 15.60 |
| 63 | Lynnwood Ridge | 0.063 | 0.233 | 2.33 | 15.35 |
| 64 | Montana | 0.045 | 0.166 | 1.66 | 10.91 |
| 65 | Faerie Glen | 0.040 | 0.146 | 1.46 | 9.64 |
| 66 | Philip Nel Park | 0.039 | 0.143 | 1.43 | 9.42 |
| 67 | Mayville | 0.028 | 0.101 | 1.01 | 6.66 |
| 68 | Erasmuskloof | 0.023 | 0.085 | 0.85 | 5.61 |
| 69 | Saulsville | 0.014 | 0.051 | 0.51 | 3.37 |
| 70 | Elardus Park | 0.013 | 0.046 | 0.46 | 3.05 |
| 71 | Hestea Park | 0.009 | 0.033 | 0.33 | 2.14 |
| 72 | Newlands | 0.006 | 0.021 | 0.21 | 1.40 |
| 73 | Wingate Park | 0.004 | 0.014 | 0.14 | 0.90 |

Table 7.6. Names of suburbs, total carbon (tonne) per suburb in descending order, total $CO_2$ eq (tonne) per suburb and the associated monetary values of the total t C and the total t $CO_2$ eq for each suburb in US$ and Rand, based on trade value of US$10.00 per tonne $CO_2$ eq and an exchange rate of US$1.00 = R6.59 (http://www.finance24.co.za/Finance/Sake/Home/, accessed 17/08/2004) as well as the percentages of the total amount. The calculations are based on mean per tree carbon values for each suburb that were derived from stem circumference measurements taken of Jacaranda street trees in February and March 2004 in the Pretoria region in the City of Tshwane

| No | Suburb | Total t C | Total t $CO_2$eq | US$ | Rand | % of total |
|---|---|---|---|---|---|---|
| 1 | Pretoria Central | 1379.037 | 5061.067 | 50610.67 | 333524.29 | 11.297 |
| 2 | Brooklyn | 1195.351 | 4386.939 | 43869.39 | 289099.26 | 9.792 |
| 3 | Waterkloof | 801.359 | 2940.988 | 29409.88 | 193811.08 | 6.565 |
| 4 | Sunnyside | 788.651 | 2894.349 | 28943.49 | 190737.60 | 6.460 |
| 5 | Arcadia | 708.776 | 2601.208 | 26012.08 | 171419.59 | 5.806 |
| 6 | Villiera | 552.806 | 2028.797 | 20287.97 | 133697.70 | 4.528 |
| 7 | Rietfontein | 473.021 | 1735.988 | 17359.88 | 114401.63 | 3.875 |
| 8 | Hatfield | 375.986 | 1379.870 | 13798.70 | 90933.43 | 3.080 |
| 9 | Pretoria-North | 372.497 | 1367.064 | 13670.64 | 90089.54 | 3.051 |
| 10 | Waterkloof Ridge | 367.287 | 1347.944 | 13479.44 | 88829.53 | 3.009 |
| 11 | Proclamation Hill | 352.157 | 1292.418 | 12924.18 | 85170.32 | 2.885 |
| 12 | Pretoria West | 297.842 | 1093.082 | 10930.82 | 72034.08 | 2.440 |
| 13 | Muckleneuk | 290.647 | 1066.675 | 10666.75 | 70293.90 | 2.381 |
| 14 | Lynnwood | 261.110 | 958.273 | 9582.73 | 63150.16 | 2.139 |
| 15 | Riviera | 239.763 | 879.928 | 8799.28 | 57987.29 | 1.964 |
| 16 | Claremont | 230.642 | 846.457 | 8464.57 | 55781.49 | 1.889 |
| 17 | Lisdogan Park | 220.387 | 808.820 | 8088.20 | 53301.21 | 1.805 |
| 18 | Rietondale | 211.941 | 777.822 | 7778.22 | 51258.45 | 1.736 |
| 19 | Colbyn | 194.436 | 713.580 | 7135.80 | 47024.92 | 1.593 |
| 20 | Laudium | 191.184 | 701.647 | 7016.47 | 46238.51 | 1.566 |
| 21 | Annlin | 176.627 | 648.222 | 6482.22 | 42717.84 | 1.447 |
| 22 | Menlo Park | 173.310 | 636.049 | 6360.49 | 41915.60 | 1.420 |
| 23 | Wes Park | 172.483 | 633.014 | 6330.14 | 41715.62 | 1.413 |
| 24 | Valhalla | 155.683 | 571.358 | 5713.58 | 37652.52 | 1.275 |
| 25 | Wonderboom South | 132.014 | 484.493 | 4844.93 | 31928.06 | 1.081 |
| 26 | Eastwood | 129.201 | 474.168 | 4741.68 | 31247.70 | 1.058 |
| 27 | Pretoria Industrial | 117.623 | 431.676 | 4316.76 | 28447.47 | 0.964 |
| 28 | Nieuw Muckleneuk | 115.723 | 424.703 | 4247.03 | 27987.93 | 0.948 |

| No | Suburb | Total t C | Total t $CO_2$eq | US$ | Rand | % of total |
|---|---|---|---|---|---|---|
| 29 | Kwaggasrand | 109.051 | 400.217 | 4002.17 | 26374.29 | 0.893 |
| 30 | Ashlea Gardens | 107.491 | 394.492 | 3944.92 | 25997.00 | 0.881 |
| 31 | Eersterust | 100.602 | 369.211 | 3692.11 | 24330.99 | 0.824 |
| 32 | Mountain View | 93.645 | 343.676 | 3436.76 | 22648.28 | 0.767 |
| 33 | Lukasrand | 80.042 | 293.753 | 2937.53 | 19358.31 | 0.656 |
| 34 | Eloffsdal | 77.396 | 284.044 | 2840.44 | 18718.52 | 0.634 |
| 35 | Pretoria Gardens | 67.445 | 247.524 | 2475.24 | 16311.82 | 0.552 |
| 36 | Watloo | 56.683 | 208.027 | 2080.27 | 13708.95 | 0.464 |
| 37 | Silverton | 55.080 | 202.144 | 2021.44 | 13321.29 | 0.451 |
| 38 | Garsfontein | 54.670 | 200.639 | 2006.39 | 13222.09 | 0.448 |
| 39 | Queenswood | 54.314 | 199.331 | 1993.31 | 13135.92 | 0.445 |
| 40 | Trevena | 53.111 | 194.918 | 1949.18 | 12845.08 | 0.435 |
| 41 | Constantia Park | 51.386 | 188.588 | 1885.88 | 12427.97 | 0.421 |
| 42 | Meyers Park | 48.855 | 179.296 | 1792.96 | 11815.62 | 0.400 |
| 43 | Asiatic Bazaar | 47.791 | 175.392 | 1753.92 | 11558.34 | 0.391 |
| 44 | Sinoville | 45.358 | 166.463 | 1664.63 | 10969.91 | 0.372 |
| 45 | Salvokop | 40.159 | 147.384 | 1473.84 | 9712.59 | 0.329 |
| 46 | Samcor Park | 36.223 | 132.938 | 1329.38 | 8760.63 | 0.297 |
| 47 | Hillcrest | 33.859 | 124.261 | 1242.61 | 8188.82 | 0.277 |
| 48 | Atteridgeville | 30.545 | 112.098 | 1120.98 | 7387.29 | 0.250 |
| 49 | Mamelodi | 28.549 | 104.775 | 1047.75 | 6904.64 | 0.234 |
| 50 | Kilner Park | 28.406 | 104.251 | 1042.51 | 6870.12 | 0.233 |
| 51 | Lynnwood Glen | 25.311 | 92.893 | 928.93 | 6121.64 | 0.207 |
| 52 | Erasmusrand | 24.692 | 90.618 | 906.18 | 5971.72 | 0.202 |
| 53 | Waterkloof Park | 24.096 | 88.432 | 884.32 | 5827.70 | 0.197 |
| 54 | Moreleta Park | 22.452 | 82.399 | 823.99 | 5430.12 | 0.184 |
| 55 | Clydesdale | 21.265 | 78.044 | 780.44 | 5143.09 | 0.174 |
| 56 | Danville | 18.051 | 66.247 | 662.47 | 4365.68 | 0.148 |
| 57 | Waterkloof Glen | 17.824 | 65.415 | 654.15 | 4310.88 | 0.146 |
| 58 | Alphen Park | 15.823 | 58.070 | 580.70 | 3826.79 | 0.130 |
| 59 | La Montagne | 10.047 | 36.874 | 368.74 | 2430.00 | 0.082 |
| 60 | Faerie Glen | 8.889 | 32.623 | 326.23 | 2149.86 | 0.073 |
| 61 | Maroelana | 7.619 | 27.963 | 279.63 | 1842.73 | 0.062 |
| 62 | Lynnwood Ridge | 6.856 | 25.161 | 251.61 | 1658.10 | 0.056 |
| 63 | Jan Niemand Park | 5.375 | 19.728 | 197.28 | 1300.05 | 0.044 |
| 64 | Hazelwood | 5.197 | 19.072 | 190.72 | 1256.82 | 0.043 |
| 65 | Montana | 4.195 | 15.395 | 153.95 | 1014.56 | 0.034 |
| 66 | Saulsville | 2.900 | 10.645 | 106.45 | 701.49 | 0.024 |
| 67 | Philip Nel Park | 2.182 | 8.007 | 80.07 | 527.65 | 0.018 |
| 68 | Elardus Park | 2.007 | 7.364 | 73.64 | 485.29 | 0.016 |
| 69 | Erasmuskloof | 1.625 | 5.963 | 59.63 | 392.95 | 0.013 |
| 70 | Mayville | 1.156 | 4.241 | 42.41 | 279.51 | 0.009 |
| 71 | Hestea Park | 0.913 | 3.352 | 33.52 | 220.87 | 0.007 |
| 72 | Newlands | 0.346 | 1.271 | 12.71 | 83.77 | 0.003 |
| 73 | Wingate Park | 0.344 | 1.261 | 12.61 | 83.10 | 0.003 |

# Discussion

## Methodological issues

### *Trees on street corners*

Whenever there were sufficient trees in a street, trees on the street corners were not measured because they are exposed to more negative environmental factors such as:

- Pavements: There are larger impermeable surfaces on street corners than elsewhere in the road reserve.
- Pollution: Trees on street corners are exposed not only to the concentrated pollution associated with an intersection but also to that of the two intersecting streets.
- Pedestrian traffic: This is possibly double compared to that along a street.
- Hawking: This is associated with soil compaction and impermeable surfaces provided for hawkers.

These corner trees are in some instances smaller and / or are more vandalized than the other trees.

### *Tree volume equation*

Equation (1) (see Methodology) is derived from measurements of *Jacaranda mimosifolia* trees in California USA conducted by the Urban Forest Ecosystem Institute at the California Polytechnic State University in San Luis Obispo in cooperation with the California Department of Forestry and Fire Protection in Riverside California (Pillsbury *et al.*, 1998). The largest stem circumference measured for the determination of equation (1) was 1844 mm (Pillsbury *et al.*, 1998). Errors could occur if equation (1) is used to estimate the volumes of trees with stem circumference values outside the sampling range from which equation (1) was derived (Pillsbury *et al.*, 1998). The stem circumferences of some of the trees measured in Tshwane exceeded 1844 mm and, therefore the results for these very large trees measured in Tshwane may be less accurate. The largest stem circumference measured for the determination of equation (1) (1844 mm) is however, larger than the largest mean stem circumference per suburb in Tshwane which was calculated for Asiatic Bazaar (1687 mm).

Trees used to determine equation (1) were trees with little or no defect but due to practical considerations the trees measured in the present study did in some instances have defects which could alter the biomass results. Pruning could also be a factor in the present study. No tree where the crown was excessively trimmed or pruned was included in the data from which equation (1) was derived (Pillsbury *et al.*, 1998). The Jacarandas of Tshwane are in some instances severely pruned to allow for overhead services. Biomass and carbon estimates calculated using equation (1) would be overestimates for these severely pruned trees. Furthermore, using equation (1) instead of a locally derived equation may result in discrepancies due to climatic, pedological and other environmental differences.

A literature search revealed no biomass or allometric equations for *Jacaranda mimosifolia* locally or internationally either in urban or natural settings. It is important to note that the volumetric equation used in this report provides only an *estimated* volume. Therefore all calculations derived from this equation are also estimates and thus all the resulting carbon calculations and the derived monetary values may only be quoted as *estimates* and should be viewed as *preliminary*.

The development of local biomass and allometric equations through destructive sampling could provide more accurate biomass estimates than those derived from equation (1). However, due to cost implications and because destructive sampling was not permissible in the urban environment (personal communication with Mr B. Dry, The Deputy Manager of Urban Forestry, Nursery and Training of the City of Tshwane Metropolitan Municipality) local equations were not developed.

Destructive sampling could be done by cutting down a number of Jacaranda trees ranging in sizes from small to large stem circumferences. The total mass of each tree should be determined and some samples should be dried to determine fresh : dry mass ratio and a mean wood density. The wood carbon content should also be determined. This process is very cumbersome, time consuming and costly. It would furthermore, mean that perfectly functional and healthy street trees would need to be destroyed. This technique, although very applicable, is not very well suited to the urban environment where every surviving tree is essential to the environmental urban well-being (Jim, 1989; McPherson *et al*., 1994; IPCC, 2000; Konijnendijk, 2000; Akbari *et al.*, 2001; Nowak & O'Connor, 2001; Akbari, 2002; Nowak *et al.*, 2002a; Nowak *et al.*, 2002b; McPherson, 2003). A future option would however be, for the municipality to go through this destructive sampling process for each tree that *by necessity* has to be removed, for example, for the widening of roads or similar infrastructural alterations. Through this procedure, a database could be built and regressions could be developed from which biomass could be more accurately calculated.

However, it is important to note that the Californian *Jacaranda mimosifolia* trees from which equation (1) was derived, were all urban trees and were therefore exposed to similar stressors that Tshwane's trees are exposed to. Furthermore, due to the limited availability of biomass equations for urban tree species, it is general practice to use those few equations that do exist for the urban and indeed natural environment in a generic manner (Goodman, 1990; McPherson *et al*.,1994; Nowak & Crane, 2002; Nowak *et al.*, 2002b). Equation (1) was also used by McPherson *et al.* (2001) for carbon sequestration calculations. This supports its applicability and appropriateness for such derivations.

*Root to shoot ratio*

Aboveground to belowground conversions (root : shoot ratios) are commonly used (Scholes & Walker, 1993; McPherson *et al.*,1994; McPherson *et al.*, 2001; Nowak & Crane, 2002; IPCC, 2003; Scholes, 2004), because it is difficult and therefore also expensive to determine belowground biomass. This is especially true of belowground biomass in urban environments. To determine root biomass, soil core samples could be taken (Scholes & Walker, 1993; Scholes, 2004). Other methods are to excavate the roots mechanically (with a backhoe or small excavator (Snowdon *et al.*, 2002)) or by excavating 1 m x 1 m x 1 m pits (Scholes & Walker, 1993) and then as in the case of the soil core and mechanical methods, to sieve, wash, oven dry, weigh and determine the carbon content of the roots and then to extrapolate to the whole tree's root system. This will have to be done for trees of various sizes to obtain a regression so that interpolation could be made.

The problems with these methods are that:

- roots of other plants may also be included in the sample
- the tree sampled may undergo crown dieback, growth retardation or in the case of smaller trees, they may even die
- it is likely that not all of the roots will be obtained because the larger trees have roots that enter private property or are beneath the road adjacent to the road reserve
- difficulty may arise in urban settings where concrete pavements may be encountered
- trenches may become hazardous to pedestrian and vehicle movement (parking) along road reserves
- this method is labour and time intensive
- the method is costly.

In the light of the above it was decided to use the root : shoot ratio (see Methodology) which was also used by McPherson *et al.* (2001) to determine urban carbon sequestration quantities for *Jacaranda mimosifolia* trees for Inland Empire Communities in California U.S.A..

*Wood density*

Carbon quantities of the trees measured are relatively low. This can largely be ascribed to the low wood density of *Jacaranda mimosifolia*. However, the density of 520 kg / m$^3$ measured for *Jacaranda mimosifolia* in Tshwane corresponds with the air dry density of 520 kg / m$^3$ for *Jacaranda acutifolia* given by J. Ilic (Email correspondence Dr Jugo Ilic, Commonwealth Scientific and Industrial Research Organization (CSIRO) Forestry and Forest Products, Private Bag 10, Clayton

South MDC, Victoria 3169, Australia. E-mail: Jugo.Ilic@csiro.au, (03/03/2004) who quoted Mainieri & Chimelo, (1989)). It also agrees well with the density of 550 kg / m$^3$ suggested by the Intergovernmental Panel for Climate Change (IPCC) for *Jacaranda* species in general (IPCC, 2003). A density of 590 kg / m$^3$ for *Jacaranda mimosifolia* in Argentina was cited by Lahitte & Hurrell (1999), but no indication could be found whether this density refers to oven-dried wood samples and it is possible that this density was that of either wet or air-dry wood.

*Termites*

Termites found at the base of Jacaranda trees in Laudium were not only concentrated at the trees but were often found elsewhere in the streets. Information received from the Institute for Commercial Forestry Research (Province of KwaZulu-Natal, South Africa) confirmed that the dead bark of Jacarandas are in some instances eaten by termites, but that they do not harm the live trees (Haigh, 1990). Therefore, the data gathered from Laudium could be included in the calculations.

### ***Intra*-street and *inter*-street comparisons**

The analysis of variance conducted for the *intra*-street and *inter*-street stem circumference variation showed no significant differences. This suggests that the socio-economic, cultural and environmental conditions within a suburb are relatively homogeneous. It could furthermore suggest that the trees in a street and suburb were planted at more or less the same time.

The standard deviations for various results are provided. These deviations should be borne in mind when using the results.

**Calculated carbon quantities**

The mean carbon per tree of some suburbs are amongst the highest calculated, yet some of these suburbs have lower total carbon quantities than suburbs with a relatively low mean carbon quantity per tree. The reason being that not only is a high mean carbon quantity per tree necessary to obtain a large total suburb carbon mass but a large number of trees is also necessary. For example, the Asiatic Bazaar has the highest mean carbon per tree (0.713 t C) but has only 67 trees and as a result has only the 43rd largest total quantity of carbon for all the suburbs (47.791 t C) (Table 7.4). On the other hand Pretoria Central is ranked 14th with regards to mean carbon per tree (0.483 t C), yet it is the suburb with the largest quantity of carbon stored in its street trees (1 379.037 t C). This can be attributed to the large number (2853) of Jacaranda street trees present in the suburb and its accompanying relatively high mean carbon quantity. The mean carbon quantity per tree is positively correlated to the mean stem circumference per tree. In the case of the three suburbs that have the lowest mean stem circumferences (Hestea Park, Newlands and Wingate Park) and therefore lowest mean carbon quantities per tree also have moderately low numbers of trees per suburb when compared with other suburbs. Consequently, these suburbs also have the lowest total quantity of carbon per suburb of all the measured suburbs.

The mean carbon per tree for the city's Jacaranda population was calculated as an estimated 0.378 t C while the highest mean carbon per tree for a single suburb was almost double this value (0.713 t C for Asiatic Bazaar). This suggests that the urban Jacaranda forest in Tshwane still has a large carbon sequestration potential. Therefore when street trees are removed (especially young trees) it should be appreciated that such a tree could have had a long life expectancy and therefore a relatively high carbon sequestration potential which is now lost. This loss should be considered when these removed trees are not replaced and can even be translated into monetary terms. However, when larger trees are removed monetary compensation may be required due to the destruction of green infrastructure but especially in context of these results, due to the release of carbon dioxide.

**Carbon trading**

It should be noted that the carbon that has been captured by the trees cannot be traded because amongst other reasons the trees were not part of a registered carbon sequestration project and most were planted before 1990 which is the Kyoto Protocol baseline year. It could furthermore be argued that the municipality would have planted the trees as a part of the normal day to day practice. This would indicate that there are no additionalities and that there is thus no extra carbon sequestrated over and above that which would have been sequestrated as part of the normal tree planting. Additionality is a prerequisite for carbon sequestration trading (see Chapter 9). Although the $CO_2$ price given is market related (Booth, 2003; McHale, 2003; www.pointcarbon.co.za accessed 31 May 2005) it still is hypothetical because as with other stock exchange commodities the value fluctuates and is exchange rate related.

## Other benefits associated with street trees

### *Increase in property values*

Increase in the value of properties can be used as an example of how street trees provide other monetary benefits. Well maintained trees on the road reserves increase the "curb appeal" of properties (McPherson *et al.*, 2001). McPherson *et al.* (2001) state the following:

> "Research comparing sales prices of residential properties with different tree resources suggests that people are willing to pay 3% - 7% more for properties with ample tree resources versus few or no trees."

In a telephonic survey conducted with various estate agents (AEA, ERA, RE/MAX, 23/08/2004) that are responsible for sales of properties in the wealthy suburb of Brooklyn a lowest price of R750 000 and a highest price of R8 million were suggested for current house prices. A mean house price of R1.5 million was however suggested for a 3 bedroom, 2 bathroom and double garage residence.

Assuming that there are three Jacaranda trees in front of each house and assuming a conservative curb appeal of 3% of the property value, it would provide an additional value to these trees of R7 500 per tree, R15 000 per tree and R80 000 per tree for the lowest, mean and highest suggested house prices in Brooklyn respectively. Even when applying a conservative 1% curb appeal value to the lowest house price in Brooklyn the value of a single street tree related to the house would still amount to R2 500.

The above increase in the value of property could then be translated to the increase in revenue from property tax and possible capital gain tax. These tax aspects are already included in the current property tax system although it has currently probably been determined on a subjective and intuitive basis. The municipality is thus already receiving this curb appeal tax value of street trees. However, more street trees planted by the municipality could contribute positively to the income of municipalities and the national government.

The "curb appeal" of Jacarandas increases the value of the trees. Although this survey was done in an affluent suburb with large trees, similar results (proportional to house prices for that area) could be expected in other areas where trees provide sufficient "curb appeal". The percentages suggested by McPherson *et al*. (2001) are not based on research conducted in South Africa and caution should therefore be used when applying these values in a South African context. Yet, the suggested percentages provide ballpark figures and due to the lack of local information could be considered when applied to the value of street trees.

*Environmental benefits*

As is the case with other urban trees, Jacaranda trees hold numerous other benefits apart from their carbon sequestration value and the increase in the value of property. Many of the benefits mentioned below can be converted to monetary values. Some of the benefits that urban trees hold are amongst others:

- Energy savings in terms of the heating and cooling of buildings (Akbari, 2002; Nowak *et al*., 2002c; Maco & McPherson, 2003)

- Reduction in soil erosion (McPhillips & Stone, 2003)
- Amelioration of the urban heat island effect (Rosenfeld *et al.*, 1998; Akbari *et al.*, 2001; Behm, 2003; January-Bevers, 2003)
- Amelioration of microclimatic conditions (Huang *et al.*, 1987; Jim, 1987; Simpson, 1998; Akbari, 2002; Nowak *et al.*, 2002a; January-Bevers, 2003)
- Air pollution reductions and air quality improvements (Rosenfeld *et al.*, 1998; Akbari, 2002; January-Bevers, 2003; Maco & McPherson, 2003; Nowak *et al.*, 2003)
- Positive impacts on human health and well being (Jim, 1987; Arnn & Svendsen, 2003; Buchner, 2003; Fowler & Hagevik, 2003; Grove, 2003; Wolf, 2003a; Wolf, 2003b)
- Rainfall interception and reduction in storm water runoff (Xiao *et al.*, 1998; McPherson, 1999; Xiao *et al.*, 2000; Gulick, 2003; Maco & McPherson, 2003)
- Wildlife habitat creation and increase in species diversity (Jim, 1987; Hosty, 2003),
- Reduced noise pollution (Jim, 1987; January-Bevers, 2003),
- Scenic beauty (Jim, 1987; McPherson, 1999; Abdollahi & Ning, 2003; Cremeens *et al.*, 2003; Hosty, 2003; January-Bevers, 2003)
- Recreation, environmental awareness and education opportunities (Jim, 1987; Coulter, 2003; de Vera, 2003; Fowler & Hagevik, 2003; Grove, 2003; Hosty, 2003; MacArthur, 2003; Malone, 2003; Roque, 2003)
- Contribution to the development of civic pride (Arnn & Svendsen, 2003; Fowler & Hagevik, 2003; Hosty, 2003)

- Reduction in the occurrence of crime (Hosty, 2003; MacArthur, 2003; Murray, 2003)
- Jacaranda flowering as tourist attraction

McPherson *et al*. (2001) determined the *annual* benefit of a 20 year old Jacaranda tree for Inland Empire Communities of California, U.S.A. According to their calculations the estimated net *annual* benefit from a public Jacaranda tree 12 m high and with a crown diameter of 10 m is US$37.44 (R246.72) (exchange rate of US$1.00 = R6.59, http://www.finance24.co.za/Finance/Sake/Home/, accessed 17/08/2004). In another study the compensatory value of an average U.S.A. urban tree was determined to be US$630 or R4 151.70 (Nowak *et al.*, 2002a). The compensatory value of urban trees represents the compensation to the owners for the loss of an individual tree and can be viewed as the value of the tree as a structural asset (Nowak *et al.*, 2002a). The Rand values of the above calculations do not take into account inflation, or other economic factors and variables since the date of publication. The above values, although not fully applicable to a South African context, do give an indication as to approximate estimated net annual benefits derived from a Jacaranda tree that is 20 years old and the compensatory value of an average urban tree.

Determining the local monetary value of the above benefits is beyond the scope of this study. However, a South African study is being undertaken to determine the value of a tree taking some of the above factors into account (personal communication, C. Marx, 2004, University of South Africa (formerly the Technikon of South Africa), cmarx@tsa.ac.za). Once the equations from that study are available the monetary value of some of the above factors could be incorporated into the estimated carbon sequestration benefits of Jacaranda trees as determined in this report.

*Costs of urban forests and trees*

Cognisance should be taken that there are also monetary and environmental costs involved with urban trees and forests (McPherson *et al*., 2002), for example:

- Propagation costs,
- Planting costs,
- Pruning costs,
- Tree and stump removal and disposal costs,
- Pests and disease control,
- Irrigation costs,
- Maintenance of infrastructure (e.g. sidewalks, storm and sewer systems and utility lines),
- Maintenance of leaf litter clean-up,
- Management of urban trees and forests,
- Administration costs,
- Carbon dioxide, other green house gas and pollutant emissions due to the above,
- Allergenic reaction to pollen,

## Tree numbers

The numbers of Jacaranda trees in the city (Table 7.7), which were quoted by various media, provide a good illustration of the uncertainty as to the total number of Jacarandas in the city's public and private land. The calculations in this report are based on tree census data, which were the most accurate data obtainable from the municipality when the field work was executed. Caution should be applied when extrapolating the results provided in this report to Jacaranda tree quantities quoted elsewhere because the carbon quantities in this report are based on a street tree sample, which may not be representative of the total Jacaranda population, which includes park and private trees.

However, Table 7.7 indicates that an appreciably larger Jacaranda population than that of the street tree population exists. This implies that the total carbon quantities of the Jacarandas in Tshwane could be much larger than suggested by this report. An extensive tree census and corresponding stem circumference sampling of public and private trees would provide valuable data to estimate the total carbon value of all of the city's Jacarandas.

Table 7.7. The year of publication and the number of Jacaranda trees quoted for streets, parks or the Pretoria region in the City of Tshwane as a whole as well as the publication name and reference is shown. "Streets" refers to street trees, "parks" refers to trees planted in public parks and "city" refers to the total number of trees planted in the whole city

| **Year of publication** | **Number of trees** | **Location of trees** | **Publication** | **Reference** |
|---|---|---|---|---|
| 1978 | 60 000 | Streets | South African Panorama | (Dellatola, 1978) |
| 1978 | 55 000 | Streets and parks | Beeld | (Van der Schijff, 1978) |
| 1980 | 50 000 | Streets | Omgewing / Environment RSA | (Department of Environment Planning and Energy, 1980) |
| 1984 | 70 000 | Streets | Pretoria News | (Boje, 1984) |
| 1984 | 55 000 - 60 000 | Streets | Beeld | (Reyneke, 1984) |
| 1985 | 70 000 | Streets | Beeld | (Robinson, 1985) |
| 1985 | 50 000 | Streets | Die Transvaler | (Botes, 1985) |
| 1987 | 50 000 | Streets | Pretoria News | (Uys, 1987) |
| 1991 | 75 000 | City | City Council of Pretoria Yearbook | (City Council of Pretoria, 1991) |
| 1991 | 63 000 | Streets | Pretoria News | (Gough, 1991) |
| 1991 | 70 000 | City | Record Moot | (Oberholzer, 1991) |
| 1998 | 70 000 | City (34 600 were planted by municipality) | Record East | (Marquart, 1998) |
| 2000 | 50 000 | City | Pretoria News | (Hlahla, 2000) |
| 2000 | 35 000 | City | Pretoria News | (Pretoria News, 2000) |
| 2002 | 40 000 | City | Record Central | (Linde, 2002) |
| 2003 | 70 000 | City (36 000 were planted by municipality) | Beeld | (Olivier, 2003) |
| 2003 | 70 000 | City | Beeld | (Williamson, 2003) |
| 2003 | 40 000 | City | Beeld | (Marais, 2003) |
| 2003 | 70 000 | City | Beeld | (Marais, 2003) |
| 2003 | 40 000 | Streets and parks | Record Central | (Record Central, 2003) |

### All trees sequestrate carbon

It should be appreciated that all trees sequestrate carbon albeit at different rates. The Jacaranda population is therefore not unique in this regard. However, due to the unique cultural importance of these trees as well as their integral part of the city's urban forest they are highly regarded by both the citizens and city urban forestry officials. It is however important to note that if *Jacaranda mimosifolia* and other trees maintain their Category 3 alien invader status it would eventually result in an establishment of a new urban forest that does not provide invasive threats. The issue of the inhabitants of Tshwane's emotional and affectionate association with the Jacaranda versus its invasive threat is however, one that can only be resolved with compromise.

## Conclusion

Mean carbon per tree per suburb, standard deviation and total carbon in each suburb were determined. The highest mean carbon quantity per tree for a suburb occurred in Asiatic Bazaar and is estimated at 0.713 t C. The lowest mean carbon quantity per tree for a suburb occurred in Hestea Park with an estimated 0.009 t C. The percentage error calculated for the mean carbon quantity per tree for all of the Jacaranda trees in Tshwane based on stem circumference measurements of 20 trees per suburb for 73 suburbs was 3.59%.

Pretoria Central, Brooklyn, and Waterkloof had the highest total quantity of carbon with an estimated 1 379.037 t C, 1 195.351 t C, and 801.359 t C respectively. In contrast, Hestea Park, Newlands and Wingate Park had the lowest total carbon quantities with an estimated 0.913 t C, 0.346 t C, and 0.344 t C respectively.

The total carbon quantity of all the suburbs in which street trees were measured (73 suburbs) and on which the calculations were based was estimated at 12 207.372 t C. A per tree mean of 0.378 t C was estimated for all the suburbs in which street trees were measured. The total quantity of carbon for all the street trees in all the suburbs of Tshwane (114 suburbs) is estimated at 12 709.241 t C. Due to discrepancies casually observed in the number of trees it is suggested that an adjusted carbon quantity be assumed. Based on the aforementioned observations an adjustment of -10% is suggested and results in a total estimated carbon quantity for Tshwane's Jacaranda street trees of 11 438.317 t C.

A per tree mean of 1.387 t $CO_2$ equivalent ($CO_2$eq) was estimated for all the measured suburbs, an estimated total of 46 642.916 t $CO_2$eq and an adjusted total of 41 978.625 t $CO_2$eq for all the Jacaranda street trees in Tshwane. Assuming a hypothetical price of US$10 tonne$^{-1}$ $CO_2$eq, the total value of all the Jacaranda street trees in Tshwane based on the suggested adjusted carbon value could be estimated at US$419 786. At the time of writing the carbon dioxide value of all the Jacaranda street trees in the City of Tshwane could thus be estimated at
R2 766 391.

The largest estimated total quantities of carbon dioxide equivalent that have been sequestrated at the time of measurements by all the Jacaranda street trees in each of the measured suburbs are 5 061.067 t $CO_2$eq, 4 386.939 t $CO_2$eq, 2

940.988 t $CO_2$eq and 2 894.349 t $CO_2$eq and are for the suburbs Pretoria Central, Brooklyn, Waterkloof and Sunnyside respectively and have an estimated monetary value of R333 524.29, R289 099.26, R193 811.08 and R190 737.60 respectively.

It should be stressed that the carbon that has been captured by the trees cannot be traded since amongst other reasons the trees were not part of a registered carbon sequestration project and most were planted before 1990 which is the Kyoto Protocol baseline year. Although the $CO_2$ price given (US$10 per ton $CO_2$eq) is market related (McHale, 2003) it is still hypothetical because as with other stock exchange commodities the prices fluctuate and are exchange rate related.

The carbon sequestration value of Jacarandas is but a portion of the total possible value of a large tree. These results do, however, give a first approximation as to the monetary value of Jacarandas. However, the Jacarandas of Tshwane are more than just a carbon sink and have additional value related to their urban environmental attributes. Furthermore, they are a part of the city's natural, cultural, and historical heritage and it should thus be appreciated that natural, cultural and historical heritage far outweighs the monetary benefits and values described in this report. Once such a heritage is lost it can become irreplaceable. Permission from the Department of Agriculture to provide the municipality the right to propagate Jacarandas for replacement purposes to maintain the city's Jacaranda population would prevent the loss of our national heritage. Although carbon sequestration estimates in this report provide tangible monetary values, it would be tragic if it were the only premise used to determine the value of the capital city of South

Africa's cultural, natural and historical heritage, especially a heritage that had its origin more than a century ago.

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# Chapter 8

## An international perspective on growth rate and carbon sequestration of urban trees

### Introduction

In this chapter comparisons are made between the growth rates of sixteen non-indigenous street tree species growing in the coastal area of southern California, USA and that of the three street tree species *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* investigated in this study. Comparisons are also made of the sequestration rate and capacity of the three species investigated in this study and that of the urban trees on other continents.

### Growth rate discussion

Peper *et al.* (2001) compared the growth of sixteen street tree species growing in southern California. These species were compared in terms of stem diameter at breast height (DBH), tree height and crown diameter growth. Their study was similar to that presented in Chapter 3 and 4 in this thesis in that predictive equations were derived and the comparisons made in Tables 8-1, 8-2 and 8-3 are based on predicted or modelled dimensions for both the local and the Californian species.

Table 8-1. Predicted stem diameter at breast height sizes for coastal southern California street tree species investigated by Peper *et al.* (2001) as well as for those investigated in this thesis. The stem diameter of *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* street tree species investigated in this thesis was measured at ground level or just above the basal swelling.

| | DBH (cm) | | DBH (cm) |
|---|---|---|---|
| | 15 years | | 30 years |
| *Combretum erythrophyllum** | 40.42 | *Combretum erythrophyllum** | 68.13 |
| *Pinus canariensis* | 36.92 | *Cedrus deodora* | 57.85 |
| *Ficus macrocarpa* | 32.74 | *Pinus canariensis* | 53.43 |
| *Cedrus deodora* | 32.69 | *Ficus macrocarpa* | 47.33 |
| *Rhus pendulina** | 29.13 | *Melaleuca quinquenervia* | 46.30 |
| *Rhus lancea** | 26.83 | *Cinnamomum camphora* | 44.93 |
| *Shinus terebinthifolius* | 26.50 | *Eucalyptus ficifolia* | 42.48 |
| *Cinnamomum camphora* | 24.00 | *Rhus lancea** | 39.00 |
| *Cupaniopsis anacardioides* | 22.70 | *Shinus terebinthifolius* | 38.52 |
| *Metrosideros excelsus* | 22.58 | *Metrosideros excelsus* | 36.99 |
| *Jacaranda mimosifolia* | 19.72 | *Ceratonia siliqua* | 36.39 |
| *Liquidambar styracifolia* | 18.93 | *Magnolia grandiflora* | 32.78 |
| *Melaleuca quinquenervia* | 18.65 | *Cupaniopsis anacardioides* | 32.61 |
| *Tristania conferta* | 18.45 | *Liquidambar styracifolia* | 27.55 |
| *Podocarpus macrophyllus* | 15.76 | *Jacaranda mimosifolia* | 26.35 |
| *Magnolia grandiflora* | 15.72 | *Tristania conferta* | 24.96 |
| *Ceratonia siliqua* | 15.32 | *Podocarpus macrophyllus* | 21.45 |
| *Callistemon citrinus* | 13.29 | *Callistemon citrinus* | 20.56 |
| *Eucalyptus ficifolia* | 12.05 | *Rhus pendulina** | # |
| Mean | 23.28 | Mean | 38.76 |

* Diameter was taken at ground level

$^{\#}$ No data

Table 8-2. Predicted tree height sizes for coastal southern California street tree species investigated by Peper *et al*. (2001) as well as for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* indigenous street trees investigated in this thesis

| | Height (m) | | Height (m) |
|---|---|---|---|
| | 15 years | | 30 years |
| *Pinus canariensis* | 16.21 | *Pinus canariensis* | 19.24 |
| *Cedrus deodora* | 11.77 | *Cedrus deodora* | 16.09 |
| *Liquidambar styracifolia* | 9.57 | *Combretum erythrophyllum* | 11.47 |
| *Combretum erythrophyllum* | 8.47 | *Liquidambar styracifolia* | 11.37 |
| *Rhus pendulina* | 8.39 | *Melaleuca quinquenervia* | 10.43 |
| *Cinnamomum camphora* | 7.74 | *Cinnamomum camphora* | 10.02 |
| *Cupaniopsis anacardioides* | 7.36 | *Metrosideros excelsus* | 10.00 |
| *Tristania conferta* | 7.22 | *Magnolia grandiflora* | 9.04 |
| *Melaleuca quinquenervia* | 6.90 | *Ficus macrocarpa* | 8.95 |
| *Ficus macrocarpa* | 6.86 | *Eucalyptus ficifolia* | 8.54 |
| *Magnolia grandiflora* | 6.59 | *Cupaniopsis anacardioides* | 8.24 |
| *Metrosideros excelsus* | 6.26 | *Tristania conferta* | 7.92 |
| *Shinus terebinthifolius* | 6.23 | *Shinus terebinthifolius* | 7.59 |
| *Jacaranda mimosifolia* | 5.95 | *Ceratonia siliqua* | 7.55 |
| *Podocarpus macrophyllus* | 5.73 | *Jacaranda mimosifolia* | 7.23 |
| *Rhus lancea* | 5.43 | *Podocarpus macrophyllus* | 6.75 |
| *Ceratonia siliqua* | 4.79 | *Rhus lancea* | 6.36 |
| *Callistemon citrinus* | 4.48 | *Callistemon citrinus* | 5.78 |
| *Eucalyptus ficifolia* | 4.11 | *Rhus pendulina* | # |
| Mean | 7.37 | Mean | 9.59 |

[#] No data

Table 8-3. Predicted crown diameter sizes for coastal southern California street tree species investigated by Peper *et al*. (2001) as well as for *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* indigenous street trees investigated in this thesis

| | Crown diameter (m) | | Crown diameter (m) |
|---|---|---|---|
| | 15 years | | 30 years |
| *Combretum erythrophyllum* | 10.37 | *Combretum erythrophyllum* | 17.56 |
| *Cedrus deodora* | 8.04 | *Cedrus deodora* | 11.70 |
| *Rhus pendulina* | 7.80 | *Cinnamomum camphora* | 10.44 |
| *Pinus canariensis* | 6.90 | *Metrosideros excelsus* | 10.01 |
| *Cinnamomum camphora* | 6.79 | *Rhus lancea* | 8.79 |
| *Cupaniopsis anacardioides* | 6.63 | *Ficus macrocarpa* | 8.73 |
| *Podocarpus macrophyllus* | 6.58 | *Magnolia grandiflora* | 8.56 |
| *Shinus terebinthifolius* | 6.53 | *Pinus canariensis* | 8.25 |
| *Rhus lancea* | 6.35 | *Cupaniopsis anacardioides* | 8.12 |
| *Ficus macrocarpa* | 5.97 | *Shinus terebinthifolius* | 8.08 |
| *Jacaranda mimosifolia* | 5.49 | *Jacaranda mimosifolia* | 8.04 |
| *Magnolia grandiflora* | 5.41 | *Ceratonia siliqua* | 7.98 |
| *Liquidambar styracifolia* | 5.33 | *Podocarpus macrophyllus* | 7.90 |
| *Tristania conferta* | 5.10 | *Eucalyptus ficifolia* | 7.66 |
| *Metrosideros excelsus* | 4.70 | *Liquidambar styracifolia* | 6.48 |
| *Ceratonia siliqua* | 4.47 | *Tristania conferta* | 6.22 |
| *Melaleuca quinquenervia* | 4.27 | *Melaleuca quinquenervia* | 6.16 |
| *Callistemon citrinus* | 3.74 | *Callistemon citrinus* | 4.85 |
| *Eucalyptus ficifolia* | 2.73 | *Rhus pendulina* | # |
| Mean | 5.96 | Mean | 8.64 |

[#] No data

In Table 8-1 it is shown that *Combretum erythrophyllum* has the largest stem diameter at an age of 15 years and 30 years. It is also shown that *Rhus pendulina* and *Rhus lancea* has the fifth and sixth largest stem diameters at age 15 years respectively. These stem diameters are inflated due to it being taken at ground level (see Chapters 2, 3 and 4) and is therefore a less accurate comparison. But it may, however, be conjectured that the diameter at breast height of these three species will be within the range of the diameter at breast height of the other sixteen species.

*Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* is positioned fourth, fifth and sixteenth respectively, when considering tree height at an age of 15 years (Table 8-2). However, both *Combretum erythrophyllum* and *Rhus pendulina* have a tree height of approximately half that of *Pinus canariensis* at an age of 15 years. At age 30 years *Combretum erythrophyllum*'s tree height is approximately 7 m less than that of the tallest tree measured namely *Pinus canariensis*.

Regarding crown diameter one observes that *Combretum erythrophyllum* has the largest crown diameter at both 15 years and 30 years. This may be attributable to the cultural practices such as pruning.

When comparing the species at an age of 15 years then both *Combretum erythrophyllum* and *Rhus lancea* show relatively high growth rates compared to the southern Californian street trees. A comparison at age 30 years indicates that *Combretum erythrophyllum* has a competitive growth rate also at this age which suggests that this species could be considered a fast growing tree when compared to those investigated by Peper *et al.* (2001).

## Carbon sequestration discussion

The carbon sequestration rates of *Combretum erythrophyllum*, *Rhus lancea* and *Rhus pendulina* street tree species investigated in this thesis are compared with those of other studies in Italy, United States of America and China. Even though comparisons are made they should be interpreted with caution due to a number of variables differing in each study. *Combretum erythrophyllum* does, however, sequestrate carbon at a similar rate to *Quercus ilex* and *Quercus pubescens* growing in Rome, Italy.

Table 8-4. Comparison of carbon sequestration rate (kg C / yr) for various cities and species

| **Author** | **City / state and country** | **Species** | **Tree size or age** | **kg C / year** |
|---|---|---|---|---|
| Current study | City of Tshwane, South Africa | *Combretum erythrophyllum* | Mean over 46 years | 29 |
| Current study | City of Tshwane, South Africa | *Rhus lancea* | Mean over 32 years | 8 |
| Current study | City of Tshwane, South Africa | *Rhus pendulina* | Mean over 15 years | 8 |
| Gratani *et al.* (2006) | Rome, Italy | *Quercus ilex* | Tree height 12 m | 22 |
| Gratani *et al.* (2006) | Rome, Italy | *Quercus pubescens* | Tree height 12 m | 30 |
| McPherson *et al.* (1999) | California, USA | *Populus 'Robusta'* | Mean over 30 years | 82 |
| McPherson *et al.* (1999) | Twin Cities, St Paul, USA | *Acer saccharum* | Mean over 60 years | 53 |
| McPherson *et al.* (1994) | Chicago, USA | Mean for study | < 80 mm DBH | 1 |
| McPherson *et al.* (1994) | Chicago, USA | Mean for study | >760 mm DBH | 93 |
| Yang *et al.* (2005) | Beijing, China | 11 main species | Mean for estimated 2.3 million trees | 5 |

Methodologies used to calculate carbon sequestration rates varied and differed in the studies presented in Table 8-4. Further to the application of the different methodologies, variation in carbon sequestration rates are due to amongst others different species, tree ages and sizes along with some of the factors mentioned below. Due to the above and amongst others the factors mentioned below, the comparisons in Table 8-4 are done with some degree of incongruence. Yet limited information exists and therefore these incongruent comparisons are inevitable.

### Factors that need consideration for growth and carbon sequestration comparisons

Caution needs to be applied when considering Tables 8-1 to 8-4 for comparative purposes. This is due to the numerous different growth conditions of trees in urban areas. The growth of trees in natural environments is the result of mainly species, genotype, climate (including rainfall), available water, geographic region, soil conditions and type as well as growth inhibitors like herbivory, pests and diseases. It should also be appreciated that trees in natural environments differ in some instances largely between species and geographic regions along with the other factors mentioned above. Urban trees share the same variables as trees in natural environments. There are, however, numerous additional factors influencing urban tree growth. Some of these factors will be discussed here to illustrate that care needs to be applied when making inter-geographic species as well as inter-species, inter-city and even intra-city growth and carbon sequestration comparisons.

The following are some factors that influence tree growth and carbon sequestration rates in urban areas which in turn influence growth prediction modelling:

1. Pruning practices differ depending on city ordinances, utilities and urban foresters' training. Pruning training also differs between training facilities.
2. Tree curb distances, tree-curb-paving distances and underground utility composition, structure and layout influence the rooting space available to trees and vary even in the same city between land uses within such a city.
3. Tree grids are often found in high density commercial areas. Often the sizes of these grids are limited. It there is no alternative direct source of water, then the

size of the tree grid as well as its position as a catchment basin is crucial to tree growth. These grids and water catchment issues vary across landuse, manufacturer specifications, cities and countries.

4. Irrigation varies greatly between landuse, for example, inner city and residential as well as between climatic zones such as for instance, arid versus mediterranean within a country. It may also differ according to income status of land owners in different landuses or suburbs.
5. Method of tree planting differs regarding, for example, the size and geometry of the planting hole, as well as the added supplements like compost or fertilisers during planting.
6. Soil compaction practices during road, pavement and lawn construction influence root penetration in these zones.
7. Soil type, texture, structure and acidity or alkalinity vary greatly even in the same city, as well as country. Tree growth may differ markedly, for instance due to differing soil pH, all other factors being equal.
8. Soil texture, structure and soil acidity or alkalinity alteration due to building, road and pavement rubble dumped in tree planting zones are problematic in South Africa and will differ in other countries and cities.
9. Municipal street tree fertilization practices as well as that in adjacent landuse for example lawn fertilization practices influence tree growth. Fertilization may also be influenced by cultural practices derived from, for example, education and income of land owners.
10. Street microclimate differs between landuses as well as within each landuse and influences tree growth.
11. Macro and local climate differs in each city and country.

12. Annual rainfall is an important factor regarding tree growth and may cause large variations in growth rates within the same and other species.
13. Number of frost free days influences the growth season of trees.
14. The number of photosynthetic sunny days and the length of photosynthetic time in those days varies.
15. There may be growth rate differences between cultivars within species.

## Conclusion

The above growth influencing factors vary in most cities across the world and also vary with time in each city. It is noteworthy that the species compared above mostly do comply within reasonable growth bounds. Large variation is, however, apparent regarding carbon sequestration rates which lead to the question as to the appropriateness of such inter-geographic and inter-city comparisons.

There are limited urban growth and carbon sequestration data and equations available. It is thus suggested that those equations and data that do exist be used in a generic manner, yet with the proviso that their original context be noted and taken into consideration during their application. These factors also need to be communicated in literature and commercial publications in which they are applied in order to remain transparent and provide results that may be judged objectively.

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# Chapter 9

## Urban forest carbon sequestration: *Quo Vadis*?

### Introduction

The monetary budgets available for urban forestry have declined over the past few years in the City of Tshwane (personal communication: B. Dry, Deputy Manager: Urban Forestry, Nursery and Training of the City of Tshwane Metropolitan Municipality, 2004). According to Mr Dry urban forestry is not viewed as a priority public service but rather as an aesthetic attribute of the city and is hence allocated less funds. It is the author's impression when discussing urban forestry monetary budgets with municipal officials that this is a common situation in South Africa and that there is a general despondency about this trend and even desperation for the acknowledgement of the importance of the urban forest as an integral part of the city's urban infrastructure. Few officials furthermore, have verification of the value that urban forests hold in a local context to be able to motivate larger budgets. The results presented in Chapter 6 and Chapter 7 have been an attempt at illustrating the importance of the urban forest as part of a city's infrastructure by quantifying the carbon stored in the trees in monetary terms. However, carbon sequestrated by past and recently established urban forests do not qualify for actual carbon trade. Hence, the following is a brief discussion as to possible carbon baselines, business as usual practices and leakages that need to be considered in carbon accounting for actual trading of the carbon stored in current and new urban forests. The concept of additionality is also discussed in order to provide some possible solutions to obtain tangible urban forest carbon monetary benefits.

### Baselines and business as usual practice

A baseline is defined by the Intergovernmental Panel on Climate Change (IPCC 2000) as: ”… a reference scenario against which a change in greenhouse gas emissions or removals is measured.” Baselines are thus the point of departure from which carbon debits or credits are calculated. The baseline for municipal urban tree planting could be taken at a specific stage since 1990, which is the Kyoto Protocol cut off date. It is crucial to determine the baseline if Municipalities desire to become carbon accountable.

Municipal tree planting baselines should, however, also be viewed in terms of business as usual practices. In this case the business as usual practice would be the continuation of tree planting which would have taken place regardless of climate change and the Kyoto Protocol. Business as usual practice is not eligible for carbon credits since it does not provide additionalities (see below). However, even though business as usual tree planting practices are viewed as non-credit situations, it still provides an opportunity for calculating the carbon value of the urban forest as has been done in this thesis. Carbon sequestration values of urban trees could be used as motivation for funding for increased tree planting by illustrating the value that these trees hold for urban and global societies.

### Leakage

#### *Urban forest and street tree leakages*

Emissions related to urban forestry tree planting programmes may in some instances be viewed as greenhouse gas “leakages”. A leakage relating to *natural* *forests* and *plantations* is defined as "… the *indirect* impact that a targeted land-use, land-use change and forestry activity in a certain place at a certain time has on carbon storage at another place or time" and also as "… *unanticipated* decrease or increase in greenhouse gas benefits outside of the project's accounting boundary … as a result of project activities" (IPCC 2000; Schwarze *et al*., 2002). In many instances urban forestry management practices have been well established and therefore the emissions resulting from an urban forestry project are not to be perceived as leakages, but rather as project debits that need to be incorporated into the initial project proposal. Schwarze *et al*. (2002) do, however, identify an alternative type of leakage, which he refers to as a "*life-cycle emissions shifting leakage*". They define it as mitigation activities (such as reforestation) that increase emissions in upstream or downstream activities of a forestry project, for example, a reforestation project in a rural setting that increases the use and operation of machinery, which results in fossil fuel emissions (Schwarze *et al*., 2002).

The concept of life-cycle emission shifting leakages may also be applicable to urban forestry and street trees. The urban forestry and urban sprawl leakages mentioned below should be viewed as a part of this broader scope of the term. The term leakage as such has not previously been applied to the urban forest or street tree setting and the leakages mentioned below are thus debateable and open for discussion. They are also not an exhaustive list and do not necessarily fit the use of the term leakages as applied to a conventional natural forest and plantation context. This is an attempt to apply the term to urban forestry and particularly to a street tree context and it is acknowledged that this application may prove to be contentious. It is, however, of paramount importance to identify possible urban forestry leakages so that holistic carbon accounting can be done and that a project may thence be considered for carbon emission reduction certification by the CDM (Clean Development Mechanism).

There are numerous possible carbon leakages relating to tree planting and maintenance. Carbon dioxide emissions from fuel in cultivation, tree planting and maintenance (wood chippers, transportation) are examples. There are other carbon emissions as well: tree branches that are pruned, inevitable tree felling due to pests, wind or disease damage and tree removal by private land owners currently result in carbon dioxide emissions due to decomposition and are hence street tree carbon leakages. There are street tree database inaccuracies as was shown in the Chapter 7. The loss of street trees, which are not accounted for in the Municipal database, could also be viewed as a leakage.

Nitrous oxide ($N_2O$) is a non-carbon greenhouse gas, which is released with the application of fertilisers. The use of fertilisers in the propagation, cultivation and planting of urban trees could thus also be seen as possible greenhouse gas emission leakage.

Tree and other vegetation waste that accumulate on landfill sites may cause increased methane (greenhouse gas) production at these sites (IPCC 2000). This possible leakage may be reduced by improving the life span of trees as well as by utilising the biomass for other purposes.

Emission leakages need to be accounted for to obtain the complete carbon stock of urban forest or tree-planting projects. The above and other possible leakages should be anticipated and leakage projections should be made when making carbon sequestration projections especially for new tree planting projects. These possible urban forest leakages were not part of this study but need to be addressed in order to obtain complete carbon accounting.

Current carbon leakage emissions emerging from current and past urban forestry establishment and maintenance are, however, not seen as carbon debit but rather as business as usual carbon emission practices. Municipalities could hence not be debited for these business as usual leakages. However, should these leakages be reduced due to other forest management practices then the reduced emission may be seen as additionality and may possibly be a carbon credit.

*Urban sprawl leakage*

Urban sprawl needs to be considered when viewing the City of Tshwane as well as South Africa in a broader potential urban vegetation carbon emission leakage perspective. Sprawl has increased due to governmental commitment to the provision of housing to the previously disadvantaged. What needs to be considered is that during the construction of the houses the stands are mostly denuded of vegetation, this results in carbon debits. Currently, neither the government, whether national, provincial or local, nor the landowner are being held responsible for the deforestation and vegetation clearing which results in carbon releases and increases the effects of global warming. Accountability for this carbon emission is necessary.

Conversely some of these housing areas are re-vegetated. Again no ownership is taken for the carbon sequestration taking place with urban tree planting and urban greening. Ownership may be viewed positively since it may produce tradable carbon credits, which may in turn aid these communities and motivate further urban tree planting. Government policy needs to be drafted in order to firstly obtain the credits and secondly to allocate them to the rightful recipients.

The east of Tshwane underwent severe urban sprawl with low-cost housing, as well as higher density and high-income housing developments. Based on visual observation areas with low income housing typically stay denuded of vegetation post construction and therefore remains at least for some time in a carbon debit situation. Tree planting may alter this debit. Higher density developments for example two-story cluster housing are possibly also built and maintained at a carbon loss when only considering pre - and post - construction vegetation. This is due to the small spaces available for greening and tree planting in these developments. They will probably remain in this carbon debit state. Some high-income residential developments in the east of Tshwane are developments with large stands and golf course estates. Due to intense landscaping these areas are possibly carbon neutral or in a carbon benefit situation. It is re-emphasized that accountability for land clearing in urban developments is necessary.

## Additionality

An "additionality" would be a prerequisite to incur urban forestry carbon credits (IPCC 2000) and certified emission reductions (CERs). Additionality is the issue of whether a forestry action enables more carbon storage than would have been stored without a specific human intervention (Scholes 2004). A policy was adopted to limit the CDM forestry projects for the first commitment period (2008 – 2012) to reforestation and afforestation projects only (UNFCCC 2001; Brown *et al*. 2002). In the view of Municipal tree planting budget cuts it is unlikely that many municipalities will be able to obtain additionality through additional afforestation and reforestation. Additional afforestation and reforestation may also be regarded as part of business as usual practice of a municipality. In the discussion below suggestions as to possible additionalities that may be taken into consideration are made. These suggestions are derived from a local South African environment and are open for discussion and it is hoped that they will fuel the debate. The term is, however, applied broadly to an urban forestry context. As yet, current and future CDM additionality in terms of alternative urban forest management practice have not been defined. The urban forest management practices suggested below, although not exhaustive, may potentially be incorporated in the consideration of urban forestry additionality for the next commitment period. It should furthermore be mentioned that alternative forest management practice additionality, although not necessarily approved by the CDM for the current commitment period, may be acceptable for trade to, for example, the World Bank's Bio Carbon Fund without prior emission reduction certification.

An example of alternative forest management practice is to use pruned branches and felled trees as structural timber in previously disadvantaged communities. The wood could also be harvested and used in furniture and curio industries. This will lengthen the carbon storage time because the wood will not decompose as speedily than had it been chipped and used as mulch. Harvestable wood products could be viewed as a beneficial additionality. However, product life cycle assessment may be complex.

If the wood of pruned and felled trees is used as biofuel for cooking and heating purposes it could also be viewed as reducing the use of fossil fuels like paraffin and coal and could hence be seen as a reduction in the latters' emissions and could thus result in additionality. Furthermore, converting biomass to energy may reduce the need for landfill space and reduce methane emissions from landfill sites (IPCC 2000) Economic benefits from the biomass energy conversion may offset the costs (IPCC 2000).

Prolonging the lifespan of trees and improving urban tree growth rates may also ensure additionality due to more carbon being sequestrated for longer time periods (IPCC 2000). These two aims could be achieved through improving urban forest maintenance and management practices.

Tree maintenance additionality could perhaps also be reached through alternative street tree pruning practices. If, for example, less power equipment is used and is replaced by conventional manpower then less fuel will be used resulting in a possible additionality. This option will also result in work creation. Furthermore if pruning cycles could be lengthened to two or three year cycles instead of business as usual annual cycles then possible additionality may also be reached through the reduction in use of fossil fuel.

A further potential and possible option to attain additionality is making use of non-government tree planting organisations like, for example, Food and Trees For Africa (FTFA). Currently FTFA focuses its tree planting programmes on new housing developments of previously disadvantaged communities. The backlog of tree planting in the older and established Townships is, however, the main focus of the Municipality. FTFA could possibly be granted permission or be requested to supplement current tree planting for these Township areas. FTFA may in turn obtain carbon credits for the trees planted because the extra trees planted may be regarded as an additionality. This is because the trees would not have been planted had an alternative forest management policy not been adopted by the Municipality and because additional trees, to that of the business as usual scenario, will be planted. It can be a condition that the proceeds from carbon credit additionality trade will be used for further urban forestry. Further tree planting once again starts the cycle of tree planting, incurring additionality and carbon trade, which will result in further trees being planted, and the cycle repeats itself. This opportunity will become even more lucrative if the Municipality accept responsibility for maintenance of the trees, which will incur carbon debits due to maintenance practices to the Municipality and result in maximum availability of carbon additionality credits for FTFA. It is suggested that potential urban forest additionalities be made a research priority so that urban tree planting may advance at a more rapid rate.

## Conclusion

Urban forest carbon sequestration research is currently one of the most important fields of urban forestry research. This is because of the fact that global warming is the single most devastating threat to biodiversity and indeed life on earth as we currently know it and urban forestry carbon sequestration research is thus of global importance. Hence, budget reduction trends and the perception of the relatively low importance of urban forests need to be altered and it probably cannot be changed by research and results based on urban carbon sequestration findings alone. Other urban forest benefits as mentioned in the previous chapters also need to be researched to complement carbon sequestration research. This is necessary so that all aspects of the attributes of urban forests could be used for the motivation to plant more trees which will hence result in more effective climate amelioration in the urban environment. The potential devastating threat of global warming could thus be addressed, albeit in moderate terms, by urban tree planting, which is motivated by the monetary value of urban forests to South African communities and especially previously disadvantaged communities. The urban forestry opportunity in previously disadvantaged communities and Townships will furthermore enable these *non-industrialised*, *poor populations* of a *developing* country to assist in the amelioration of the effects of industrialisation and deforestation on global warming.

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# Appendix A

The following is a South African patent written in collaboration with a local patent law firm. The patent was based on the research done for this thesis.

## The patent reads as follows:

THIS INVENTION relates to ecological management. In particular, the invention provides a method of ameliorating the ecological effects of carbon emissions. The invention also relates to a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period. The invention further extends to carbon credits for offsetting carbon emissions.

The invention provides a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 4.44032 - 4.72672, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

The stem circumference *(c)* is preferably estimated by using a point value for *A* of 4.58352, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804.

The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Combretum erythrophyllum*. It should be appreciated, though, that the abovementioned values and equation could also be applied to trees of other species. In particular, the values given below for use in respect of trees of various associated species can be used for any tree which has a sufficiently similar size for such application to be made with botanical assurance.

By the natural logarithm is meant $\log_e$, also referred to as ln.

It will be appreciated that trees assimilate atmospheric carbon during their growth process. To curb carbon emissions, which serve to increase the atmospheric carbon concentration and contribute to global warming, industrially active entities may be set limits as to the quantity of carbon they are allowed to emit. Application of the method enables such entities to exercise the option of buying carbon credits in respect of trees which have been planted by themselves or by others, thus increasing the quantity of carbon which that entity may emit by the quantity of carbon sequestered by the associated trees.

It should further be appreciated that the carbon credits relate to a predetermined time period, and that the quantity of carbon offset by the carbon credits is equal to the quantity of carbon sequestered by the associated trees over the predetermined period. If the predetermined period starts at planting of the trees, calculation of the quantity of carbon sequestered by the trees at the end of the period will provide the quantity of carbon emissions which the carbon credits permit. Otherwise, the quantity of carbon sequestered by the trees at the start of the period is subtracted from the quantity of carbon sequestered at the end of the period, to provide the total quantity of carbon sequestered by the trees in the predetermined period.

Stem circumference or stem diameter at ground level implies a measurement taken at 0 - 20 cm above the ground or appropriately measured above the basal swelling. Furthermore, the basic equation and associated values of *A*, *b* and *MSE* are intended for use in respect of trees having an age of up to about thirty years, with the accuracy of the equation declining for trees above that age. For trees of the species *Combretum Erythrophyllum*, the given equations are accurate up to an age of about 47 years, while the equations are accurate in respect of *Rhus lancea* up to 32 years and up to 15 years for *Rhus pendulina*.

The above equation implies a relationship between appropriately paired values of tree age and the stem circumference of a plurality of trees. By use of pre-estimated point values for *A*, *b* and *MSE*, an estimated stem circumference *(c)* for one of the trees can be found. It should be appreciated that the stem circumference which is estimated in this way represents the stem circumference of a tree which is statistically representative of the plurality of trees. This representative tree is referred to in the above equation as the $i^{th}$ tree. In other embodiments of the invention, which are defined below, there is provided equations which describe a relationship between appropriately paired values of tree age and stem diameter.

The point values for *A*, *b*, and *MSE* are statistically the best estimates to use in estimating the stem circumference or stem diameter, as the case may be, of one of the plurality of trees, while the ranges of values for *A*, *b*, and *MSE* represent the 95% confidence intervals for each. It will be appreciated that the values of *A*, *b*, and *MSE* vary for different tree species. This applies also to the point values and to the value ranges for use in respect of the respective tree species.

The invention extends to a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 4.84110 - 5.01122, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

The stem circumference *(c)* may be estimated by using a point value for *A* of 4.92616, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522. The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus lancea*.

The invention further provides a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the i$^{th}$ tree, in millimeters;

*EXP* = the inverse of the natural logarithm;

*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and

$x_i$ = the value of the age of the i$^{th}$ tree, in years,

using a value for *A* of 4.32945 - 4.73904, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

The stem circumference *(c)* is preferably estimated by using a point value for *A* of 4.53425, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892.

The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus pendulina*.

It may sometimes be necessary to calculate the quantity of carbon sequestered by trees which are not of the species *Combretum erythrophyllum*, *Rhus pendulina*, or *Rhus lancea,* and of which the mean approximate tree size is not sufficiently similar to one of the abovementioned species to justify application of the equation and values for one of said species. In such case, values of *A, b* and *MSE* are used for an appropriate combination of the abovementioned three species.

The invention thus extends to a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

using a value for *A* of 4.68409 - 4.85555, a value for *b* of 1.90258 - 2.20418, and a value for *MSE* of 0.093359 - 0.13699.

The stem circumference *(c)* is preferably estimated by using a point value for *A* of 4.76982, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204.

The method as defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea.*

The invention also extends to a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

using a value for *A* of 4.79386 - 4.95424, a value for *b* of 1.65237 - 1.90861, and a value for *MSE* of 0.048428 - 0.073722.

The stem circumference *(c)* is typically estimated by using a point value for *A* of 4.87405, a point value for *b* of 1.78049, and a point value for *MSE* of 0.059088.

The method as defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

The invention yet further provides a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the i$^{th}$ tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A$, $b$, $MSE$ = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the i$^{th}$ tree, in years,

and by using a value for *A* of 3.29559 - 3.58199, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

The stem diameter *(d)* is preferably estimated by using a point value for *A* of 3.43879, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804.

The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Combretum erythrophyllum*.

The invention also extends to a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the i$^{th}$ tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A$, $b$, $MSE$ = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the i$^{th}$ tree, in years,

using a value for *A* of 3.69637 - 3.86649, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

The stem diameter *(d)* is preferably estimated by using a point value for *A* of 3.78143, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522.

The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus lancea*.

The invention further provides a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 3.18472 - 3.59431, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

The stem diameter *(d)* is typically estimated by using a point value for *A* of 3.38952, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892.

The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus pendulina*.

The invention also provides a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 3.53936 - 3.71082, a value for *b* of 1.90258 - 2.20418, and a value for *MSE* of 0.093359 - 0.13699.

The stem diameter *(d)* is preferably estimated by using a point value for *A* of 3.62509, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204.

The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea.*

The invention extends to a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{ \frac{MSE}{2} + \left( A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 3.64913 - 3.80951, a value for *b* of 1.65237 - 1.90861, and a value for *MSE* of 0.048428 - 0.073722.

The stem diameter *(d)* is preferably estimated by using a point value for *A* of 3.72932, a point value for *b* of 1.78049, and a point value for *MSE* of 0.059088.

The method as defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

The estimated stem diameter at ground level *(d)* may be used to obtain an estimated stem circumference at ground level *(c)*.

Typically, the calculation of carbon sequestered by said one of the trees includes the intermediate step of calculating an aboveground dry biomass of said tree, preferably by use of the following equation:

$$\log TDM = 2.397(\log c) - 2.441$$

where:

*TDM* = the estimated aboveground dry biomass of the tree in kilograms; and
*c* = the stem circumference of the tree at ground level, in centimetres.

The method may include the step of calculating the quantity of carbon sequestered by said one of the trees by estimating a fraction of the calculated aboveground dry biomass of the tree which is constituted by sequestered carbon. Calculating the quantity of carbon sequestered by the tree may for instance be by multiplying the aboveground dry biomass (*TDM*) by a factor of 0.6 - 0.9, preferably by a factor of 0.7 - 0.8, and most preferably by a factor of 0.7533.

The abovementioned factor is arrived at by assuming that the total belowground dry biomass is equal to 65-87%, preferably 78% of the aboveground dry biomass (*TDM*). Furthermore, it is assumed that 3-10%, preferably 5.4% of aboveground dry biomass (TDM) is leaf- or foliage dry biomass and should be disregarded. It is estimated that 40-55%, preferably 45% of aboveground dry biomass (*TDM*) is comprised of carbon and in respect of belowground dry biomass, it is estimated that 40-55%, preferably 42% thereof comprises carbon. These estimates translate, when the preferred values are used, to a ratio of 0.7533 of sequestered carbon to aboveground dry biomass.

The method may include calculating the total quantity of carbon sequestered by one of the trees at the end of the predetermined time period, calculating the total quantity of carbon sequestered by that tree at the beginning of the predetermined time period, and subtracting the one calculated value from the other to find the total quantity of carbon sequestered by that tree in the predetermined time period.

Typically, the quantity of sequestered carbon is calculated simultaneously for a plurality of trees of the same species and of the same age, the calculated quantity of carbon sequestered by one of the trees over the predetermined time period being multiplied by the number of trees, to obtain the total quantity of carbon sequestered by the plurality of trees. It should be appreciated that the carbon sequestered by a plurality of trees of varying but similar ages may also be used, the age (*x*) used for this purpose being the mean age of the trees.

The method may include the prior step of planting the trees in respect of which the carbon credits are provided. The method may in such case further include cultivating the trees for the extent of the predetermined time period.

The method will further typically include receiving financial compensation, e.g. payment, in return for providing the carbon credits.

The invention also provides a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x+1))\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.44032 - 4.72672, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

The system is preferably arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.58352, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Combretum erythrophyllum*.

The invention yet further provides a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x + 1\right)\right)\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.84110 - 5.01122, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

The system is preferably arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.92616, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus lancea*.

The invention extends to a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x + 1\right)\right)\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.32945 - 4.73904, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

The system is preferably arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.53425, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus pendulina*.

The invention further extends to a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x + 1\right)\right)\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;

*EXP* = the inverse of the natural logarithm;

*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and

*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.68409 - 4.85555, a value for *b* of 1.90258 - 2.20418, and a value for *MSE* of 0.093359 - 0.13699.

The system is preferably arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.76982, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of the trees of the species *Rhus lancea*.

The invention also provides a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x+1))\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;

*EXP* = the inverse of the natural logarithm;

*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and

*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.79386 - 4.95424, a value for *b* of 1.65237 - 1.90861, and a value for *MSE* of 0.048428 - 0.073722.

The system is preferably arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.87405, a point value for *b* of 1.78049, and a point value for *MSE* of 0.059088. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

The invention yet further provides a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x+1))\right)\right\}$$

where:

$d$ = the estimated value of the stem diameter of the tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x$ = the value of the age of the tree, in years,

and by using a value for $A$ of 3.29559 - 3.58199, a value for $b$ of 2.17927 - 2.70242, and a value for $MSE$ of 0.11467 - 0.19853.

The system is preferably arranged to calculate the stem diameter $(d)$ by using a point value for $A$ of 3.43879, a point value for $b$ of 2.44085, and a point value for $MSE$ of 0.14804. The system is typically arranged automatically to use said values for $A$, $b$, and $MSE$ when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Combretum erythrophyllum*.

The invention also extends to a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter $(d)$ at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

$d$ = the estimated value of the stem diameter of the tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x$ = the value of the age of the tree, in years,

and by using a value for $A$ of 3.69637 - 3.86649, a value for $b$ of 1.60305 - 1.89217, and a value for $MSE$ of 0.044657 - 0.076904.

The system is preferably arranged to calculate the stem diameter $(d)$ by using a point value for $A$ of 3.78143, a point value for $b$ of 1.74761, and a point value for $MSE$ of 0.057522. The system is typically arranged automatically to use said values for $A$, $b$, and $MSE$ when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus lancea*.

The invention further provides a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter $(d)$ at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

$d$ = the estimated value of the stem diameter of the tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x$ = the value of the age of the tree, in years,

and by using a value for *A* of 3.18472 - 3.59431, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

The system is preferably arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.38952, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus pendulina*.

The invention yet further extends to a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

*d* = the estimated value of the stem diameter of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 3.53936 - 3.71082, a value for *b* of 1.90258 - 2.20418, and a value for *MSE* of 0.093359 - 0.13699.

The system is preferably arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.62509, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea*.

The invention also provides a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

*d* = the estimated value of the stem diameter of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 3.64913 - 3.80951, a value for *b* of 1.65237 - 1.90861, and a value for *MSE* of 0.048428 - 0.073722.

The system is preferably arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.72932, a point value for *b* of 1.78049, and a point value for *MSE* of 0.059088. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

In instances where the system is arranged to calculate the stem diameter at ground level, the system will preferably be arranged to convert the calculated stem diameter at ground level *(d)* to a corresponding stem circumference at ground level *(c)*.

The system may be arranged to calculate an aboveground dry biomass of the tree as an intermediate step to calculating the quantity of carbon sequestered by the tree, preferably by means of the following equation:

$$\log TDM = 2.397(\log c) - 2.441$$

where:

$TDM$ = the estimated aboveground dry biomass of the tree in kilograms; and
$c$ = the stem circumference of the tree at ground level, in centimetres.

The system may advantageously be arranged to calculate the quantity of carbon sequestered by the tree by estimating a fraction of the calculated dry biomass of the tree which is constituted by sequestered carbon. The system may thus be arranged to calculate the quantity of carbon sequestered by multiplying the estimated aboveground dry biomass (*TDM*) by a factor of 0.6 - 0.9, preferably by a factor of 0.7 - 0.8, and most preferably be a factor of 0.7533.

The system may further be arranged to calculate the quantity of carbon sequestered by the tree at the end of the predetermined time period, to calculate the total quantity of carbon sequestered by the tree at the beginning of the predetermined time period, and to subtract the one calculated value from the other to find the total quantity of carbon sequestered by the tree in the predetermined time period.

Conveniently, the system may be arranged to calculate the quantity of carbon sequestered by a plurality of trees of the same species and of the same age by multiplying the calculated quantity of carbon sequestered by one of the trees by the number of trees. As explained above, the system may instead be used for a plurality of trees of varying but closely related ages.

Typically, the system comprises an electronic processor and a computer program which contains computer readable instructions for enabling the processor to calculate the quantity of carbon sequestered by a tree or by a plurality of trees, when the program is executed on the processor. The system will thus typically have input means for receiving input from a user, and display means for displaying a calculated quantity of sequestered carbon. The system may preferably be arranged to receive input as to the species of the tree/trees in question, the age of the tree/trees at the start and at the end of the predetermined time period respectively, and the number of trees. The electronic processor, through operation of the computer program, then automatically calculates the quantity of carbon sequestered by the said trees in the time period.

The invention yet further provides carbon credits for offsetting or permitting a particular quantity of carbon emissions, the carbon credits relating to a plurality of trees which sequester carbon over a specific period of time, the particular quantity of emitted carbon permitted or offset by each of the trees being equal to 0.6 - 0.9 times the aboveground dry biomass of the tree, the aboveground dry biomass (*TDM*) of the tree, in kilograms, being such as to satisfy the equation:

$$\log TDM = 2.397(\log c) - 2.441$$

where:

$c$ = the stem circumference of the tree at ground level, in centimetres, and c equals:

$$EXP\left\{\frac{MSE}{2}+\left(A+b.\ln\left(\ln(x+1)\right)\right)\right\}$$

wherein:

$x$ = the age of said one of the trees at the end of the period, in years,

a set of values for *A, b* and *MSE* being selected from the group of value sets comprising:

*A* = 4.58352, *b* = 2.44085, *MSE* = 0.14804;
*A* = 4.92616, *b* = 1.74761, *MSE* = 0.057522;
*A* = 4.53425, *b* = 2.21533, *MSE* = 0.051892;
*A* = 4.76982, *b* = 2.05338, *MSE* = 0.11204; and
*A* = 4.87405, *b* = 1.78049, *MSE* = 0.059088.

It should be appreciated that the values for *A, b* and *MSE* are selected from one of the five listed groups of value sets, and that the combination of values in different value sets does not form part of the invention.

The particular quantity of carbon offset by the carbon credits for each tree may be equal to 0.7 - 0.8 times the aboveground dry biomass (*TDM*) of the tree. Preferably, the particular quantity of carbon offset by the carbon credits for each tree is equal to about 0.75 times the aboveground dry biomass (*TDM*) of the tree, most preferably being equal to 0.7533 times the aboveground dry biomass (*TDM*) of the tree.

The carbon credits will typically relate to a plurality of trees of a species of African Savannah tree. When the carbon credits relate to a plurality of trees of the species *Combretum erythrophyllum,* the values of *A, b* and *MSE* will typically be equal to 4.58352, 2.44085 and 0.14804 respectively.

In cases where the carbon credits relate to a plurality of trees of the species *Rhus lancea*, the values of *A, b* and *MSE* will typically be 4.92616, 1.74761 and 0.057522 respectively. However, when the carbon credits relate to a plurality of trees of the species *Rhus pendulina,* the values of *A, b* and *MSE* will preferably be equal to 4.53425, 2.21533 and 0.051892 respectively.

In cases where the carbon credits relate to a plurality of trees of a species of indigenous South African Savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea*, the values of *A, b* and *MSE* may be equal to 4.76982, 2.05338 and 0.11204 respectively. Instead, in cases where the carbon credits relate to a plurality of trees of a species of indigenous South African Savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus lancea* and the mean approximate tree size of trees of the species *Rhus pendulina,* the values of *A, b* and *MSE* may be equal to 4.87405, 1.78049 and 0.059088 respectively.

As explained above, the carbon credits may relate to a quantity of carbon equal to the quantity of carbon sequestered by a representative one of the trees multiplied by the total number of trees.

The invention will now be further described, by way of example.

In this example, a city Municipality plants 500 trees of the African Savannah species *Combretum erythrophyllum*. As an additional source of revenue, the Municipality wishes to sell carbon credits in respect of these trees to an entity, typically a manufacturing company, which emits carbon during manufacture of its products.

It will be appreciated that in terms of international protocols and national guidelines, such companies may be restricted as to the quantity of carbon which may be emitted, and purchase of carbon credits by such a company will serve to offset a particular quantity of carbon emissions, thus increasing the quantity of carbon which the company may emit. It will further be appreciated that, during the growth of a tree, carbon is sequestered from the atmosphere in biochemical processes, thus increasing the dry biomass of the tree, and it is this carbon sequestration which forms the basis for allowing the company to increase its carbon emissions in return for obtaining carbon credits from the Municipality. The total quantity of carbon offset by the carbon credits will thus be equal to the quantity of carbon sequestered by the trees.

The carbon credits are time-based, in that they apply to a predetermined time period. The quantity of carbon emissions offset by the carbon credits is thus equal to the quantity of carbon sequestered by the trees over the predetermined time period. Thus, when the carbon credits apply to, for instance, the first five years of the life of the trees, the total sequestered carbon in the trees at the end of the five years will be offset. However, when the predetermined time period, for instance, applies to years 5 - 10 of the trees' life, the carbon credits will offset the difference between the sequestered carbon at ten years and the sequestered carbon at five years.

In this example, the quantity of carbon offset by the carbon credits relating to the abovementioned 500 *Combretum erythrophyllum* trees is calculated by use of a system for calculating carbon sequestered by the trees. The system comprises an electronic processor provided by a conventional desktop personal computer, and a computer program loaded on the computer. The computer program contains program instructions for enabling the processor of the computer to perform calculation of the quantity of carbon sequestered by the trees, as is explained in more detail below.

When the computer program is executed on the computer, a user is prompted to enter the species of trees in respect of which the sequestered carbon is to be calculated, the number of trees, and the age of the trees at the start and at the end of the time period respectively. In this case, the user will thus enter or select *Combretum erythrophyllum*; 500 trees; an end age of 5 years and a start age of 0 years. The computer then automatically calculates the quantity of carbon sequestered by the trees, and displays the result of this calculation on a display screen.

The computer program is arranged to calculate the quantity of sequestered carbon with reference to the following equation, established by P.J. Peper, E.G. McPherson and S.M. Mori:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\} \quad \text{.................................. (1)}$$

where:

*c* = the estimated stem circumference of one of the trees at ground level, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years.

It should be appreciated that the computer program can be arranged to estimate either the stem circumference *(c)* of one of the trees at ground level, or to estimate the stem diameter *(d)* at ground level. In this example, the stem circumference *(c)* is calculated. Furthermore, the values of *A, b,* and *MSE* vary from species to species, and the computer automatically assigns appropriate values to these constants with reference to Table 1 below:

| **Species** | ***A*** | ***b*** | ***MSE*** |
|---|---|---|---|
| *Combretum erythrophyllum* | 4.58352 | 2.44085 | 0.14804 |
| *Rhus lancea* | 4.92616 | 1.74761 | 0.057522 |
| *Rhus pendulina* | 4.53425 | 2.21533 | 0.051892 |
| Combined *C. erythrophyllum* *R. lancea* | 4.76982 | 2.05338 | 0.11204 |
| Combined *R. lancea* and *R. pendulina* | 4.87405 | 1.78049 | 0.059088 |

**Table 1**

Naturally, these constants will also be different when the computer program is arranged to calculate the stem diameter *(d)* of one of the trees. The respective values of the constants for such a case are set out in Table 2 below.

Use of equation (1) for *Combretum erythrophyllum* at age 5 years, automatically using 4.58352 for *A*, 2.44085 for *b*, and 0.14804 for *MSE*, renders a stem circumference of 437.5 mm, or 43.75 cm. Thereafter, the computer automatically uses the following equation, presented by C.M. Shackleton for South African savannah trees, to calculate the aboveground dry biomass of one of the trees:

$$\log TDM = 2.397(\log c) - 2.441 \qquad (2)$$

where:

*TDM* = the estimated aboveground dry biomass of the tree in kilograms; and
*c* = the stem circumference of the tree at ground level, in centimetres.

This results in an estimated aboveground dry biomass (*TDM*) of 31.07 kilograms. It should be borne in mind that carbon is sequestered not only to form aboveground dry biomass (*TDM*), but also to form roots or belowground dry biomass of the tree. The belowground dry biomass (*RDM*), also referred to as root dry matter, of the tree is estimated to be equal to 0.78 x *TDM*, in this case being equal to 24.24 kilograms. It is estimated that 45% of the aboveground dry biomass (*TDM*) consists of carbon, while an estimated 5.4% of aboveground dry biomass (*TDM*) consists of leaves and foliage, which should be disregarded. The aboveground carbon (*AGC*) of one of the trees is thus equal to 0.45(*TDM* - (0.054x*TDM*)) = 13.23 kilograms. The root carbon (*RC*) is estimated to be equal to 42% of the belowground dry biomass (*RDM*), thus being equal to 10.18 kilograms.

The total carbon sequestered by one of the trees is equal to the sum of the root carbon (*RC*) and the aboveground carbon (*AGC*), thus being equal to 23.41 kilograms. It will be appreciated that the total quantity of carbon sequestered by the tree is thus equal to about 0.7533 times the aboveground dry biomass (*TDM*), and that this ratio remains the same for any calculation.

This calculated quantity of carbon sequestered by one of the trees is multiplied by the total number of trees, i.e. 500, to reach a total quantity of sequestered carbon of 11703 kilograms. The Municipality thereafter sells carbon credits to the quantity of 11.70 metric tons of carbon to the manufacturing company, to offset this quantity of emissions by the company.

Carbon emission and sequestrations are sometimes calculated and/or reported in terms of a corresponding quantity of carbon dioxide ($CO_2$), and to this end, the calculated total quantity of carbon may be multiplied by a factor of 3.67, to obtain the quantity of carbon dioxide which may be emitted in return for purchase of the carbon credits. In this example, the quantity of permitted carbon dioxide emissions will be 42.95 metric tons of $CO_2$.

It should be appreciated that, although calculation of the quantity of sequestered carbon is performed by the computer in this example, the calculation can be performed manually in other examples. For ease of description, the results of the various equations in the above example are shown to have been rounded off, but it should be appreciated that no rounding off will typically take place when using one result to calculate the next.

In another example of the invention, the Municipality plants 200 trees of the species *Rhus leptodictya*. In this example, the carbon credits relate to a ten year period commencing when the trees are five years of age. As in the example above, a user enters into the computer data in the respective data fields, in particular entering a value of 200 for the number of trees, a value of 5 for the start of the time period, and a value of 15 for the end of the time period.

Since the trees are of a species for which there are no specific values for *A, b,* and *MSE*, respective values for a combination of *Rhus lancea* and *Rhus pendulina* are used. These values are used in this example because the mean approximate tree size of trees of the species *Rhus leptodictya* lies between the mean approximate tree size of trees of the specie *Rhus lancea* and trees of the species *Rhus pendulina*.

The computer automatically assigns the values for *A, b,* and *MSE* according to Table 2 below, the computer in this example being arranged to estimate a stem diameter *(d)* of one of the trees at ground level at the start and at the end of the period.

| **Species** | ***A*** | ***b*** | ***MSE*** |
|---|---|---|---|
| *Combretum erythrophyllum* | 3.43879 | 2.44085 | 0.14804 |
| *Rhus lancea* | 3.78143 | 1.74761 | 0.057522 |
| *Rhus pendulina* | 3.38952 | 2.21533 | 0.051892 |
| Combined *C. erythrophyllum R. lancea* | 3.62509 | 2.05338 | 0.11204 |
| Combined *R. lancea R pendulina* | 3.72932 | 1.78049 | 0.059088 |

**Table 2**

The following equation is used to calculate the respective stem diameters:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x+1))\right)\right\} \quad \text{....................................(3)}$$

where:

*d* = the estimated value of the diameter of the tree at ground level, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years.

When the values of 3.72932 for *A*, 1.78049 for *b*, and 0.059088 for *MSE*, which are automatically assigned by the computer, are used in equation (3) above, an estimated stem diameter *(d)* of 121.18 mm is obtained. Assuming a circular stem cross-section, the circumference of the tree at five years of age is thus 38.07 centimetres.

Use of equation (2) for this stem circumference, results in an estimated aboveground dry biomass (*TDM*) of 22.27 kilograms. Multiplication of the calculated aboveground dry biomass (*TDM*) with a factor of 0.7533, as explained above, provides a total quantity of carbon sequestered by one of the trees at age five of 16.77 kilograms.

Similar calculation of the total carbon sequestered by one of the trees at age fifteen provides 108.09 kilograms. The difference between these two values indicates the total quantity of carbon sequestered by one of the trees during the ten year period to which the carbon credits apply, thus equaling 91.32 kilograms. In total, the 200 trees thus sequestered 18.26 metric tons of carbon, and the carbon credits sold in respect of these trees offsets an equal quantity of carbon emissions.

## CLAIMS

1. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x_i + 1))\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 4.44032 - 4.72672, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

2. A method as claimed in claim 1, in which the stem circumference *(c)* is estimated by using a point value for *A* of 4.58352, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804.

3. A method as claimed in claim 1 or claim 2, in which the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Combretum erythrophyllum*.

4. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x_i + 1))\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 4.84110 - 5.01122, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

5. A method as claimed in claim 4, in which the stem circumference *(c)* is estimated by using a point value for *A* of 4.92616, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522.

6. A method as claimed in claim 4 or claim 5, in which the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus lancea*.

7. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

using a value for $A$ of 4.32945 - 4.73904, a value for $b$ of 1.91382 - 2.51685, and a value for $MSE$ of 0.038070 - 0.074931.

8. A method as claimed in claim 7, in which the stem circumference *(c)* is estimated by using a point value for $A$ of 4.53425, a point value for $b$ of 2.21533, and a point value for $MSE$ of 0.051892.

9. A method as claimed in claim 7 or claim 8, in which the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus pendulina*.

10. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

using a value for $A$ of 4.68409 - 4.85555, a value for $b$ of 1.90258 - 2.20418, and a value for $MSE$ of 0.093359 - 0.13699.

11. A method as claimed in claim 10, in which the stem circumference *(c)* is estimated by using a point value for *A* of 4.76982, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204.

12. A method as claimed in claim 10 or claim 11, in which the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea.*

13. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the i$^{th}$ tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the i$^{th}$ tree, in years,

using a value for *A* of 4.79386 - 4.95424, a value for *b* of 1.65237 - 1.90861, and a value for *MSE* of 0.048428 - 0.073722.

14. A method as claimed in claim 13, in which the stem circumference *(c)* is estimated by using a point value for *A* of 4.87405, a point value for *b* of 1.78049, and a point value for *MSE* of 0.059088.

15. A method as claimed in claim 13 or claim 14, in which the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

16. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;

$EXP$ = the inverse of the natural logarithm;

$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and

$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 3.29559 - 3.58199, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

17. A method as claimed in claim 16, in which the stem diameter *(d)* is estimated by using a point value for *A* of 3.43879, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804.

18. A method as claimed in claim 16 or claim 17, in which the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Combretum erythrophyllum*.

19. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;

$EXP$ = the inverse of the natural logarithm;

$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and

$x_i$ = the value of the age of the $i^{th}$ tree, in years,

using a value for *A* of 3.69637 - 3.86649, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

20. A method as claimed in claim 19, in which the stem diameter *(d)* is estimated by using a point value for *A* of 3.78143, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522.

21. A method as claimed in claim 19 or claim 20, in which the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus lancea*.

22. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;

$EXP$ = the inverse of the natural logarithm;

$A$, $b$, $MSE$ = pre-estimated constants which have different values for different species of tree; and

$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 3.18472 - 3.59431, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

23. A method as claimed in claim 22, in which the stem diameter *(d)* is estimated by using a point value for *A* of 3.38952, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892.

24. A method as claimed in claim 22 or claim 23, in which the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus pendulina*.

25. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;

$EXP$ = the inverse of the natural logarithm;

$A$, $b$, $MSE$ = pre-estimated constants which have different values for different species of tree; and

$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 3.53936 - 3.71082, a value for *b* of 1.90258 - 2.20418, and a value for *MSE* of 0.093359 - 0.13699.

26. A method as claimed in claim 25, in which the stem diameter *(d)* is estimated by using a point value for *A* of 3.62509, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204.

27. A method as claimed in claim 25 or claim 26, in which the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea.*

28. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon

sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x_i + 1))\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 3.64913 - 3.80951, a value for *b* of 1.65237 - 1.90861, and a value for *MSE* of 0.048428 - 0.073722.

29. A method as claimed in claim 28, in which the stem diameter *(d)* is estimated by using a point value for *A* of 3.72932, a point value for *b* of 1.78049, and a point value for *MSE* of 0.059088.

30. A method as claimed in claim 28 or claim 29, in which the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

31. A method as claimed in any one of claims 16 to 30 inclusive, in which the estimated stem diameter at ground level *(d)* is used to obtain an estimated stem circumference at ground level *(c)*.

32. A method as claimed in any one of claims 1 to 31 inclusive, in which the calculation of carbon sequestered by said one of the trees includes the intermediate step of calculating an aboveground dry biomass of said tree.

33. A method as claimed in claim 32, in which calculating the aboveground dry biomass of said one of the trees is by means of the following equation:

$$\log TDM = 2.397(\log c) - 2.441$$

where:

*TDM* = the estimated aboveground dry biomass of the tree in kilograms; and
*c* = the stem circumference of the tree at ground level, in centimetres.

34. A method as claimed in claim 32 or claim 33, which includes the step of calculating the quantity of carbon sequestered by said one of the trees by estimating a fraction of the calculated aboveground dry biomass of the tree which is constituted by sequestered carbon.

35. A method as claimed in claim 34, in which calculating the quantity of carbon sequestered is by multiplying the aboveground dry biomass (*TDM*) by a factor of 0.6 - 0.9.

36. A method as claimed in claim 34, in which calculating the carbon sequestered by said tree is by multiplying the aboveground dry biomass (*TDM*) by a factor of 0.7533.

37. A method as claimed in any one of the preceding claims, which includes calculating the total quantity of carbon sequestered by one of the trees at the end of the predetermined time period, calculating the total quantity of carbon sequestered by that tree at the beginning of the predetermined time period, and subtracting the one calculated value from the other to find the total quantity of carbon sequestered by that tree in the predetermined time period.

38. A method as claimed in any one of the preceding claims, in which the quantity of sequestered carbon is calculated simultaneously for a plurality of trees of the same species and of the same age, the calculated quantity of carbon sequestered by one of the trees over the predetermined time period being multiplied by the number of trees, to obtain the total quantity of carbon sequestered by the plurality of trees.

39. A method as claimed in any one of the preceding claims, which includes receiving financial compensation in return for the provision of the carbon credits.

40. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.44032 - 4.72672, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

41. A system as claimed in claim 40, which is arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.58352, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804.

42. A system as claimed in claim 40 or claim 41, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Combretum erythrophyllum*.

43. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.84110 - 5.01122, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

44. A system as claimed in claim 43, which is arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.92616, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522.

45. A system as claimed in claim 43 or claim 44, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus lancea*.

46. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.32945 - 4.73904, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

47. A system as claimed in claim 46, which is arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.53425, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892.

48. A system as claimed in claim 46 or claim 47, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus pendulina*.

49. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.68409 - 4.85555, a value for *b* of 1.90258 - 2.20418, and a value for *MSE* of 0.093359 - 0.13699.

50. A system as claimed in claim 49, which is arranged to calculate the stem

circumference *(c)* by using a point value for *A* of 4.76982, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204.

51. A system as claimed in claim 49 or claim 50, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of the trees of the species *Rhus lancea*.

52. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x+1))\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.79386 - 4.95424, a value for *b* of 1.65237 - 1.90861, and a value for *MSE* of 0.048428 - 0.073722.

53. A system as claimed in claim 52, which is arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.87405, a point value for *b* of 1.78049, and a point value for *MSE* of 0.059088.

54. A system as claimed in claim 52 or claim 53, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

55. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x+1))\right)\right\}$$

where:

*d* = the estimated value of the stem diameter of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 3.29559 - 3.58199, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

56. A system as claimed in claim 55, which is arranged to calculate the stem diameter

*(d)* by using a point value for *A* of 3.43879, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804.

57. A system as claimed in claim 55 or claim 56, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Combretum erythrophyllum*.

58. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

$d$ = the estimated value of the stem diameter of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x$ = the value of the age of the tree, in years,

and by using a value for *A* of 3.69637 - 3.86649, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

59. A system as claimed in claim 58, which is arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.78143, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522.

60. A system as claimed in claim 58 or claim 59, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus lancea*.

61. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

$d$ = the estimated value of the stem diameter of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x$ = the value of the age of the tree, in years,

and by using a value for *A* of 3.18472 - 3.59431, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

62. A system as claimed in claim 61, which is arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.38952, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892.

63. A system as claimed in claim 61 or claim 62, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus pendulina*.

64. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

*d* = the estimated value of the stem diameter of the tree, in millimeters;

*EXP* = the inverse of the natural logarithm;

*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and

*x* = the value of the age of the tree, in years,

and by using a value for *A* of 3.53936 - 3.71082, a value for *b* of 1.90258 - 2.20418, and a value for *MSE* of 0.093359 - 0.13699.

65. A system as claimed in claim 64, which is arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.62509, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204.

66. A system as claimed in claim 64 or claim 65, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea*.

67. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

*d* = the estimated value of the stem diameter of the tree, in millimeters;

*EXP* = the inverse of the natural logarithm;

*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and

*x* = the value of the age of the tree, in years,

and by using a value for *A* of 3.64913 - 3.80951, a value for *b* of 1.65237 - 1.90861, and a value for *MSE* of 0.048428 - 0.073722.

68. A system as claimed in claim 67, which is arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.72932, a point value for *b* of 1.78049, and a point value for *MSE* of 0.059088.

69. A system as claimed in claim 67 or claim 68, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon

is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

70. A system as claimed in any one of claims 55 to 69 inclusive, which is arranged to convert the calculated stem diameter at ground level *(d)* to a corresponding stem circumference at ground level *(c)*.

71. A system as claimed in any one of claims 40 to 70 inclusive, which is arranged to calculate an aboveground dry biomass of the tree as an intermediate step to calculating the quantity of carbon sequestered by the tree.

72. A system as claimed in claim 71, which is arranged to calculate the aboveground dry biomass of each tree by means of the following equation:

$$\log TDM = 2.397(\log c) - 2.441$$

where:

*TDM* = the estimated aboveground dry biomass of the tree in kilograms; and
*c* = the stem circumference of the tree at ground level, in centimetres.

73. A system as claimed in claim 71 or claim 72, which is arranged to calculate the quantity of carbon sequestered by the tree by estimating a fraction of the calculated dry biomass of the tree which is constituted by sequestered carbon.

74. A system as claimed in claim 73, which is arranged to calculate the quantity of carbon sequestered by multiplying the estimated aboveground dry biomass (*TDM*) by a factor of 0.6 - 0.9.

75. A system as claimed in claim 73, which is arranged to calculate the carbon sequestered by each tree by multiplying the estimated aboveground dry biomass (*TDM*) by a factor of 0.7533.

76. A system as claimed in any one of claims 40 to 75 inclusive, which is arranged to calculate the quantity of carbon sequestered by the tree at the end of the predetermined time period, to calculate the total quantity of carbon sequestered by the tree at the beginning of the predetermined time period, and to subtract the one calculated value from the other to find the total quantity of carbon sequestered by the tree in the predetermined time period.

77. A system as claimed in any one of claims 40 to 76, which is arranged to calculate the quantity of carbon sequestered by a plurality of trees of the same species and of the same age by multiplying the calculated quantity of carbon sequestered by one of the trees by the number of trees.

78. A system as claimed in any one of claims 40 to 77, which comprises an electronic processor and a computer program having computer readable instructions for enabling the processor to calculate the quantity of carbon sequestered by a tree or by a plurality of trees, when the program is executed on the processor.

79. Carbon credits for offsetting or permitting a particular quantity of carbon emissions, the carbon credits relating to a plurality of trees which sequester carbon over a specific period of time, the particular quantity of emitted carbon permitted or offset by each of the trees being equal to about 0.6 - 0.9 times the aboveground dry biomass of the tree, the aboveground dry biomass (*TDM*) of the tree, in kilograms, being such as to satisfy the equation:

$$\log TDM = 2.397(\log c) - 2.441$$

where:

$c$ = the stem circumference of the tree at ground level, in centimetres, and c equals, in millimetres:

$$EXP\left\{\frac{MSE}{2}+\left(A+b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

$x$ = the age of the tree at the end of the period, in years,

a set of values for $A$, $b$ and $MSE$ being selected from the group of value sets comprising:

$A = 4.58352$, $b = 2.44085$, $MSE = 0.14804$;
$A = 4.92616$, $b = 1.74761$, $MSE = 0.057522$;
$A = 4.53425$, $b = 2.21533$, $MSE = 0.051892$;
$A = 4.76982$, $b = 2.05338$, $MSE = 0.11204$; and
$A = 4.87405$, $b = 1.78049$, $MSE = 0.059088$.

80. Carbon credits as claimed in claim 79, in which the particular quantity of carbon offset by each tree is equal to 0.7 - 0.8 times the aboveground dry biomass (*TDM*) of the tree.

81. Carbon credits as claimed in claim 79, in which the particular quantity of carbon offset by each tree is equal to about 0.75 times the aboveground dry biomass (*TDM*) of the tree.

82. Carbon credits as claimed in claim 79, in which the particular quantity of carbon offset by each tree is equal to about 0.7533 times the aboveground dry biomass (*TDM*) of the tree.

83. Carbon credits as claimed in any one of claims 79 to 82 inclusive, in which the carbon credits relate to a plurality of trees of a species of African Savannah tree.

84. Carbon credits as claimed in claim 83, in which the carbon credits relate to a plurality of trees of the species *Combretum erythrophyllum*, the values of *A, b* and *MSE* being equal to 4.58352, 2.44085 and 0.14804 respectively.

85. Carbon credits as claimed in claim 83, in which the carbon credits relate to a plurality of trees of the species *Rhus lancea,* the values of *A, b* and *MSE* being equal to 4.92616, 1.74761 and 0.057522 respectively.

86. Carbon credits as claimed in claim 83, in which the carbon credits relate to a plurality of trees of the species *Rhus pendulina,* the values of *A, b* and *MSE* being equal to 4.53425, 2.21533 and 0.051892 respectively.

87. Carbon credits as claimed in claim 83, in which the carbon credits relate to a plurality of trees of a species of indigenous South African Savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea,* the values of *A, b* and *MSE* being equal to 4.76982, 2.05338 and 0.11204 respectively.

88. Carbon credits as claimed in claim 83, in which the carbon credits relate to a plurality of trees of a species of indigenous South African Savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus lancea* and the mean approximate tree size of trees of the species *Rhus pendulina,* the values of *A, b* and *MSE* being equal to 4.87405, 1.78049 and 0.059088 respectively.

89. A method as claimed in any one of claims 1, 4, 7, 10, 13, 16, 19, 22, 25 and 28 inclusive, substantially as herein described and illustrated.

90. A system as claimed in any one of claims 40, 43, 46, 49, 52, 55, 58, 61, 64 and 67 inclusive, substantially as herein described and illustrated.

91. Carbon credits as claimed in claim 79, substantially as herein described and illustrated.

# Appendix A

The following is a South African patent written in collaboration with a local patent law firm. The patent was based on the research done for this thesis.

### The patent reads as follows:

THIS INVENTION relates to ecological management. In particular, the invention provides a method of ameliorating the ecological effects of carbon emissions. The invention also relates to a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period. The invention further extends to carbon credits for offsetting carbon emissions.

The invention provides a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x_i + 1))\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A$, $b$, $MSE$ = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 4.44032 - 4.72672, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

The stem circumference *(c)* is preferably estimated by using a point value for *A* of 4.58352, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804.

The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Combretum erythrophyllum*. It should be appreciated, though, that the abovementioned values and equation could also be applied to trees of other species. In particular, the values given below for use in respect of trees of various associated species can be used for any tree which has a sufficiently similar size for such application to be made with botanical assurance.

By the natural logarithm is meant $\log_e$, also referred to as ln.

It will be appreciated that trees assimilate atmospheric carbon during their growth process. To curb carbon emissions, which serve to increase the atmospheric carbon concentration and contribute to global warming, industrially active entities may be set limits as to the quantity of carbon they are allowed to emit. Application of the method enables such entities to exercise the option of buying carbon credits in respect of trees which have been planted by themselves or by others, thus increasing the quantity of carbon which that entity may emit by the quantity of carbon sequestered by the associated trees.

It should further be appreciated that the carbon credits relate to a predetermined time period, and that the quantity of carbon offset by the carbon credits is equal to the quantity of carbon sequestered by the associated trees over the predetermined period. If the predetermined period starts at planting of the trees, calculation of the quantity of carbon sequestered by the trees at the end of the period will provide the quantity of carbon emissions which the carbon credits permit. Otherwise, the quantity of carbon sequestered by the trees at the start of the period is subtracted from the quantity of carbon sequestered at the end of the period, to provide the total quantity of carbon sequestered by the trees in the predetermined period.

Stem circumference or stem diameter at ground level implies a measurement taken at 0 - 20 cm above the ground or appropriately measured above the basal swelling. Furthermore, the basic equation and associated values of *A*, *b* and *MSE* are intended for use in respect of trees having an age of up to about thirty years, with the accuracy of the equation declining for trees above that age. For trees of the species *Combretum Erythrophyllum*, the given equations are accurate up to an age of about 47 years, while the equations are accurate in respect of *Rhus lancea* up to 32 years and up to 15 years for *Rhus pendulina*.

The above equation implies a relationship between appropriately paired values of tree age and the stem circumference of a plurality of trees. By use of pre-estimated point values for *A*, *b* and *MSE*, an estimated stem circumference *(c)* for one of the trees can be found. It should be appreciated that the stem circumference which is estimated in this way represents the stem circumference of a tree which is statistically representative of the plurality of trees. This representative tree is referred to in the above equation as the $i^{th}$ tree. In other embodiments of the invention, which are defined below, there is provided equations which describe a relationship between appropriately paired values of tree age and stem diameter.

The point values for *A*, *b*, and *MSE* are statistically the best estimates to use in estimating the stem circumference or stem diameter, as the case may be, of one of the plurality of trees, while the ranges of values for *A*, *b*, and *MSE* represent the 95% confidence intervals for each. It will be appreciated that the values of *A*, *b*, and *MSE* vary for different tree species. This applies also to the point values and to the value ranges for use in respect of the respective tree species.

The invention extends to a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 4.84110 - 5.01122, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

The stem circumference *(c)* may be estimated by using a point value for *A* of 4.92616, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522. The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus lancea*.

The invention further provides a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;

*EXP* = the inverse of the natural logarithm;

*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and

$x_i$ = the value of the age of the $i^{th}$ tree, in years,

using a value for *A* of 4.32945 - 4.73904, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

The stem circumference *(c)* is preferably estimated by using a point value for *A* of 4.53425, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892.

The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus pendulina*.

It may sometimes be necessary to calculate the quantity of carbon sequestered by trees which are not of the species *Combretum erythrophyllum*, *Rhus pendulina*, or *Rhus lancea,* and of which the mean approximate tree size is not sufficiently similar to one of the abovementioned species to justify application of the equation and values for one of said species. In such case, values of *A, b* and *MSE* are used for an appropriate combination of the abovementioned three species.

The invention thus extends to a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

using a value for $A$ of 4.68409 - 4.85555, a value for $b$ of 1.90258 - 2.20418, and a value for $MSE$ of 0.093359 - 0.13699.

The stem circumference *(c)* is preferably estimated by using a point value for $A$ of 4.76982, a point value for $b$ of 2.05338, and a point value for $MSE$ of 0.11204.

The method as defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea.*

The invention also extends to a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x_i + 1))\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

using a value for $A$ of 4.79386 - 4.95424, a value for $b$ of 1.65237 - 1.90861, and a value for $MSE$ of 0.048428 - 0.073722.

The stem circumference *(c)* is typically estimated by using a point value for $A$ of 4.87405, a point value for $b$ of 1.78049, and a point value for $MSE$ of 0.059088.

The method as defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

The invention yet further provides a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{ \frac{MSE}{2} + \left( A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;

$EXP$ = the inverse of the natural logarithm;

$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and

$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 3.29559 - 3.58199, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

The stem diameter *(d)* is preferably estimated by using a point value for *A* of 3.43879, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804.

The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Combretum erythrophyllum*.

The invention also extends to a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{ \frac{MSE}{2} + \left( A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;

$EXP$ = the inverse of the natural logarithm;

$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and

$x_i$ = the value of the age of the $i^{th}$ tree, in years,

using a value for *A* of 3.69637 - 3.86649, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

The stem diameter *(d)* is preferably estimated by using a point value for *A* of 3.78143, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522.

The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus lancea*.

The invention further provides a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{ \frac{MSE}{2} + \left( A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 3.18472 - 3.59431, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

The stem diameter *(d)* is typically estimated by using a point value for *A* of 3.38952, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892.

The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus pendulina*.

The invention also provides a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{ \frac{MSE}{2} + \left( A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 3.53936 - 3.71082, a value for *b* of 1.90258 - 2.20418, and a value for *MSE* of 0.093359 - 0.13699.

The stem diameter *(d)* is preferably estimated by using a point value for *A* of 3.62509, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204.

The method defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea.*

The invention extends to a method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x_i + 1))\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;

$EXP$ = the inverse of the natural logarithm;

$A$, $b$, $MSE$ = pre-estimated constants which have different values for different species of tree; and

$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for $A$ of 3.64913 - 3.80951, a value for $b$ of 1.65237 - 1.90861, and a value for $MSE$ of 0.048428 - 0.073722.

The stem diameter *(d)* is preferably estimated by using a point value for $A$ of 3.72932, a point value for $b$ of 1.78049, and point value for $MSE$ of 0.059088.

The method as defined above is typically used when the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

The estimated stem diameter at ground level *(d)* may be used to obtain an estimated stem circumference at ground level *(c)*.

Typically, the calculation of carbon sequestered by said one of the trees includes the intermediate step of calculating an aboveground dry biomass of said tree, preferably by use of the following equation:

$$\log TDM = 2.397(\log c) - 2.441$$

where:

$TDM$ = the estimated aboveground dry biomass of the tree in kilograms; and

$c$ = the stem circumference of the tree at ground level, in centimetres.

The method may include the step of calculating the quantity of carbon sequestered by said one of the trees by estimating a fraction of the calculated aboveground dry biomass of the tree which is constituted by sequestered carbon. Calculating the quantity of carbon sequestered by the tree may for instance be by multiplying the aboveground dry biomass (*TDM*) by a factor of 0.6 - 0.9, preferably by a factor of 0.7 - 0.8, and most preferably by a factor of 0.7533.

The abovementioned factor is arrived at by assuming that the total belowground dry biomass is equal to 65-87%, preferably 78% of the aboveground dry biomass (*TDM*). Furthermore, it is assumed that 3-10%, preferably 5.4% of aboveground dry biomass (TDM) is leaf- or foliage dry biomass and should be disregarded. It is estimated that 40-55%, preferably 45% of aboveground dry biomass (*TDM*) is comprised of carbon and in respect of belowground dry biomass, it is estimated that 40-55%, preferably 42% thereof comprises carbon. These estimates translate, when the preferred values are used, to a ratio of 0.7533 of sequestered carbon to aboveground dry biomass.

The method may include calculating the total quantity of carbon sequestered by one of the trees at the end of the predetermined time period, calculating the total quantity of carbon sequestered by that tree at the beginning of the predetermined time period, and subtracting the one calculated value from the other to find the total quantity of carbon sequestered by that tree in the predetermined time period.

Typically, the quantity of sequestered carbon is calculated simultaneously for a plurality of trees of the same species and of the same age, the calculated quantity of carbon sequestered by one of the trees over the predetermined time period being multiplied by the number of trees, to obtain the total quantity of carbon sequestered by the plurality of trees. It should be appreciated that the carbon sequestered by a plurality of trees of varying but similar ages may also be used, the age ($x$) used for this purpose being the mean age of the trees.

The method may include the prior step of planting the trees in respect of which the carbon credits are provided. The method may in such case further include cultivating the trees for the extent of the predetermined time period.

The method will further typically include receiving financial compensation, e.g. payment, in return for providing the carbon credits.

The invention also provides a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

$c$ = the estimated value of the stem circumference of the tree, in millimeters;

$EXP$ = the inverse of the natural logarithm;

$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and

$x$ = the value of the age of the tree, in years,

and by using a value for *A* of 4.44032 - 4.72672, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

The system is preferably arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.58352, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Combretum erythrophyllum*.

The invention yet further provides a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

$c$ = the estimated value of the stem circumference of the tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x$ = the value of the age of the tree, in years,

and by using a value for $A$ of 4.84110 - 5.01122, a value for $b$ of 1.60305 - 1.89217, and a value for $MSE$ of 0.044657 - 0.076904.

The system is preferably arranged to calculate the stem circumference *(c)* by using a point value for $A$ of 4.92616, a point value for $b$ of 1.74761, and a point value for $MSE$ of 0.057522. The system is typically arranged automatically to use said values for $A$, $b$, and $MSE$ when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus lancea*.

The invention extends to a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

$c$ = the estimated value of the stem circumference of the tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x$ = the value of the age of the tree, in years,

and by using a value for $A$ of 4.32945 - 4.73904, a value for $b$ of 1.91382 - 2.51685, and a value for $MSE$ of 0.038070 - 0.074931.

The system is preferably arranged to calculate the stem circumference *(c)* by using a point value for $A$ of 4.53425, a point value for $b$ of 2.21533, and a point value for $MSE$ of 0.051892. The system is typically arranged automatically to use said values for $A$, $b$, and $MSE$ when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus pendulina*.

The invention further extends to a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

$c$ = the estimated value of the stem circumference of the tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x$ = the value of the age of the tree, in years,

and by using a value for $A$ of 4.68409 - 4.85555, a value for $b$ of 1.90258 - 2.20418, and a value for $MSE$ of 0.093359 - 0.13699.

The system is preferably arranged to calculate the stem circumference *(c)* by using a point value for $A$ of 4.76982, a point value for $b$ of 2.05338, and a point value for $MSE$ of 0.11204. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of the trees of the species *Rhus lancea*.

The invention also provides a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

$c$ = the estimated value of the stem circumference of the tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x$ = the value of the age of the tree, in years,

and by using a value for $A$ of 4.79386 - 4.95424, a value for $b$ of 1.65237 - 1.90861, and a value for $MSE$ of 0.048428 - 0.073722.

The system is preferably arranged to calculate the stem circumference *(c)* by using a point value for $A$ of 4.87405, a point value for $b$ of 1.78049, and a point value for $MSE$ of 0.059088. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

The invention yet further provides a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

*d* = the estimated value of the stem diameter of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 3.29559 - 3.58199, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

The system is preferably arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.43879, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Combretum erythrophyllum*.

The invention also extends to a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

*d* = the estimated value of the stem diameter of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 3.69637 - 3.86649, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

The system is preferably arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.78143, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus lancea*.

The invention further provides a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

*d* = the estimated value of the stem diameter of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 3.18472 - 3.59431, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

The system is preferably arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.38952, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus pendulina*.

The invention yet further extends to a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x+1))\right)\right\}$$

where:

*d* = the estimated value of the stem diameter of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 3.53936 - 3.71082, a value for *b* of 1.90258 - 2.20418, and a value for *MSE* of 0.093359 - 0.13699.

The system is preferably arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.62509, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea*.

The invention also provides a system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x+1))\right)\right\}$$

where:

*d* = the estimated value of the stem diameter of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 3.64913 - 3.80951, a value for *b* of 1.65237 - 1.90861, and a value for *MSE* of 0.048428 - 0.073722.

The system is preferably arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.72932, a point value for *b* of 1.78049, and a point value for *MSE* of 0.059088. The system is typically arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

In instances where the system is arranged to calculate the stem diameter at ground level, the system will preferably be arranged to convert the calculated stem diameter at ground level *(d)* to a corresponding stem circumference at ground level *(c)*.

The system may be arranged to calculate an aboveground dry biomass of the tree as an intermediate step to calculating the quantity of carbon sequestered by the tree, preferably by means of the following equation:

$$\log TDM = 2.397(\log c) - 2.441$$

where:

$TDM$ = the estimated aboveground dry biomass of the tree in kilograms; and

$c$ = the stem circumference of the tree at ground level, in centimetres.

The system may advantageously be arranged to calculate the quantity of carbon sequestered by the tree by estimating a fraction of the calculated dry biomass of the tree which is constituted by sequestered carbon. The system may thus be arranged to calculate the quantity of carbon sequestered by multiplying the estimated aboveground dry biomass (*TDM*) by a factor of 0.6 - 0.9, preferably by a factor of 0.7 - 0.8, and most preferably be a factor of 0.7533.

The system may further be arranged to calculate the quantity of carbon sequestered by the tree at the end of the predetermined time period, to calculate the total quantity of carbon sequestered by the tree at the beginning of the predetermined time period, and to subtract the one calculated value from the other to find the total quantity of carbon sequestered by the tree in the predetermined time period.

Conveniently, the system may be arranged to calculate the quantity of carbon sequestered by a plurality of trees of the same species and of the same age by multiplying the calculated quantity of carbon sequestered by one of the trees by the number of trees. As explained above, the system may instead be used for a plurality of trees of varying but closely related ages.

Typically, the system comprises an electronic processor and a computer program which contains computer readable instructions for enabling the processor to calculate the quantity of carbon sequestered by a tree or by a plurality of trees, when the program is executed on the processor. The system will thus typically have input means for receiving input from a user, and display means for displaying a calculated quantity of sequestered carbon. The system may preferably be arranged to receive input as to the species of the tree/trees in question, the age of the tree/trees at the start and at the end of the predetermined time period respectively, and the number of trees. The electronic processor, through operation of the computer program, then automatically calculates the quantity of carbon sequestered by the said trees in the time period.

The invention yet further provides carbon credits for offsetting or permitting a particular quantity of carbon emissions, the carbon credits relating to a plurality of trees which sequester carbon over a specific period of time, the particular quantity of emitted carbon permitted or offset by each of the trees being equal to 0.6 - 0.9 times the aboveground dry biomass of the tree, the aboveground dry biomass (*TDM*) of the tree, in kilograms, being such as to satisfy the equation:

$$\log TDM = 2.397(\log c) - 2.441$$

where:

*c* = the stem circumference of the tree at ground level, in centimetres, and c equals:

$$EXP\left\{\frac{MSE}{2}+\left(A+b.\ln\left(\ln(x+1)\right)\right)\right\}$$

wherein:

*x* = the age of said one of the trees at the end of the period, in years,

a set of values for *A, b* and *MSE* being selected from the group of value sets comprising:

*A* = 4.58352, *b* = 2.44085, *MSE* = 0.14804;
*A* = 4.92616, *b* = 1.74761, *MSE* = 0.057522;
*A* = 4.53425, *b* = 2.21533, *MSE* = 0.051892;
*A* = 4.76982, *b* = 2.05338, *MSE* = 0.11204; and
*A* = 4.87405, *b* = 1.78049, *MSE* = 0.059088.

It should be appreciated that the values for *A, b* and *MSE* are selected from one of the five listed groups of value sets, and that the combination of values in different value sets does not form part of the invention.

The particular quantity of carbon offset by the carbon credits for each tree may be equal to 0.7 - 0.8 times the aboveground dry biomass (*TDM*) of the tree. Preferably, the particular quantity of carbon offset by the carbon credits for each tree is equal to about 0.75 times the aboveground dry biomass (*TDM*) of the tree, most preferably being equal to 0.7533 times the aboveground dry biomass (*TDM*) of the tree.

The carbon credits will typically relate to a plurality of trees of a species of African Savannah tree. When the carbon credits relate to a plurality of trees of the species *Combretum erythrophyllum,* the values of *A, b* and *MSE* will typically be equal to 4.58352, 2.44085 and 0.14804 respectively.

In cases where the carbon credits relate to a plurality of trees of the species *Rhus lancea*, the values of *A, b* and *MSE* will typically be 4.92616, 1.74761 and 0.057522 respectively. However, when the carbon credits relate to a plurality of trees of the species *Rhus pendulina,* the values of *A, b* and *MSE* will preferably be equal to 4.53425, 2.21533 and 0.051892 respectively.

In cases where the carbon credits relate to a plurality of trees of a species of indigenous South African Savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea*, the values of *A, b* and *MSE* may be equal to 4.76982, 2.05338 and 0.11204 respectively. Instead, in cases where the carbon credits relate to a plurality of trees of a species of indigenous South African Savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus lancea* and the mean approximate tree size of trees of the species *Rhus pendulina,* the values of *A, b* and *MSE* may be equal to 4.87405, 1.78049 and 0.059088 respectively.

As explained above, the carbon credits may relate to a quantity of carbon equal to the quantity of carbon sequestered by a representative one of the trees multiplied by the total number of trees.

The invention will now be further described, by way of example.

In this example, a city Municipality plants 500 trees of the African Savannah species *Combretum erythrophyllum*. As an additional source of revenue, the Municipality wishes to sell carbon credits in respect of these trees to an entity, typically a manufacturing company, which emits carbon during manufacture of its products.

It will be appreciated that in terms of international protocols and national guidelines, such companies may be restricted as to the quantity of carbon which may be emitted, and purchase of carbon credits by such a company will serve to offset a particular quantity of carbon emissions, thus increasing the quantity of carbon which the company may emit. It will further be appreciated that, during the growth of a tree, carbon is sequestered from the atmosphere in biochemical processes, thus increasing the dry biomass of the tree, and it is this carbon sequestration which forms the basis for allowing the company to increase its carbon emissions in return for obtaining carbon credits from the Municipality. The total quantity of carbon offset by the carbon credits will thus be equal to the quantity of carbon sequestered by the trees.

The carbon credits are time-based, in that they apply to a predetermined time period. The quantity of carbon emissions offset by the carbon credits is thus equal to the quantity of carbon sequestered by the trees over the predetermined time period. Thus, when the carbon credits apply to, for instance, the first five years of the life of the trees, the total sequestered carbon in the trees at the end of the five years will be offset. However, when the predetermined time period, for instance, applies to years 5 - 10 of the trees' life, the carbon credits will offset the difference between the sequestered carbon at ten years and the sequestered carbon at five years.

In this example, the quantity of carbon offset by the carbon credits relating to the abovementioned 500 *Combretum erythrophyllum* trees is calculated by use of a system for calculating carbon sequestered by the trees. The system comprises an electronic processor provided by a conventional desktop personal computer, and a computer program loaded on the computer. The computer program contains program instructions for enabling the processor of the computer to perform calculation of the quantity of carbon sequestered by the trees, as is explained in more detail below.

When the computer program is executed on the computer, a user is prompted to enter the species of trees in respect of which the sequestered carbon is to be calculated, the number of trees, and the age of the trees at the start and at the end of the time period respectively. In this case, the user will thus enter or select *Combretum erythrophyllum*; 500 trees; an end age of 5 years and a start age of 0 years. The computer then automatically calculates the quantity of carbon sequestered by the trees, and displays the result of this calculation on a display screen.

The computer program is arranged to calculate the quantity of sequestered carbon with reference to the following equation, established by P.J. Peper, E.G. McPherson and S.M. Mori:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x+1))\right)\right\} \quad \text{..................................} \ (1)$$

where:

$c$ = the estimated stem circumference of one of the trees at ground level, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x$ = the value of the age of the tree, in years.

It should be appreciated that the computer program can be arranged to estimate either the stem circumference *(c)* of one of the trees at ground level, or to estimate the stem diameter *(d)* at ground level. In this example, the stem circumference *(c)* is calculated. Furthermore, the values of *A, b,* and *MSE* vary from species to species, and the computer automatically assigns appropriate values to these constants with reference to Table 1 below:

| Species | *A* | *b* | *MSE* |
|---|---|---|---|
| *Combretum erythrophyllum* | 4.58352 | 2.44085 | 0.14804 |
| *Rhus lancea* | 4.92616 | 1.74761 | 0.057522 |
| *Rhus pendulina* | 4.53425 | 2.21533 | 0.051892 |
| Combined *C. erythrophyllum R. lancea* | 4.76982 | 2.05338 | 0.11204 |
| Combined *R. lancea* and *R. pendulina* | 4.87405 | 1.78049 | 0.059088 |

**Table 1**

Naturally, these constants will also be different when the computer program is arranged to calculate the stem diameter *(d)* of one of the trees. The respective values of the constants for such a case are set out in Table 2 below.

Use of equation (1) for *Combretum erythrophyllum* at age 5 years, automatically using 4.58352 for *A*, 2.44085 for *b*, and 0.14804 for *MSE*, renders a stem circumference of 437.5 mm, or 43.75 cm. Thereafter, the computer automatically uses the following equation, presented by C.M. Shackleton for South African savannah trees, to calculate the aboveground dry biomass of one of the trees:

$$\log TDM = 2.397(\log c) - 2.441 \ldots\ldots (2)$$

where:

$TDM$ = the estimated aboveground dry biomass of the tree in kilograms; and

$c$ = the stem circumference of the tree at ground level, in centimetres.

This results in an estimated aboveground dry biomass (*TDM*) of 31.07 kilograms. It should be borne in mind that carbon is sequestered not only to form aboveground dry biomass (*TDM*), but also to form roots or belowground dry biomass of the tree. The belowground dry biomass (*RDM*), also referred to as root dry matter, of the tree is estimated to be equal to 0.78 x *TDM*, in this case being equal to 24.24 kilograms. It is estimated that 45% of the aboveground dry biomass (*TDM*) consists of carbon, while an estimated 5.4% of aboveground dry biomass (*TDM*) consists of leaves and foliage, which should be disregarded. The aboveground carbon (*AGC*) of one of the trees is thus equal to 0.45(*TDM* - (0.054x*TDM*)) = 13.23 kilograms. The root carbon (*RC*) is estimated to be equal to 42% of the belowground dry biomass (*RDM*), thus being equal to 10.18 kilograms.

The total carbon sequestered by one of the trees is equal to the sum of the root carbon (*RC*) and the aboveground carbon (*AGC*), thus being equal to 23.41 kilograms. It will be appreciated that the total quantity of carbon sequestered by the tree is thus equal to about 0.7533 times the aboveground dry biomass (*TDM*), and that this ratio remains the same for any calculation.

This calculated quantity of carbon sequestered by one of the trees is multiplied by the total number of trees, i.e. 500, to reach a total quantity of sequestered carbon of 11703 kilograms. The Municipality thereafter sells carbon credits to the quantity of 11.70 metric tons of carbon to the manufacturing company, to offset this quantity of emissions by the company.

Carbon emission and sequestrations are sometimes calculated and/or reported in terms of a corresponding quantity of carbon dioxide ($CO_2$), and to this end, the calculated total quantity of carbon may be multiplied by a factor of 3.67, to obtain the quantity of carbon dioxide which may be emitted in return for purchase of the carbon credits. In this example, the quantity of permitted carbon dioxide emissions will be 42.95 metric tons of $CO_2$.

It should be appreciated that, although calculation of the quantity of sequestered carbon is performed by the computer in this example, the calculation can be performed manually in other examples. For ease of description, the results of the various equations in the above example are shown to have been rounded off, but it should be appreciated that no rounding off will typically take place when using one result to calculate the next.

In another example of the invention, the Municipality plants 200 trees of the species *Rhus leptodictya*. In this example, the carbon credits relate to a ten year period commencing when the trees are five years of age. As in the example above, a user enters into the computer data in the respective data fields, in particular entering a value of 200 for the number of trees, a value of 5 for the start of the time period, and a value of 15 for the end of the time period.

Since the trees are of a species for which there are no specific values for *A, b,* and *MSE*, respective values for a combination of *Rhus lancea* and *Rhus pendulina* are used. These values are used in this example because the mean approximate tree size of trees of the species *Rhus leptodictya* lies between the mean approximate tree size of trees of the specie *Rhus lancea* and trees of the species *Rhus pendulina*.

The computer automatically assigns the values for *A, b,* and *MSE* according to Table 2 below, the computer in this example being arranged to estimate a stem diameter *(d)* of one of the trees at ground level at the start and at the end of the period.

| **Species** | ***A*** | ***b*** | ***MSE*** |
|---|---|---|---|
| *Combretum erythrophyllum* | 3.43879 | 2.44085 | 0.14804 |
| *Rhus lancea* | 3.78143 | 1.74761 | 0.057522 |
| *Rhus pendulina* | 3.38952 | 2.21533 | 0.051892 |
| Combined *C. erythrophyllum* *R. lancea* | 3.62509 | 2.05338 | 0.11204 |
| Combined *R. lancea R pendulina* | 3.72932 | 1.78049 | 0.059088 |

**Table 2**

The following equation is used to calculate the respective stem diameters:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x+1))\right)\right\} \quad \text{..................................(3)}$$

where:

*d* = the estimated value of the diameter of the tree at ground level, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years.

When the values of 3.72932 for *A*, 1.78049 for *b*, and 0.059088 for *MSE*, which are automatically assigned by the computer, are used in equation (3) above, an estimated stem diameter *(d)* of 121.18 mm is obtained. Assuming a circular stem cross-section, the circumference of the tree at five years of age is thus 38.07 centimetres.

Use of equation (2) for this stem circumference, results in an estimated aboveground dry biomass (*TDM*) of 22.27 kilograms. Multiplication of the calculated aboveground dry biomass (*TDM*) with a factor of 0.7533, as explained above, provides a total quantity of carbon sequestered by one of the trees at age five of 16.77 kilograms.

Similar calculation of the total carbon sequestered by one of the trees at age fifteen provides 108.09 kilograms. The difference between these two values indicates the total quantity of carbon sequestered by one of the trees during the ten year period to which the carbon credits apply, thus equaling 91.32 kilograms. In total, the 200 trees thus sequestered 18.26 metric tons of carbon, and the carbon credits sold in respect of these trees offsets an equal quantity of carbon emissions.

**CLAIMS**

1. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x_i + 1)\right)\right)\right\}$$

where:

| | | |
|---|---|---|
| $c_i$ | = | the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters; |
| *EXP* | = | the inverse of the natural logarithm; |
| *A, b, MSE* | = | pre-estimated constants which have different values for different species of tree; and |
| $x_i$ | = | the value of the age of the $i^{th}$ tree, in years, |

and by using a value for *A* of 4.44032 - 4.72672, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

2. A method as claimed in claim 1, in which the stem circumference *(c)* is estimated by using a point value for *A* of 4.58352, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804.

3. A method as claimed in claim 1 or claim 2, in which the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Combretum erythrophyllum*.

4. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x_i + 1)\right)\right)\right\}$$

where:

| | | |
|---|---|---|
| $c_i$ | = | the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters; |
| *EXP* | = | the inverse of the natural logarithm; |
| *A, b, MSE* | = | pre-estimated constants which have different values for different species of tree; and |
| $x_i$ | = | the value of the age of the $i^{th}$ tree, in years, |

and by using a value for *A* of 4.84110 - 5.01122, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

5. A method as claimed in claim 4, in which the stem circumference *(c)* is estimated by using a point value for *A* of 4.92616, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522.

6. A method as claimed in claim 4 or claim 5, in which the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus lancea*.

7. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the i$^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the i$^{th}$ tree, in years,

using a value for *A* of 4.32945 - 4.73904, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

8. A method as claimed in claim 7, in which the stem circumference *(c)* is estimated by using a point value for *A* of 4.53425, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892.

9. A method as claimed in claim 7 or claim 8, in which the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus pendulina*.

10. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the i$^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the i$^{th}$ tree, in years,

using a value for *A* of 4.68409 - 4.85555, a value for *b* of 1.90258 - 2.20418, and a value for *MSE* of 0.093359 - 0.13699.

11. A method as claimed in claim 10, in which the stem circumference *(c)* is estimated by using a point value for *A* of 4.76982, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204.

12. A method as claimed in claim 10 or claim 11, in which the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea.*

13. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem circumference *(c)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$c_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x_i + 1))\right)\right\}$$

where:

$c_i$ = the estimated value of the stem circumference of the $i^{th}$ tree, in millimeters;

*EXP* = the inverse of the natural logarithm;

*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and

$x_i$ = the value of the age of the $i^{th}$ tree, in years,

using a value for *A* of 4.79386 - 4.95424, a value for *b* of 1.65237 - 1.90861, and a value for *MSE* of 0.048428 - 0.073722.

14. A method as claimed in claim 13, in which the stem circumference *(c)* is estimated by using a point value for *A* of 4.87405, a point value for *b* of 1.78049, and a point value for *MSE* of 0.059088.

15. A method as claimed in claim 13 or claim 14, in which the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

16. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x_i + 1))\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the i$^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the i$^{th}$ tree, in years,

and by using a value for *A* of 3.29559 - 3.58199, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

17. A method as claimed in claim 16, in which the stem diameter *(d)* is estimated by using a point value for *A* of 3.43879, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804.

18. A method as claimed in claim 16 or claim 17, in which the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Combretum erythrophyllum*.

19. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x_i + 1)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the i$^{th}$ tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the i$^{th}$ tree, in years,

using a value for *A* of 3.69637 - 3.86649, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

20. A method as claimed in claim 19, in which the stem diameter *(d)* is estimated by using a point value for *A* of 3.78143, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522.

21. A method as claimed in claim 19 or claim 20, in which the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus lancea*.

22. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A$, $b$, $MSE$ = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 3.18472 - 3.59431, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

23. A method as claimed in claim 22, in which the stem diameter *(d)* is estimated by using a point value for *A* of 3.38952, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892.

24. A method as claimed in claim 22 or claim 23, in which the trees in respect of which the quantity of sequestered carbon is calculated are of the species *Rhus pendulina*.

25. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the $i^{th}$ tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A$, $b$, $MSE$ = pre-estimated constants which have different values for different species of tree; and
$x_i$ = the value of the age of the $i^{th}$ tree, in years,

and by using a value for *A* of 3.53936 - 3.71082, a value for *b* of 1.90258 - 2.20418, and a value for *MSE* of 0.093359 - 0.13699.

26. A method as claimed in claim 25, in which the stem diameter *(d)* is estimated by using a point value for *A* of 3.62509, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204.

27. A method as claimed in claim 25 or claim 26, in which the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea.*

28. A method of ameliorating the ecological effects of carbon emissions, which method includes providing carbon credits to an entity to offset a quantity of emitted carbon, the quantity of emitted carbon offset by the carbon credits being equal to a calculated quantity of carbon

sequestered by an associated plurality of trees over a predetermined time period, the method including the step of calculating the quantity of carbon sequestered by each of the trees over the predetermined period by estimating the value of the stem diameter *(d)* of one of the trees at ground level at the end of the predetermined time period by use of the following equation:

$$d_i = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x_i + 1\right)\right)\right)\right\}$$

where:

$d_i$ = the estimated value of the stem diameter of the i$^{th}$ tree, in millimeters;

$EXP$ = the inverse of the natural logarithm;

$A$, $b$, $MSE$ = pre-estimated constants which have different values for different species of tree; and

$x_i$ = the value of the age of the i$^{th}$ tree, in years,

and by using a value for *A* of 3.64913 - 3.80951, a value for *b* of 1.65237 - 1.90861, and a value for *MSE* of 0.048428 - 0.073722.

29. A method as claimed in claim 28, in which the stem diameter *(d)* is estimated by using a point value for *A* of 3.72932, a point value for *b* of 1.78049, and a point value for *MSE* of 0.059088.

30. A method as claimed in claim 28 or claim 29, in which the trees in respect of which the quantity of sequestered carbon is calculated are of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

31. A method as claimed in any one of claims 16 to 30 inclusive, in which the estimated stem diameter at ground level *(d)* is used to obtain an estimated stem circumference at ground level *(c)*.

32. A method as claimed in any one of claims 1 to 31 inclusive, in which the calculation of carbon sequestered by said one of the trees includes the intermediate step of calculating an aboveground dry biomass of said tree.

33. A method as claimed in claim 32, in which calculating the aboveground dry biomass of said one of the trees is by means of the following equation:

$$\log TDM = 2.397(\log c) - 2.441$$

where:

$TDM$ = the estimated aboveground dry biomass of the tree in kilograms; and

$c$ = the stem circumference of the tree at ground level, in centimetres.

34. A method as claimed in claim 32 or claim 33, which includes the step of calculating the quantity of carbon sequestered by said one of the trees by estimating a fraction of the calculated aboveground dry biomass of the tree which is constituted by sequestered carbon.

35. A method as claimed in claim 34, in which calculating the quantity of carbon sequestered is by multiplying the aboveground dry biomass (*TDM*) by a factor of 0.6 - 0.9.

36. A method as claimed in claim 34, in which calculating the carbon sequestered by said tree is by multiplying the aboveground dry biomass (*TDM*) by a factor of 0.7533.

37. A method as claimed in any one of the preceding claims, which includes calculating the total quantity of carbon sequestered by one of the trees at the end of the predetermined time period, calculating the total quantity of carbon sequestered by that tree at the beginning of the predetermined time period, and subtracting the one calculated value from the other to find the total quantity of carbon sequestered by that tree in the predetermined time period.

38. A method as claimed in any one of the preceding claims, in which the quantity of sequestered carbon is calculated simultaneously for a plurality of trees of the same species and of the same age, the calculated quantity of carbon sequestered by one of the trees over the predetermined time period being multiplied by the number of trees, to obtain the total quantity of carbon sequestered by the plurality of trees.

39. A method as claimed in any one of the preceding claims, which includes receiving financial compensation in return for the provision of the carbon credits.

40. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;

*EXP* = the inverse of the natural logarithm;

*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and

*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.44032 - 4.72672, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

41. A system as claimed in claim 40, which is arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.58352, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804.

42. A system as claimed in claim 40 or claim 41, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Combretum erythrophyllum*.

43. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;

*EXP* = the inverse of the natural logarithm;

*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and

*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.84110 - 5.01122, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

44. A system as claimed in claim 43, which is arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.92616, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522.

45. A system as claimed in claim 43 or claim 44, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus lancea*.

46. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{ \frac{MSE}{2} + \left( A + b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.32945 - 4.73904, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

47. A system as claimed in claim 46, which is arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.53425, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892.

48. A system as claimed in claim 46 or claim 47, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus pendulina*.

49. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{ \frac{MSE}{2} + \left( A + b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.68409 - 4.85555, a value for *b* of 1.90258 - 2.20418, and a value for *MSE* of 0.093359 - 0.13699.

50. A system as claimed in claim 49, which is arranged to calculate the stem

circumference *(c)* by using a point value for *A* of 4.76982, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204.

51. A system as claimed in claim 49 or claim 50, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of the trees of the species *Rhus lancea*.

52. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem circumference *(c)* at ground level of the tree at the end of the time period by means of the following equation:

$$c = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x+1))\right)\right\}$$

where:

*c* = the estimated value of the stem circumference of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 4.79386 - 4.95424, a value for *b* of 1.65237 - 1.90861, and a value for *MSE* of 0.048428 - 0.073722.

53. A system as claimed in claim 52, which is arranged to calculate the stem circumference *(c)* by using a point value for *A* of 4.87405, a point value for *b* of 1.78049, and a point value for *MSE* of 0.059088.

54. A system as claimed in claim 52 or claim 53, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

55. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln(\ln(x+1))\right)\right\}$$

where:

*d* = the estimated value of the stem diameter of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 3.29559 - 3.58199, a value for *b* of 2.17927 - 2.70242, and a value for *MSE* of 0.11467 - 0.19853.

56. A system as claimed in claim 55, which is arranged to calculate the stem diameter

*(d)* by using a point value for *A* of 3.43879, a point value for *b* of 2.44085, and a point value for *MSE* of 0.14804.

57. A system as claimed in claim 55 or claim 56, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Combretum erythrophyllum*.

58. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

*d* = the estimated value of the stem diameter of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 3.69637 - 3.86649, a value for *b* of 1.60305 - 1.89217, and a value for *MSE* of 0.044657 - 0.076904.

59. A system as claimed in claim 58, which is arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.78143, a point value for *b* of 1.74761, and a point value for *MSE* of 0.057522.

60. A system as claimed in claim 58 or claim 59, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus lancea*.

61. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln(x+1)\right)\right)\right\}$$

where:

*d* = the estimated value of the stem diameter of the tree, in millimeters;
*EXP* = the inverse of the natural logarithm;
*A, b, MSE* = pre-estimated constants which have different values for different species of tree; and
*x* = the value of the age of the tree, in years,

and by using a value for *A* of 3.18472 - 3.59431, a value for *b* of 1.91382 - 2.51685, and a value for *MSE* of 0.038070 - 0.074931.

62. A system as claimed in claim 61, which is arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.38952, a point value for *b* of 2.21533, and a point value for *MSE* of 0.051892.

63. A system as claimed in claim 61 or claim 62, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of the species *Rhus pendulina*.

64. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

$d$ = the estimated value of the stem diameter of the tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x$ = the value of the age of the tree, in years,

and by using a value for *A* of 3.53936 - 3.71082, a value for *b* of 1.90258 - 2.20418, and a value for *MSE* of 0.093359 - 0.13699.

65. A system as claimed in claim 64, which is arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.62509, a point value for *b* of 2.05338, and a point value for *MSE* of 0.11204.

66. A system as claimed in claim 64 or claim 65, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size lies between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea*.

67. A system for calculating the quantity of carbon sequestered by a tree over a predetermined time period, the system being arranged to estimate the stem diameter *(d)* at ground level of the tree at the end of the time period by means of the following equation:

$$d = EXP\left\{\frac{MSE}{2} + \left(A + b.\ln\left(\ln\left(x+1\right)\right)\right)\right\}$$

where:

$d$ = the estimated value of the stem diameter of the tree, in millimeters;
$EXP$ = the inverse of the natural logarithm;
$A, b, MSE$ = pre-estimated constants which have different values for different species of tree; and
$x$ = the value of the age of the tree, in years,

and by using a value for *A* of 3.64913 - 3.80951, a value for *b* of 1.65237 - 1.90861, and a value for *MSE* of 0.048428 - 0.073722.

68. A system as claimed in claim 67, which is arranged to calculate the stem diameter *(d)* by using a point value for *A* of 3.72932, a point value for *b* of 1.78049, and a point value for *MSE* of 0.059088.

69. A system as claimed in claim 67 or claim 68, which is arranged automatically to use said values for *A, b,* and *MSE* when the tree in respect of which the quantity of sequestered carbon

is calculated is of a species of indigenous African savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus pendulina* and the mean approximate tree size of trees of the species *Rhus lancea.*

70. A system as claimed in any one of claims 55 to 69 inclusive, which is arranged to convert the calculated stem diameter at ground level *(d)* to a corresponding stem circumference at ground level *(c)*.

71. A system as claimed in any one of claims 40 to 70 inclusive, which is arranged to calculate an aboveground dry biomass of the tree as an intermediate step to calculating the quantity of carbon sequestered by the tree.

72. A system as claimed in claim 71, which is arranged to calculate the aboveground dry biomass of each tree by means of the following equation:

$$\log TDM = 2.397(\log c) - 2.441$$

where:

$TDM$ = the estimated aboveground dry biomass of the tree in kilograms; and
$c$ = the stem circumference of the tree at ground level, in centimetres.

73. A system as claimed in claim 71 or claim 72, which is arranged to calculate the quantity of carbon sequestered by the tree by estimating a fraction of the calculated dry biomass of the tree which is constituted by sequestered carbon.

74. A system as claimed in claim 73, which is arranged to calculate the quantity of carbon sequestered by multiplying the estimated aboveground dry biomass (*TDM*) by a factor of 0.6 - 0.9.

75. A system as claimed in claim 73, which is arranged to calculate the carbon sequestered by each tree by multiplying the estimated aboveground dry biomass (*TDM*) by a factor of 0.7533.

76. A system as claimed in any one of claims 40 to 75 inclusive, which is arranged to calculate the quantity of carbon sequestered by the tree at the end of the predetermined time period, to calculate the total quantity of carbon sequestered by the tree at the beginning of the predetermined time period, and to subtract the one calculated value from the other to find the total quantity of carbon sequestered by the tree in the predetermined time period.

77. A system as claimed in any one of claims 40 to 76, which is arranged to calculate the quantity of carbon sequestered by a plurality of trees of the same species and of the same age by multiplying the calculated quantity of carbon sequestered by one of the trees by the number of trees.

78. A system as claimed in any one of claims 40 to 77, which comprises an electronic processor and a computer program having computer readable instructions for enabling the processor to calculate the quantity of carbon sequestered by a tree or by a plurality of trees, when the program is executed on the processor.

79. Carbon credits for offsetting or permitting a particular quantity of carbon emissions, the carbon credits relating to a plurality of trees which sequester carbon over a specific period of time, the particular quantity of emitted carbon permitted or offset by each of the trees being equal to about 0.6 - 0.9 times the aboveground dry biomass of the tree, the aboveground dry biomass (*TDM*) of the tree, in kilograms, being such as to satisfy the equation:

$$\log TDM = 2.397(\log c) - 2.441$$

where:

$c$ = the stem circumference of the tree at ground level, in centimetres, and c equals, in millimetres:

$$EXP\left\{\frac{MSE}{2}+\left(A+b.\ln(\ln(x+1))\right)\right\}$$

where:

$x$ = the age of the tree at the end of the period, in years,

a set of values for $A$, $b$ and $MSE$ being selected from the group of value sets comprising:

$A$ = 4.58352, $b$ = 2.44085, $MSE$ = 0.14804;
$A$ = 4.92616, $b$ = 1.74761, $MSE$ = 0.057522;
$A$ = 4.53425, $b$ = 2.21533, $MSE$ = 0.051892;
$A$ = 4.76982, $b$ = 2.05338, $MSE$ = 0.11204; and
$A$ = 4.87405, $b$ = 1.78049, $MSE$ = 0.059088.

80. Carbon credits as claimed in claim 79, in which the particular quantity of carbon offset by each tree is equal to 0.7 - 0.8 times the aboveground dry biomass (*TDM*) of the tree.

81. Carbon credits as claimed in claim 79, in which the particular quantity of carbon offset by each tree is equal to about 0.75 times the aboveground dry biomass (*TDM*) of the tree.

82. Carbon credits as claimed in claim 79, in which the particular quantity of carbon offset by each tree is equal to about 0.7533 times the aboveground dry biomass (*TDM*) of the tree.

83. Carbon credits as claimed in any one of claims 79 to 82 inclusive, in which the carbon credits relate to a plurality of trees of a species of African Savannah tree.

84. Carbon credits as claimed in claim 83, in which the carbon credits relate to a plurality of trees of the species *Combretum erythrophyllum*, the values of *A, b* and *MSE* being equal to 4.58352, 2.44085 and 0.14804 respectively.

85. Carbon credits as claimed in claim 83, in which the carbon credits relate to a plurality of trees of the species *Rhus lancea,* the values of *A, b* and *MSE* being equal to 4.92616, 1.74761 and 0.057522 respectively.

86. Carbon credits as claimed in claim 83, in which the carbon credits relate to a plurality of trees of the species *Rhus pendulina,* the values of *A, b* and *MSE* being equal to 4.53425, 2.21533 and 0.051892 respectively.

87. Carbon credits as claimed in claim 83, in which the carbon credits relate to a plurality of trees of a species of indigenous South African Savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Combretum erythrophyllum* and the mean approximate tree size of trees of the species *Rhus lancea,* the values of *A, b* and *MSE* being equal to 4.76982, 2.05338 and 0.11204 respectively.

88. Carbon credits as claimed in claim 83, in which the carbon credits relate to a plurality of trees of a species of indigenous South African Savannah tree of which the mean approximate tree size is between the mean approximate tree size of trees of the species *Rhus lancea* and the mean approximate tree size of trees of the species *Rhus pendulina,* the values of *A, b* and *MSE* being equal to 4.87405, 1.78049 and 0.059088 respectively.

89. A method as claimed in any one of claims 1, 4, 7, 10, 13, 16, 19, 22, 25 and 28 inclusive, substantially as herein described and illustrated.

90. A system as claimed in any one of claims 40, 43, 46, 49, 52, 55, 58, 61, 64 and 67 inclusive, substantially as herein described and illustrated.

91. Carbon credits as claimed in claim 79, substantially as herein described and illustrated.