University of São Paulo
"Luiz de Queiroz" College of Agriculture

Stem profile modeling in Cerrado and tropical forests formations in Brazil

Matheus Henrique Nunes

A thesis submitted in fulfillment of the requirements for the degree of Master of Science. Program: Forest resources. Option in: Silviculture and Forest Management

Piracicaba
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À minha mãe Rosana, meu exemplo de vida, força, vontade e humildade

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CONTENTS

RESUMO

Modelagem do perfil do tronco em Cerrado e formações florestais tropicais no Brasil

Informações corretas sobre o volume de árvores em formações de vegetação natural são fundamentais para a identificação de áreas potenciais para produção madeireira sustentável, estimativa de carbono e conservação da biodiversidade. Dificuldade de acesso e altos custos na obtenção de amostras necessárias para estimativas precisas de volume e biomassa são barreiras frequentes na condução de inventários e estudos florestais no Brasil. Dessa forma, o desenvolvimento de técnicas mais eficientes de mensuração em florestas tropicais é um importante mecanismo para o avanço da conservação, manejo e produção. Os principais objetivos deste trabalho foram: introduzir um novo método de quantificação das estruturas vertical e horizontal por meio do uso de análise de componentes principais (ACP); desenvolver modelos volumétricos baseados em DAP e modelos baseados em área de copa; propor uma nova função de afilamento aplicada a três diferentes formações vegetais; e estimar alturas em que deverão ter diâmetros medidos ao longo da árvore para tornar o método geométrico útil em formações naturais no Brasil, e reduzindo a necessidade de mensurações que requerem o abatimento das árvores.

Palavras-chave: Análise de componentes principais; Modelagem volumétrica; Função de afilamento; Modelagem de forma geométrica; Geometria analítica

ABSTRACT

Stem profile modeling in Cerrado and tropical forests formations in Brazil

Accurate information about tree volume in tropical vegetation formations is critical for the identification of potential areas for sustainable timber production, carbon estimation and biodiversity conservation. Difficult access and the cost of obtaining a large number of samples needed for accurate wood volume and biomass determination are often barriers for carrying out inventories and studies in natural forests in Brazil. Therefore, the development of more efficient techniques of mensuration in tropical forests is an important mechanism for conservation, management and production advancement. The main purposes of this thesis are: introducing a new method for quantifying vertical and horizontal structures by using principal component analysis (PCA); developing two different approaches of volume modeling, one based on DBH and another based on crown area; proposing a new taper equation for native vegetation in three different formations; and estimating upper section diameters to become the geometric form method useful in natural vegetation in Brazil and reducing dependence on destructive measurements.

Keywords: Principal component analysis; Volume modeling; Taper equation; Geometric form modeling; Analytic geometry

1 INTRODUCTION

The goal of biodiversity hotspots is to identify regions around the world where conservation priorities should be focused (CONSERVATION INTERNATIONAL, 2009; MYERS et al., 2000). A total of 34 biodiversity hotspots have been identified that cover only 2.3 % of the earth's land surface, but contain over 50 % of the world's plant species and 42 % of all terrestrial vertebrate species (CONSERVATION INTERNATIONAL, 2009). Within these biodiversity hotspots, there is a diverse number of forests types that provide the foundation of biodiversity for a number of species due to their complex vertical structure (MYERS et al., 2000).

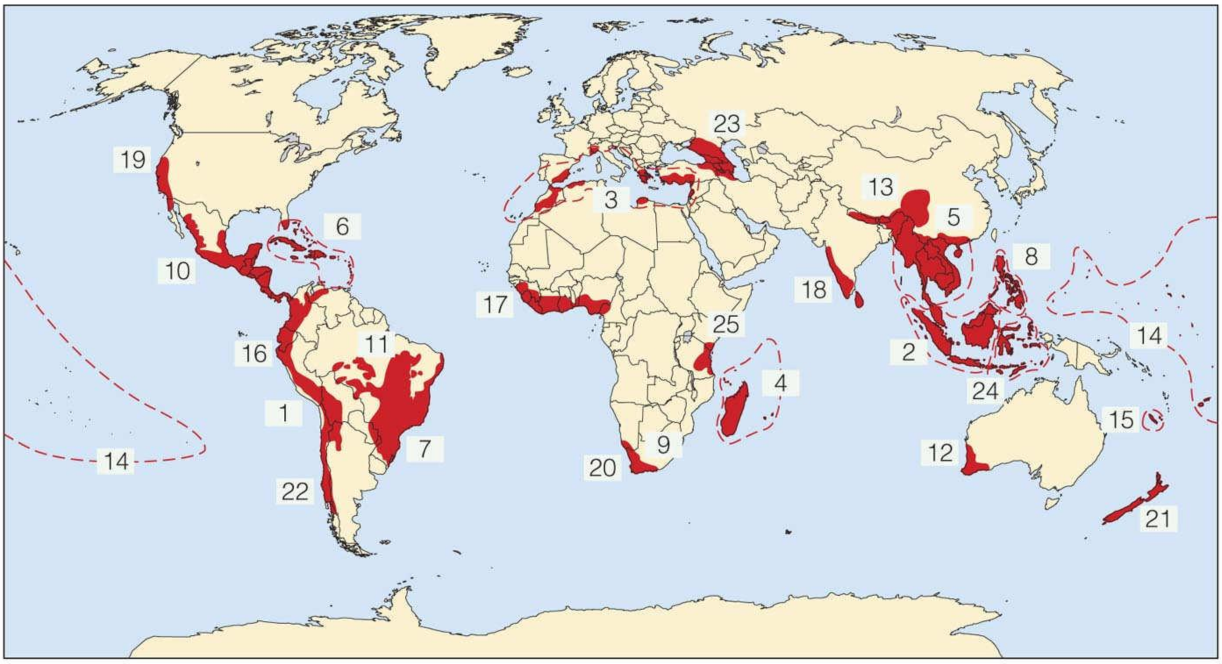

Figure 1 - Biodiversity hotspots. Places around the world which support 1500 or more endemic plant species and have lost more than 70% of original habitat. Image source: Pearson Education, Inc

According to Gillespie et al. (2012), Atlantic forest are divided into 9 forest ecoregions, 1,289,656 km^2 of forest ecoregion areas, 353,516 km^2 covered by forest which represent 27% of ecoregion forested, 96,311 km^2 of forest in protected areas and representing 27% of forests in protected areas. Cerrado is divided into 2 forest ecoregions, 2,111,587 km^2 of forest ecoregion areas, covered by forest in 301,697 km^2, representing 14% of ecoregions forested, 167,924 km^2 of forest in protected areas and representing 56% of forests in protected areas.

The information on biomass amounts helps not only to understand energy accumulation within forest ecosystems, but also serves as an ecological indicator for sustainability. The ability to accurately estimate forest carbon stocks is essential in Reducing Emissions from Deforestation and Forest Degradation (REDD+) mechanisms in order to establish reliable National Reference Emission Levels (NREL) and to estimate carbon stock changes. However, forest biomass stocks are still poorly estimated in most tropical regions and remain a major uncertainty in our understanding of the potential of tropical forests in mitigating climate change (HOUGHTON, 2005). Firstly, it is necessary and required enhancing volume modeling and methods to determine volume, since carbon stocks are quantified in terms of volume of stem wood (PETERSSON, 2012).

In natural forests, equations must incorporate a variety of species to provide accurate biomass estimates (NAVAR, 2009). The most accurate method to determine tree volume is the destructive method, which requires felling of trees and measurement of tree components. This method is labour intensive and time consuming and is in most cases restricted to small trees at small scales (LI; XIAO, 2007). Harvesting trees in natural forests requires in general special authorization which is not often easy to acquire. The use of regression equations allows estimating the total volume of trees with easily measured parameters such as diameter and height.

Another way to modeling volume forests is by the use of taper equations. These models provide diameter estimates at any given height along a tree bole (BIGING, 1984). The ability of taper equations to estimate total and merchantable stem volume has long been a subject in the forestry literature. The advantage of estimating volume through taper equations over existing volume tables lies in the ability of taper equations to accurately predict diameter at any given height of individual trees, hence allowing the acquisition of merchantable volume information to any desired specification. Therefore, it is necessary and beneficial to further study the characteristics of taper profile equations and extend their use to other species besides the ones for which they were originally developed. Another purpose of all taper tables is to show upper stem diameters, which can then be used to calculate the volume of the sections of a tree and the entire tree.

Nonetheless, accurate measurements to compose database is required to provide volume tables, leading to the difficulty in measuring volume trees in natural forests. Girard

(1933) suggested that a reliable volume table can be constructed by measuring diameter at a determined height above diameter at breast height (DBH) without measuring trees in all diameter classes. However, which height exactly this diameter is located in? In natural forests in Brazil, a method able to determine volume by non-destructive methods would be extremely useful to profit and non-profit organizations and boosting volume tables as a component for estimating parameters in specific localities.

This thesis is structured in 3 chapters with different purposes. (1) The first chapter introduced the structure and species in three forest types: Cerrado, semideciduous forest and dense ombrophilous forests. A new method for quantifying the vertical and horizontal structures is developed using principal component analysis (PCA). (2) In the second chapter, two different approaches of volume modeling are performed: DBH-based and crown-based volume models. Additionally, a new taper equation is proposed for the three forest types, concentrating efforts on modeling multi-stemmed trees. (3) In the third chapter, we manipulated the geometric form method, as proposed by Andrade and Leite (1998), to determine volume as a non-destructive method in the three forest types. Upper section diameters were modeled to become useful for practitioners as another specific purpose in this last chapter.

References

ANDRADE, V.C.L.; LEITE, H.G. Uso da geometria analítica para descrever o taper e quantificar o volume de árvores individuais. **Revista Árvore,** Viçosa, v. 25, n. 4, p. 481-486, 1998.

BIGING, G.S. Taper equations for 2nd-growth mixed conifers of Northern California. **Forest Science,** Washington, v. 30, n. 4, p. 1103-1117, 1984.

CONSERVATION INTERNATIONAL. **Biodiversity hotspots-resources-maps and GIS data**. 2009. Disponível em: <http:/, /www.biodiversityhotspots.org/xp/Hotspots/resources/pages/maps.aspx>. Acesso em: 16 ago. 2013.

GILLESPIE, T.W.; LIPKIN, B.; SULLIVAN, L.; BENOWITZ, D.R.; PAU, S.; KEPPEL, G. The rarest and least protected forests in biodiversity hotspots. **Biodiversity and Conservation,** London, v. 21, n. 14, p. 3597-3611, 2012.

GIRARD, J.W. Volume tables for Mississippi bottomland hardwoods and southern pines. **Journal of Forestry,** Washington, v. 31, n. 1, p. 34-41, 1933.

HOUGHTON, R.A. Aboveground forest biomass and the global carbon balance. **Global Change Biology,** Oxford, v. 11, n. 6, p. 945-958, 2005.

LI, C.P.; XIAO, C.W. Above-and belowground biomass of *Artemisia ordosica* communities in three contrasting habitats of the Mu Us desert, northern China. **Journal of arid environments,** London, v. 70, n. 2, p. 195-207, 2007.

MYERS, N.; MITTERMEIER, R.A.; MITTERMEIER, C.G.; FONSECA, G.A.B.; KENT, J. Biodiversity hotspots for conservation priorities. **Nature,** London, v. 403, n. 6772, p. 853-858, 2000.

NÁVAR, J. Allometric equations for tree species and carbon stocks for forests of northwestern Mexico. **Forest Ecology and Management,** Amsterdam, v. 257, n. 2, p. 427-434, 2009.

PETERSSON, H.; HOLM, S.; STÅHL, G.; ALGER, D.; FRIDMAN, J.; LEHTONEN, A.; LUNDSTRÖM, A.; MÄKIPÄÄ, R. Individual tree biomass equations or biomass expansion factors for assessment of carbon stock changes in living biomass: a comparative study. **Forest Ecology and Management,** Amsterdam, v. 270, p. 78-84, 2012.

2 COMPOSITION, FOREST STRUCTURE AND HEIGHT AND DIAMETER STRATIFICATION IN THREE VEGETATION FORMATIONS

Abstract

This work introduces species and respective relative parameters and importance values for each species found in an inventory carried out in Cerrado, Semi-deciduous and Ombrophilous forests in São Paulo State. Additionally, the work presents a stratification method based on the principal component analysis in order to stratify height and diameter classes. Similar groups were formed based on the number of individuals, species and basal area, stratifying diameter and height classes.

Keywords: Principal component analysis; Forest structure; Floristic

2.1 **Introduction**

An effective forest management depends upon the ability of land managers to objectively quantify biologically-significant attributes of forest stands. Some changes in structure and composition of tropical forest fragments can be studied through physiognomic-unit structure. The term physiognomic unit refers to a spatial unit in the forest that has a specific physiognomy.

The species present in a stand have always been an important parameter in describing forest stands. Different species represent not only different forest products and values, but are also important indicators of wildlife habitat, site quality, and a past disturbance history. Typically, species composition can be expressed as the distribution of individuals among the different species present in a stand, using number of individuals, basal area, or volume and can be either the sum of this parameter or a percentage of the total.

The three-dimensional microenvironment (light, humidity, temperature, and wind) of forests is spatially heterogeneous based on composition and structure of the forest. Even though it can be said that all tropical rain forests have a basically similar structure, there is considerable variation among them. This is partly caused by the differences between the phases of development, but even if only the mature or “high forest” phase is considered, structure can vary considerably. Forest structure also depends greatly on species composition (RICHARDS, 1996).

According to Oliveira-Filho and Fontes (2000), Cerrados shared 55% of their flora with Atlantic Forests, including semi-deciduous forests and rain forests. Also, the Cerrado flora was much more closely related to Atlantic semi-deciduous forest than to the Atlantic rain forests.

According to Smith (1973), stratification proposes predictable vertical separation of canopy components such as forest leaves and other structures, species, or individual organisms into distinct horizons, layers, or gradients. The stratification optimizes light utilization, CO2 concentrations, pollination, and dispersal; reduces predation on flowers, fruits, and leaves; and increases structural integrity of the forest.

Many methods can be used to stratify height in natural forests. Souza and Souza (2004) verified that by using cluster and discriminant analysis it was possible to distinguish strata according to the diversity, species richness, density and dominance. According to Péllico-Netto, Sanquetta and Mendes (1995), stratification might take into account minimizing the variance of the mean of strata heights.

The continuous vertical strata may develop from multiple fine-scale disturbances, extended periods of stand initiation, or extreme patterns of crown differentiation (LATHAM, 1996). In other cases, it may be difficult to distinguish differences in patterns of vertical stratification because stands are in transition between structural stages. The number of vertical strata that develop in forests is an emergent characteristic of natural stands related to differences in species composition, competitive relationships, environmental constraints, and disturbance (LATHAM; ZUURING; COBLE, 1998).

This study aimed (a) to describe three tree communities of a cerrado, seasonal semideciduous forest and montane Atlantic rain forest; (b) to investigate the horizontal and vertical structure of such communities, assessing how the stratification or the horizontal and vertical structure can be defined along a section of the forest and in which ways the composition and importance of species in each stratum can vary.

2.2 **Material and methods**

2.2.1 Study sites

The study areas were Mogi Guaçu Biological Reserve, Caetetus Ecological Station and "Carlos Botelho" State Park, state of São Paulo, southeast Brazil (Figure 2.1).

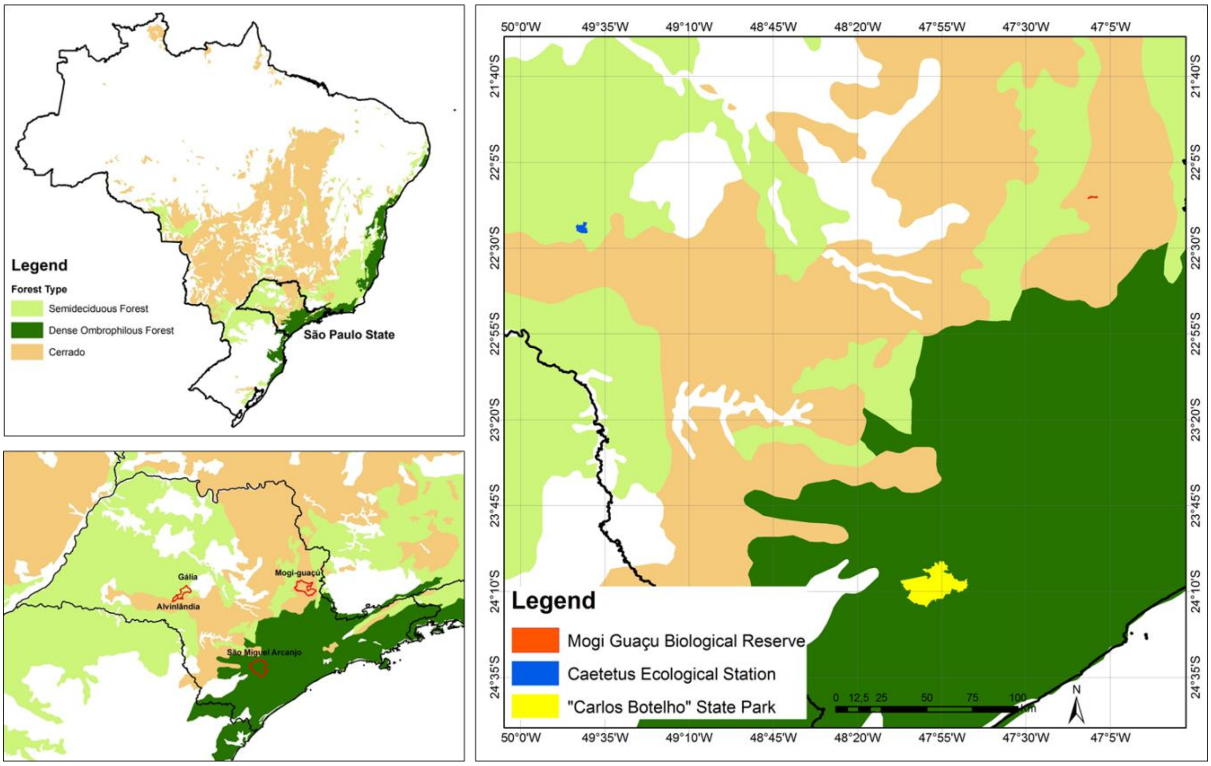

Figure 2.1 - The location of the Mogi Guaçu Biological Reserve in Cerrado, Caetetus Ecological Station in semideciduous forest and “Carlos Botelho” State Park in dense ombrophilous forest study sites

Mogi Guaçu Biological Reserve – Belonging to the *Instituto de Botânica* is situated at 22°15’17’’ S, 47°10’20’’ W, and 620 m of altitude. The reserve has 343 ha covered mainly by cerrado and, according to Eiten (1963), the relief is flat to gently rolling. The climate is classified as Cwa, according to Koöppen (1936), with a clearly rainy summer and a mild and dry winter. The mean annual temperature and rainfall are 20.8 ºC and 1.359 mm, respectively (BURGER; DELITTI, 1999). The soil is red-yellow latosol (oxisol), sandy-phase (LVa), deep (10-20 m), and well-drained with low fertility. It contains well-developed Al, and the pH range is from 4 to 5. The soil contains low nutrient concentrations and amounts in the first meter soil-layer and the values decrease from the surface to deeper soil-layer (DELITTI, 1998).

Caetetus Ecological Station – Belonging to the *Instituto Florestal* is situated at 22°24’15’’ S, 49°41’47’’ W, and 587 m of altitude, and the vegetation consists of a 2,178 ha of tropical seasonal semi-deciduous forest. The climate is classified as Cwa, according to the Koöppen (1936). A distinct dry season lasts 5 to 6 months, from April or May through September or October. The average rainfall is 1200–1600 mm, most of which falls between October and March, and average monthly temperatures range from 16° C in the dry season to 25° C in the wet (PASSOS, 1997). The predominant geological formation is sandstone, from

Marília and Adamantina formations of the Bauru group. Secondarily, undifferentiated continental and alluvial sediments are found in the region.

"Carlos Botelho" Park Station –The plots are located in the north of the park, situated at 24°03'54'' S, 47°57'29'' W, and 776 m of altitude. The park total area consists of a 37,797.43 ha area of dense ombrophilous montane forest and belongs to the *Instituto Florestal*. According to the Koöppen (1936), the type climate in the studied area is Cfb, comprising no hydric deficiency and accompanied by hot temperatures in the summer, although the average temperature is below 20° C. The temperature normally ranges between 0° and 34° C, with an annual average temperature of 19° C and an average rainfall of 1,685 mm over 20 years (range: 1,475 – 2,185 mm). Most rainfall is concentrated between September and March of each year. The mean annual rainfall and temperature between 1965 and 1990 were 1,530 mm and 19,4°C, respectively, with about 83% of annual rainfall concentrated between November and March (MORAES, 1992).The predominant geo-morphological units in these areas of Brazilian Atlantic Forest are the Paranapiacaba Hills and Guapiara Plateau, with features revealing the presence of high slopes and high summits formed by pre-Cambrian rocks. Sedimentary plateaus and marine deposits occur along the coastal zone (MANTOVANI, 1993) with prevalence of tropical nutrient-impoverished yellow-red latosol, podzols and lithosols (RADAMBRASIL, 1983), which support moist-evergreen-forest.

2.2.2 Data collection and analyses

Were surveyed the tree community in 10 plots of 300 m^2 (total area 0.3 ha) at each forest type placed casually along roads into the forest. Plot dimensions were 10 x 30 meters. We identified to species level all live trees in the plots with a circumference at breast height (CBH) $\geq$ 15.7cm, measuring this with a tape and estimating total height with the help of a pole. When a tree could not be identified to the species level it was identified to the genus level.

In the case of multi-stemmed trees, Macdicken, Wolf and Briscoe (1991) recommends that all of the stems be measured at 1.3 m above the root collar along the axis of each stem and combined with the formula below:

$$D_{combined} = \sqrt{(d_1^2 + d_2^2 + \ldots + d_n^2)}$$

We calculated for each species structural parameters of density, frequency, dominance (derived from tree basal area), and importance values (MUELLER-DOMBOIS; ELLENBERG, 1974) to describe the tree community structure. Importance values (IV) were calculated from the relative values of species density (D = number of individuals of the i^{th} species by area), frequency (F = number of sites occupied by the i^{th} species/total number of sites) and dominance (Do = sum of the basal area of all plants of the i^{th} species/total basal area), as IV = RD + RF + RDo. Let IV = Importance values, RD = relative density, RF = relative frequency and RDo = relative dominance.

In order to identify the main variation patterns of the diameter and height classes distribution in each area, a correlation-based principal component analyses (PCA) was performed to identify similar groups of diameter and height according to structural variables. Introduced by Pearson (1901) and developed by Hotelling (1933), a principal component analysis is concerned with explaining the variance-covariance structure of a set of variables through a few linear combinations of these variables. Its general objectives are data reduction and interpretation. Although *p* components are required to reproduce the total system variability, often much of this variability can be accounted for by a small number *k* of the principal components. The *k* principal components can then replace the initial *p* variables, and the original data set, consisting of *n* measurements on *p* variables, is reduced to a data set consisting of *n* measurements on *k* principal components. Correlation analysis was performed. For PCA, all the data were standardized to zero mean and unit variance, and the analysis was done on the correlation matrix. The components were retained and rotated using Varimax rotation (KAISER, 1958). The latter redistributes the variance in each variable so that each contributes strongly to one of the components and little to the others (SHARMA, 1995).

The PCA variables included number of species (Nspe), number of individuals (Nind) and basal area (BA) of each diameter and height class. The size of the diameter classes depended on the variation between maximum and minimum values of diameters and the number of diameter classes varies according to its variation. In Mogi-Guaçu Biological Reserve, the distribution was divided by classes of 3 cm, while Caetetus Ecological Station and "Carlos Botelho" State Park had classes divided by 5 cm. The size of height classes was 1 meter at all of the forest types and the number of classes varied according to the height variation in each forest type. For representation in this study, the number of each class was represented by the number of the class herein found instead of the real diameter or height value. All calculations were performed using the R Core Team (2012) software.

2.3 **Results**

2.3.1 Cerrado composition and structure

In the Mogi Guaçu Biological Reserve plot inventory, a total of 401 individual trees were measured and 59 species were registered. Stand physical structure in the area is summarized in Table 2.1. The estimated total density was 1,366.67 N/ha and the estimated basal area was 18.89 $m^2.ha^{-1}$. Ecological dominance was substantial: the 10 species with the highest densities accounted for 65.37% of all individuals while the 10 with the highest basal areas accounted for 73.18% of total basal area. The highest density species, *Vochysia tucanorum*, contained approximately 12% of total number of individuals. This species showed the highest basal area, almost 16% of total basal area.

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(it continues)

SPECIES	**N**	**BA (m^2)**	**P**	**RD (%)**	**RDo (%)**	**RF (%)**	**VI (%)**
Vochysia tucanorum Mart.	46	0.89	7	11.22	15.64	1.71	28.57
Qualea grandiflora Mart.	39	0.79	9	9.51	13.93	2.20	25.64
Copaifera langsdorffii Desf.	25	0.56	6	6.10	9.81	1.46	17.37
Xylopia aromatica (Lam.) Mart.	42	0.20	10	10.24	3.55	2.44	16.24
Anadenanthera peregrina (L.) Speg.	15	0.63	5	3.66	11.18	1.22	16.06
Syagrus flexuosa (Mart.) Becc.	28	0.38	7	6.83	6.67	1.71	15.21
Ocotea pulchella Mart.	22	0.17	8	5.37	3.04	1.95	10.36
Couepia grandiflora (Mart. & Zucc.) Benth. ex Hook.f.	13	0.30	4	3.17	5.22	0.98	9.37
Acosmium subelegans (Mohlenbr.) Yakovlev	22	0.13	6	5.37	2.22	1.46	9.05
Ouratea spectabilis (Mart. & Engl.) Engl.	16	0.11	8	3.90	1.90	1.95	7.76
Myrsine coriacea (Sw.) Roem. & Schult.	12	0.06	5	2.93	1.12	1.22	5.27
Tapirira obtusa (Benth.) J.D.Mitch.	9	0.09	3	2.20	1.58	0.73	4.50
Styrax ferrugineus Nees & Mart.	9	0.06	5	2.20	1.03	1.22	4.44

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(continuing)

SPECIES	**N**	**BA (m^2)**	**P**	**RD (%)**	**RDo (%)**	**RF (%)**	**VI (%)**
Siparuna guianensis Aubl.	9	0.03	7	2.20	0.50	1.71	4.40
Aspidosperma tomentosum Mart.	8	0.04	5	1.95	0.73	1.22	3.90
Pouteria ramiflora (Mart.) Radlk.	6	0.11	2	1.46	1.88	0.49	3.83
Ficus citrifolia Mill.	1	0.18	1	0.24	3.24	0.24	3.73
Schefflera macrocarpa (Cham. & Schltdl.) Frodin	4	0.10	3	0.98	1.70	0.73	3.41
Roupala montana Aubl.	6	0.06	3	1.46	0.99	0.73	3.19
Connarus suberosus Planch.	7	0.05	2	1.71	0.82	0.49	3.01
Prunus myrtifolia (L.) Urb.	4	0.07	2	0.98	1.32	0.49	2.78
Eriotheca gracilipes (K.Schum.) A.Robyns	4	0.06	3	0.98	1.04	0.73	2.75
Pera glabrata (Schott) Poepp. ex Baill.	3	0.06	3	0.73	1.02	0.73	2.48
Tapirira guianensis Aubl.	4	0.04	3	0.98	0.75	0.73	2.46
Pseudobombax longiflorum (Mart. & Zucc.) A.Robyns	3	0.04	2	0.73	0.77	0.49	1.99
Kielmeyera rubriflora Cambess.	4	0.03	1	0.98	0.62	0.24	1.84
Miconia rubiginosa (Bonpl.) DC.	3	0.01	3	0.73	0.24	0.73	1.71
Diospyros hispida A.DC.	3	0.01	3	0.73	0.19	0.73	1.66
Bowdichia virgilioides Kunth	1	0.07	1	0.24	1.17	0.24	1.65
Plenckia populnea Reissek	2	0.03	2	0.49	0.59	0.49	1.57
Stryphnodendron adstringens (Mart.) Cov.	3	0.03	1	0.73	0.58	0.24	1.55
Virola sebifera Aubl.	2	0.02	2	0.49	0.29	0.49	1.26
Miconia ferruginata DC.	2	0.01	2	0.49	0.26	0.49	1.23
Piptocarpha rotundifolia (Less.) Baker	2	0.01	2	0.49	0.24	0.49	1.22
Annona crassiflora Mart.	1	0.04	1	0.24	0.72	0.24	1.21
Lafoensia vandelliana Cham. & Schltdl.	2	0.01	2	0.49	0.17	0.49	1.14
Protium heptaphyllum (Aubl.) Marchand	2	0.01	2	0.49	0.15	0.49	1.13
Kielmeyera coriacea Mart. & Zucc.	2	0.01	1	0.49	0.25	0.24	0.99
Byrsonima coccolobifolia Kunth	1	0.02	1	0.24	0.43	0.24	0.91
Qualea parviflora Mart.	1	0.02	1	0.24	0.41	0.24	0.90
Guapira noxia (Netto) Lundell	2	0.01	1	0.49	0.12	0.24	0.85
Miconia albicans (Sw.) Triana	2	0.01	1	0.49	0.11	0.24	0.84

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(conclusion)

SPECIES	N	BA (m^2)	P	RD (%)	RDo (%)	RF (%)	VI (%)
Rudgea viburnoides (Cham.) Benth.	2	0.01	1	0.49	0.09	0.24	0.82
Tabebuia ochracea (Cham.) Standl.	1	0.02	1	0.24	0.31	0.24	0.80
Cryptocarya aschersoniana Mez	1	0.02	1	0.24	0.27	0.24	0.76
Nectandra grandiflora Nees	1	0.01	1	0.24	0.23	0.24	0.72
Ficus sp.	1	0.01	1	0.24	0.14	0.24	0.63
Campomanesia guaviroba (DC.) Kiaersk.	1	0.00	1	0.24	0.09	0.24	0.57
Guatteria australis A.St.-Hil.	1	0.00	1	0.24	0.08	0.24	0.57
Cupania vernalis Cambess.	1	0.00	1	0.24	0.08	0.24	0.57
Caryocar brasiliense Cambess.	1	0.00	1	0.24	0.08	0.24	0.56
Coussarea hydrangeifolia (Benth.) Müll.Arg.	1	0.00	1	0.24	0.07	0.24	0.56
Myrsine guianensis (Aubl.) Kuntze	1	0.00	1	0.24	0.07	0.24	0.56
Duguetia furfuracea (St. Hil.) Benth. & Hook.	1	0.00	1	0.24	0.06	0.24	0.55
Acosmium dasycarpum (Vogel) Yakovlev	1	0.00	1	0.24	0.05	0.24	0.54
Qualea multiflora Mart.	1	0.00	1	0.24	0.05	0.24	0.54
Erythroxylum tortuosum Mart.	1	0.00	1	0.24	0.04	0.24	0.53
Casearia sylvestris Sw.	1	0.00	1	0.24	0.04	0.24	0.53
Cordiera macrophylla Kuntze	1	0.00	1	0.24	0.04	0.24	0.53

2.3.2 Diametric stratification in Cerrado

Nearly all of the measured information on forest pattern was contained in the first two principal components, which explained 96.1% of the variation (Table 2.2). The first principal component explained 80.93% of the variation and was essentially equivalent to the number of individuals and species. The second principal component explained 15.16% of the variation, mainly related to basal area.

The diameter of all trees and species combined showed a reversed-J shape distribution typical of uneven-aged forests (Figure 2.1 a). Using principal component analysis (PCA) it was possible to identify 3 groups by the graph and define the diametric limits of each class: 5≤ DBH <8cm, 8≤ DBH <20cm and DBH ≥ 20cm (Figure 2.1 b). Most of individuals and species are concentrated in the first group, between 5 and 8 centimeters and represented by the class number 1, characterized by high number of individuals and species. The second group, represented by the classes 2 to 6 in the diameter distribution and PCA analysis, showed a high total basal area compared to the third and lower number of individuals and species than the first. The third group, observable in the graph by the classes 7 to 14, is featured by low number of individuals and species, thereby resulting in a small basal area group. Through the median values (Table 2.3), a majority of total basal area is concentrated in the first two classes, up to 20 centimeters. The difference between these 2 classes, confirmed by the principal component graph, is the number of individuals and species, concentrated in the first group. 43.90% of individuals and 10.40% of basal area are smaller than 8.0cm of diameter, distributed in 50 species, containing 84.74% of the total number of species. On the other hand, 53.90% of individuals and 70.18% of basal area are distributed in group B, including 40 species which is 67.79% of the total number of species. The greater than 20.0 cm class contains 2.19% of the number of individuals and 19.41% of basal area, including 15 species, representing 25.42% of the total number of species. In Cerrado, *Xylopia aromatica* (29), *Acosmium subelegans* (15) and *Ocotea pulchella* (14) were the species with the highest density in the first horizontal stratum. *Vochysia tucanorum* (32), *Qualea grandiflora* (22) and *Syagrus flexuosa* (15) in the second horizontal stratum. *Ananadenanthera peregrine* (6), *Vochysia tucanorum* (6), *Copaifera langsdorffii* (5) and *Qualea grandiflora* (5) were the principal species in the largest diameter stratum.

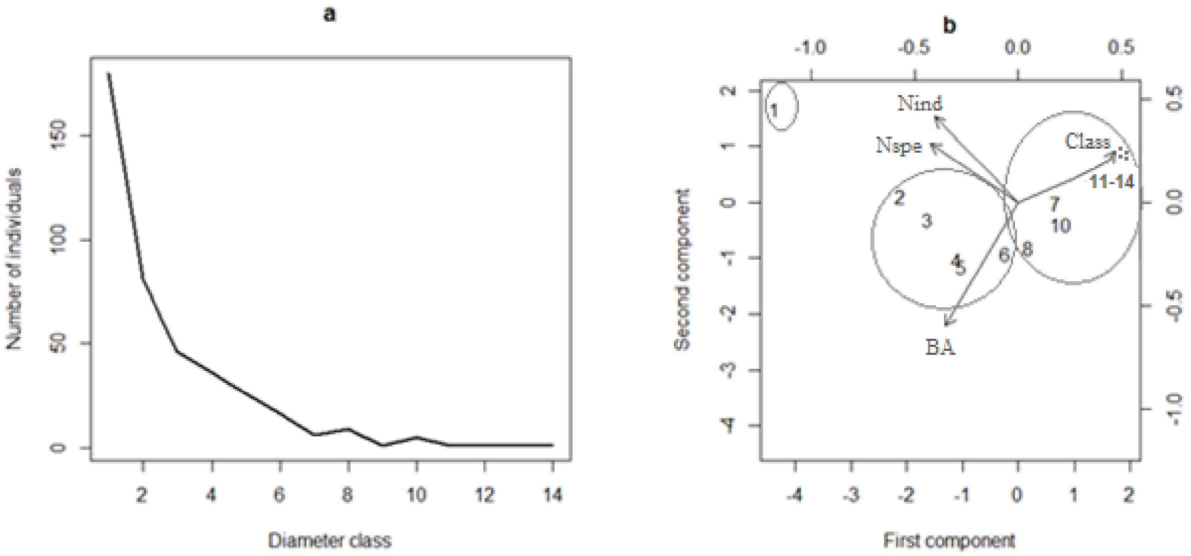

Figure 2.2 - a) Diameter classes' distribution and b) Plotted values of the first two components for 14 diameter classes in Mogi Guaçu Biological Reserve. Let BA = Basal area, Nind = Number of individuals, Nspe = Number of species and Class = number of the classes

Table 2.2 - Principal components analysis of horizontal structure: eigenvalues, proportion of variance of each component, cumulative proportion of variance and eigenvectors for four components of variables in Mogi Guaçu Biological Reserve

Item	**Comp.1**	**Comp.2**	**Comp.3**	**Comp.4**
Eigenvalue	1.7993	0.7787	0.3765	0.1194
Proportion of variance	0.8093	0.1516	0.0354	0.0035
Cumulative proportion	0.8093	0.9610	0.9964	1.0000
Class of diameter	0.519	0.229	0.818	-
Number of individuals	-0.504	0.516	0.250	0.646
Number of species	-0.531	0.353	0.152	-0.755
Basal area	-0.440	-0.746	0.495	-

Table 2.3 - Forest structure data for three horizontal strata (A, B and C) based on diameter classes of Cerrado in Mogi Guaçu Biological Reserve

Variable	**Strata**		
	A	**B**	**C**
Basal area (m^2)	0.58952	0.56188	0.18386
Number of individuals	180	21	9.5
Number of species	50	1	1

2.3.3 Height stratification in Cerrado

Most of the information on forest vertical structure was contained in the first two principal components, which explained 96.22% of the variation (Table 2.4). The first principal component explained 81.68% of the variation and was explained mainly by the number of individuals and species. The second principal component explained 14.54% of the variation, essentially related to basal area.

According to Figure 2.3 b, the principal component analysis (PCA) of individuals' distribution throughout the height classes for all the species surveyed in Mogi Guaçu Biological Reserve presented a gradient in 3 groups or strata: stratum A ($h \geq 11.7$ m), stratum B ($7.7 \text{ m} \leq h < 11.7$m) and stratum C ($h < 7.7$ m). Most of individuals and species are concentrated in the group C, represented by classes number 1 to 6, characterized by high number of individuals and species and showed the same total basal area than group B, classes 7 to 10. The group A, represented by classes 11 to 16, including the highest trees in the study site, is featured by low number of individuals and species, thereby resulting in a small basal area group. Through the median values (Table 5), a majority of total basal area is concentrated in the groups B and C, up to 11.7 meters. The difference between these 2 classes, confirmed by the principal component graph, is the number of individuals and species, concentrated in the group C. 75.8% of individuals and 43.8% are lower than 7.7 m, distributed in 53 species, containing 89.8% of the total number of species. On the other hand, 20.0% of individuals and 35.4% of basal area are distributed in group B, including 23 species which is 39.0% of the total number of species. The greater than 11.7m height class contains 20.7% of the basal area and 4.1% of the number of individuals with 7 species representing 11.9% of the total number of species. *Ficus citrifolia* was the exclusive species in the highest stratum. Considering the height stratification, *Xylopia aromatica* (33), *Qualea grandiflora* (30) and *Syagrus flexuosa* (28) were the principal species in the shortest individuals. *Vochysia tucanorum* (24), *Copaifera langsdorffii* (16) and *Qualea grandiflora* (9) distributed in the intermediary stratum. *Anadenanthera peregrina* (6) and *Copaifera langsdorffi* (5) are the most frequent species in the dominant stratum. *Annona crassiflora, Bowdichia virgilioides and Ficus citrifolia* were exclusive species in the largest diameter group.

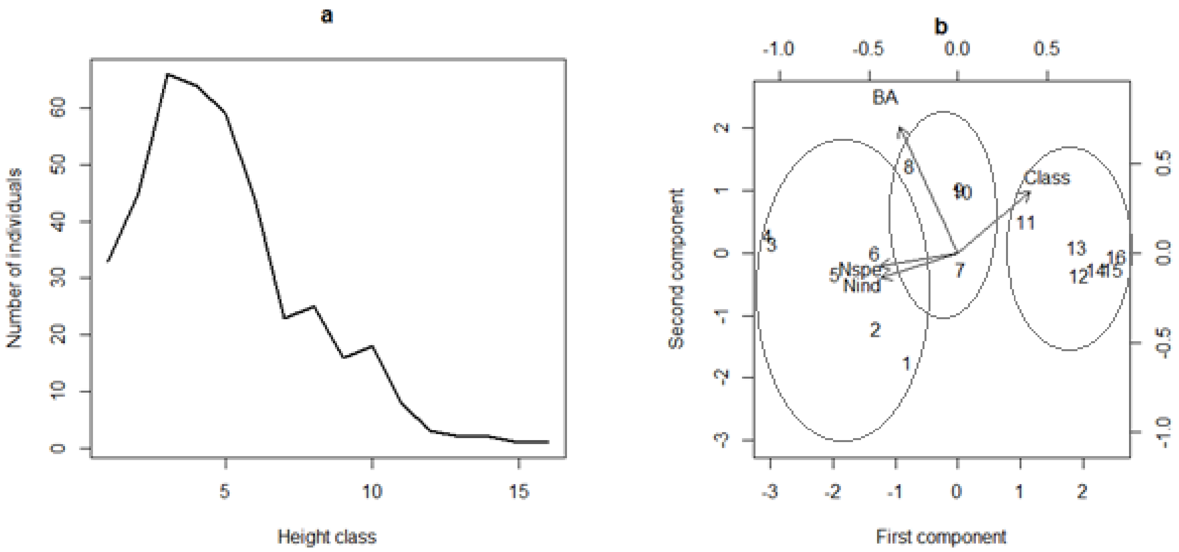

Figure 2.3 - a) Height classes' distribution and b) Plotted values of the first two components for 16 height classes in Mogi Guaçu Biological Reserve. Let BA = Basal area, Nind = Number of individuals, Nspe = Number of species and Class = number of the class

Table 2.4 - Principal components analysis of vertical structure: eigenvalues, proportion of variance of each component, cumulative proportion of variance and eigenvectors for four components of variables in Mogi Guaçu Biological Reserve

Item	**Comp.1**	**Comp.2**	**Comp.3**	**Comp.4**
Eigenvalue	1.8275	0.7626	0.3751	0.1013
Proportion of variance	0.8168	0.1454	0.0351	0.0025
Cumulative proportion	0.8168	0.9622	0.9974	1.0000
Class of height	0.499	0.432	-0.750	-
Number of individuals	-0.537	-0.172	-0.498	-0.659
Number of species	-0.545	-	-0.369	0.747
Basal area	-0.407	0.880	0.232	-

Table 2.5 - Forest structure data for three vertical strata (A, B and C) of Cerrado in Mogi Guaçu Biological Reserve. The values represent the median values of each stratum

	Strata		
Variables	**A**	**B**	**C**
Basal area (m^2)	0.15482	0.52113	0.43558
Number of individuals	2	20.5	52
Number of species	2	9	17.5

2.3.4 Semideciduous forests composition and structure

In the Caetetus Ecological Station plot inventory, a total of 422 individuals were measured and 86 species were registered. Stand physical structure in the area is summarized in Table 2.6. The estimated total density was 1,406.67 N/ha and the estimated basal area was 37.11 $m^2.ha^{-1}$ Ecological dominance was substantial: the 10 species with the highest densities accounted for 51.66% of all individuals while the 10 with the highest basal areas accounted for 44.09% of total basal area. The highest density species, *Savia dictyocarpa*, contained approximately 12% of total number of individuals. This species showed the highest basal area, but contained less than 13% of total basal area.

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(it continues)

SPECIES	**N**	**BA (m^2)**	**P**	**RD (%)**	**RDo (%)**	**RF (%)**	**IVI (%)**
Savia dictyocarpa Müll.Arg.	51	1.40	5	12.09	12.61	2.91	27.60
Metrodorea nigra A.St.-Hil.	53	0.42	5	12.56	3.78	2.91	19.24
Ocotea indecora (Schott) Mez	17	1.06	8	4.03	9.50	4.65	18.18
Aspidosperma polyneuron Müll.Arg.	15	0.47	6	3.55	4.22	3.49	11.26
Centrolobium tomentosum Guillem. ex Benth.	8	0.51	5	1.90	4.62	2.91	9.42
Pilocarpus pauciflorus A.St.-Hil.	21	0.17	4	4.98	1.56	2.33	8.86
Actinostemon concepcionis (Chodat & Hassl.) Hochr.	25	0.08	3	5.92	0.72	1.74	8.39
Chrysophyllum gonocarpum (Mart. & Eichler) Engl.	8	0.31	5	1.90	2.76	2.91	7.57
Rhamnidium elaeocarpum Reissek	10	0.21	5	2.37	1.91	2.91	7.19
Piptadenia gonoacantha (Mart.) J.F.Macbr.	10	0.27	4	2.37	2.41	2.33	7.11
Astronium graveolens Jacq.	10	0.17	5	2.37	1.56	2.91	6.84
Ficus enormis (Mart. ex Miq.) Mart.	1	0.62	1	0.24	5.60	0.58	6.42
Eugenia ramboi D.Legrand	10	0.04	6	2.37	0.38	3.49	6.24
Alchornea glandulosa Poepp. & Endl.	3	0.45	2	0.71	4.03	1.16	5.91
Syagrus romanzoffiana (Cham.) Glassman	6	0.15	5	1.42	1.38	2.91	5.71
Cariniana estrellensis (Raddi) Kuntze	2	0.44	2	0.47	3.93	1.16	5.57
Trichilia catigua A.Juss.	11	0.07	3	2.61	0.59	1.74	4.94
Copaifera langsdorffii Desf.	1	0.41	1	0.24	3.72	0.58	4.53
Syagrus oleracea (Mart.) Becc.	5	0.15	3	1.18	1.38	1.74	4.31
Ceiba speciosa (A.St.-Hil.) Ravenna	2	0.29	2	0.47	2.58	1.16	4.22
Casearia sylvestris Sw.	6	0.05	4	1.42	0.45	2.33	4.20
Pilocarpus pennatifolius Lem.	12	0.06	1	2.84	0.57	0.58	4.00
Trichilia claussenii C.DC.	7	0.06	3	1.66	0.52	1.74	3.93
Cabralea canjerana (Vell.) Mart.	3	0.22	2	0.71	2.01	1.16	3.88
Ficus citrifolia Mill.	1	0.34	1	0.24	3.02	0.58	3.84
Albizia polycephala (Benth.) Killip ex Record	4	0.23	1	0.95	2.07	0.58	3.60
Cordia superba Cham.	3	0.15	2	0.71	1.35	1.16	3.22

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(continuing)

SPECIES	**N**	**BA (m^2)**	**P**	**RD (%)**	**RDo (%)**	**RF (%)**	**IVI (%)**
Cordia ecalyculata Vell.	4	0.05	3	0.95	0.42	1.74	3.12
Cedrela fissilis Vell.	1	0.25	1	0.24	2.29	0.58	3.11
Coutarea hexandra (Jacq.) K.Schum.	3	0.12	2	0.71	1.08	1.16	2.96
Alchornea triplinervia (Spreng.) Müll.Arg.	4	0.15	1	0.95	1.34	0.58	2.87
Trichilia pallida Sw.	4	0.02	3	0.95	0.16	1.74	2.85
Holocalyx balansae Micheli	6	0.03	2	1.42	0.25	1.16	2.84
Inga striata Benth.	4	0.07	2	0.95	0.66	1.16	2.77
Machaerium stipitatum (DC.) Vogel	4	0.06	2	0.95	0.57	1.16	2.68
Acacia polyphylla DC.	3	0.08	2	0.71	0.76	1.16	2.63
Esenbeckia leiocarpa Engl.	5	0.02	2	1.18	0.21	1.16	2.56
Cupania vernalis Cambess.	4	0.04	2	0.95	0.39	1.16	2.50
Myroxylon peruiferum L.f.	4	0.03	2	0.95	0.27	1.16	2.38
Eugenia blastantha (O.Berg) D.Legrand	4	0.03	2	0.95	0.26	1.16	2.37
Aparisthmium cordatum (Juss.) Baill.	4	0.02	2	0.95	0.16	1.16	2.27
Balfourodendron riedelianum (Engl.) Engl.	5	0.05	1	1.18	0.49	0.58	2.25
Nectandra oppositifolia Nees	2	0.13	1	0.47	1.15	0.58	2.20
Colubrina glandulosa Perkins	1	0.15	1	0.24	1.32	0.58	2.14
Mabea fistulifera Mart.	4	0.06	1	0.95	0.53	0.58	2.06
Maytenus robusta Reissek	1	0.13	1	0.24	1.20	0.58	2.02
Diatenopteryx sorbifolia Radlk.	2	0.03	2	0.47	0.28	1.16	1.91
Schefflera morototoni (Aubl.) Maguire et al.	2	0.03	2	0.47	0.25	1.16	1.88
Hymenaea courbaril L.	1	0.12	1	0.24	1.05	0.58	1.86
Xylopia brasiliensis Spreng.	2	0.02	2	0.47	0.15	1.16	1.79
Nectandra megapotamica (Spreng.) Mez	2	0.02	2	0.47	0.14	1.16	1.77
Neomitranthes glomerata (D.Legrand) D.Legrand	2	0.01	2	0.47	0.10	1.16	1.74
Ficus eximia Schott	1	0.09	1	0.24	0.80	0.58	1.62
Jacaranda macrantha Cham.	1	0.07	1	0.24	0.65	0.58	1.47

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(continuing)

SPECIES	**N**	**BA (m^2)**	**P**	**RD (%)**	**RDo (%)**	**RF (%)**	**IVI (%)**
Euterpe edulis Mart.	3	0.02	1	0.71	0.17	0.58	1.46
Calyptranthes clusiifolia O.Berg	1	0.06	1	0.24	0.50	0.58	1.32
Matayba elaeagnoides Radlk.	2	0.03	1	0.47	0.24	0.58	1.30
Jacaratia spinosa (Aubl.) A.DC.	1	0.05	1	0.24	0.47	0.58	1.29
Myrcia sp.1	1	0.05	1	0.24	0.42	0.58	1.23
Croton floribundus Spreng.	1	0.04	1	0.24	0.40	0.58	1.22
Nectandra lanceolata Nees	1	0.04	1	0.24	0.37	0.58	1.18
Guarea kunthiana A.Juss.	2	0.01	1	0.47	0.05	0.58	1.11
Myrciaria floribunda (H.West ex Willd.) O.Berg	2	0.01	1	0.47	0.05	0.58	1.10
Zanthoxylum caribaeum Lam.	1	0.02	1	0.24	0.15	0.58	0.97
Tapirira guianensis Aubl.	1	0.01	1	0.24	0.13	0.58	0.94
Myrcia splendens (Sw.) DC.	1	0.01	1	0.24	0.09	0.58	0.91
Bauhinia longifolia (Bong.) D.Dietr.	1	0.01	1	0.24	0.07	0.58	0.89
Aspidosperma cylindrocarpon Müll.Arg.	1	0.01	1	0.24	0.06	0.58	0.88
Endlicheria paniculata (Spreng.) J.F.Macbr.	1	0.01	1	0.24	0.06	0.58	0.88
Ocotea corymbosa (Meisn.) Mez	1	0.01	1	0.24	0.06	0.58	0.87
Sorocea bonplandii (Baill.) W.C.Burger et al.	1	0.01	1	0.24	0.05	0.58	0.87
Roupala montana Aubl.	1	0.01	1	0.24	0.05	0.58	0.87
Myrcia sp.2	1	0.01	1	0.24	0.05	0.58	0.87
Ocotea velloziana (Meisn.) Mez	1	0.01	1	0.24	0.05	0.58	0.87
Rollinia sylvatica (A.St.-Hil.) Mart.	1	0.00	1	0.24	0.04	0.58	0.86
Sloanea monosperma Vell.	1	0.00	1	0.24	0.04	0.58	0.85
Duguetia lanceolata A.St.-Hil.	1	0.00	1	0.24	0.03	0.58	0.85
Zanthoxylum rhoifolium Lam.	1	0.00	1	0.24	0.03	0.58	0.85
Amaioua guianensis Aubl.	1	0.00	1	0.24	0.03	0.58	0.85
Celtis iguanaea (Jacq.) Sarg.	1	0.00	1	0.24	0.03	0.58	0.84

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(conclusion)

SPECIES	**N**	**BA (m^2)**	**P**	**RD (%)**	**RDo (%)**	**RF (%)**	**IVI (%)**
Lacistema hasslerianum Chodat	1	0.00	1	0.24	0.02	0.58	0.84
Ocotea diospyrifolia (Meisn.) Mez	1	0.00	1	0.24	0.02	0.58	0.84
Sloanea stipitata Spruce ex Benth.	1	0.00	1	0.24	0.02	0.58	0.84
Gymnanthes concolor (Spreng.) Müll.Arg.	1	0.00	1	0.24	0.02	0.58	0.84
Cupania tenuivalvis Radlk.	1	0.00	1	0.24	0.02	0.58	0.84
Seguieria aculeata Jacq.	1	0.00	1	0.24	0.02	0.58	0.84

2.3.5 Diameter stratification in semideciduous forest

In the seasonal semi-deciduous forest, nearly all of the measured information on forest pattern was contained in the first two principal components, which explained 93.80% of the variation (Table 2.7). The first principal component explained 75.25% of the variation. The second principal component explained 18.55% of the variation, mainly related to basal area.

The diameter of all trees and species combined showed a reversed-J shape distribution (Fig 2.4a). Using principal component analysis it was possible to identify 3 groups and define the diameter limits of each class: 5≤ DBH <10cm, 10≤ DBH <35cm and DBH ≥ 35cm (Fig 2.4b). Most of individuals and species are concentrated in the first group, represented by class 1, between 5 and 10 centimeters, characterized by high number of individuals and species. The second group showed a high total basal area compared to the third and lower number of individuals and species than the first, represented by the classes 2 to 6. The third group, as seen in Figure 3.b by classes 7 to 17, is featured by low number of individuals and species, thereby resulting in a small basal area group. Through the median values (Table 2.7), a majority of total basal area is concentrated in the first two classes, up to 35 centimeters. The difference between these 2 classes, confirmed by the principal component graph, is the number of individuals and species, concentrated in the first group. 54 .7% of individuals and 8.3% of basal area are smaller than 10.0 cm in diameter, distributed in 58 species and containing 67.44% of the total number of species. On the other hand, 39.57% of the number of individuals and 43.25% of basal area are distributed in group B. Group B includes 52 species, which is 60.46% of the total number of species. The greater than 35.0 cm class contains 5.68% of the number of individuals and 48.38% of basal area, including in 18 species, representing 20.93% of the total number of species. *Cariniana estrellensis, Cedrella fissilis, Colubrin glandulosa, Copaifera langsdorffii, Ficus enormis, Ficus guaranitica, Hymenaea courbaril and Maytenus robusta* were exclusive species in the largest diameter group.

In the seasonal semideciduous forest, *Metrodorea nigra* (36), *Actnostemon concepciones* (25) and *Savia dictyocarpa* (21) were the most frequent species amongst the smallest diameter species. *Savia dictyocarpa* (28*), Metrodorea nigra* (17) and *Aspidosperma polyneuron* (9) were the most common species in the medium diameter stratum. *Savia dictyocarpa* (25), *Metrodorea nigra* (13), *Aspidosperma polyneuron* (9) and *Ocotea indecora* (9) were the most frequent species in the largest diameter group.

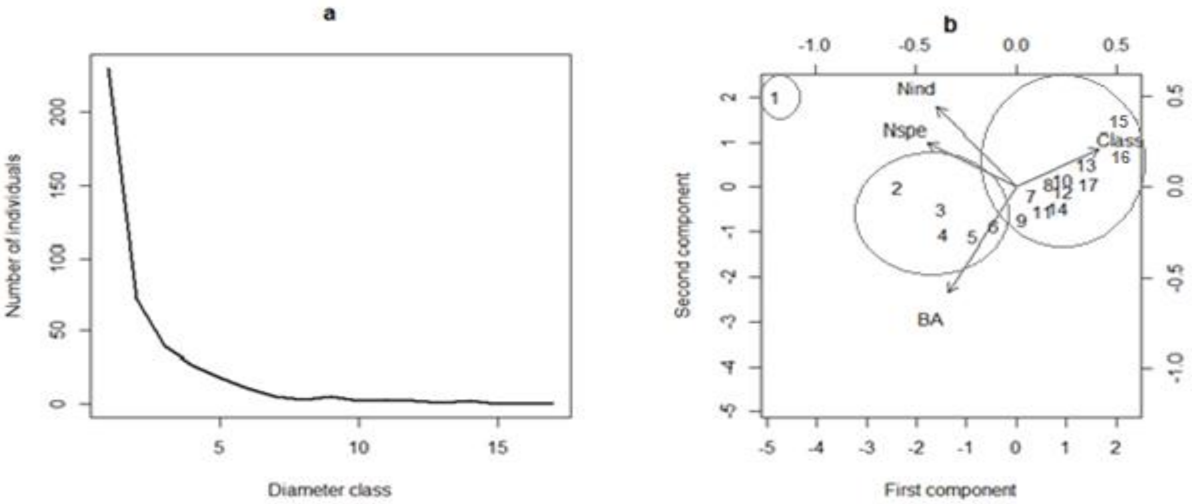

Figure 2.4 - Plotted diameter classes' distribution and b) Plotted values of the first two components for 17 diameter classes in Caetetus Ecological Station. Let BA = Basal area, Nind = Number of individuals, Nspe = Number of species and Class = number of the class

Table 2.7 - Principal components analysis of horizontal structure: eigenvalues, proportion of variance of each component, cumulative proportion of variance and eigenvectors of variables in semidiciduous forest

Item	**Comp.1**	**Comp.2**	**Comp.3**	**Comp.4**
Eigenvalue	1.7359	0.8614	0.4774	0.1410
Proportion of variance	0.7525	0.1855	0.0570	0.0049
Cumulative proportion	0.7525	0.9380	0.9950	1.0000
Class of diameter	0.517	0.267	0.786	-0.209
Number of individuals	-0.498	0.551	0.300	0.599
Number of species	-0.551	0.312	-	-0.772
Basal area	-0.424	-0.727	0.539	-

Table 2.8 - Forest structure data for three horizontal strata (A, B and C) based on diameter classes of seasonal semideciduous forest in Caetetus Ecological Station. The values represent the median values of each stratum

	Strata		
Variables	**A**	**B**	**C**
Basal area (m^2)	0.929978	0.909241	0.550899
Number of individuals	231	27	2
Number of species	58	19	2

2.3.6 Height stratification in semideciduous forest

In the seasonal semi-deciduous forest, nearly all of the measured information on forest pattern was contained in the first two principal components, which explained 91.12% of the variation (Table 2.9). The first principal component explained 57.34% of the variation related to the number of individuals and species. The second principal component explained 33.78% of the variation, mainly associated with basal area.

According to Figure 2.5 b, the principal component analysis (PCA) of individuals' distribution throughout the height classes for all the species surveyed in Caetetus Ecological Station presented a gradient in 4 groups or strata: stratum A ($h \geq 19.0$m), B ($11.0 \leq h < 19.0$ m), C ($6.0 \leq h < 11.0$) and D ($h < 6.0$). The analysis showed similarity between strata A and D, distributed along the axis 1 due to the small number of individuals and species. Group A, consisted in the classes 18 to 23, included 3.3% of individuals and 27.2% of basal area distributed in 13 species, representing 8.2% of the tree species. On the other hand, in the up to 6 meters class (D), classes 1 to 4, 9.7% of individuals and 1.4% of total basal area were distributed in 13 species which represented 15.3% of all species. These low densities in stratum A and D resulted in a lower floristic richness (Table 2.10). Stratum B, consisted in the classes 11 to 17, contained the highest basal area, 56.6% of total basal area, and 36.0% of the total number of individuals in 56 species, that is, 65.9% of all species. Stratum C, classes 5 to 10, had 14.7% of the basal area and the highest number of individuals, 50.9% of the total number distributed in 56 species, that is, 65.9% of all species. *Cedrella fissilis, Copaifera langsdorffii, Ficus enormis* and *Ficus guaranitica* were exclusive species of the highest stratum. The lowest stratum did not have any exclusive species. *Aspidosperma polyneuron* and *Metrodorea nigra* were the only species occurring in the 4 strata in the seasonal semideciduous forest. Considering height, *Metrodorea nigra* (5), *Actinostemon concepciones* (3) and *Trichilia catigua* (2) were the most frequent in the lowest height stratum. *Metrodorea* *nigra* (47), *Actinostemon concepciones* (22) and *Savia disctyocarpa* (19) were the most important in the stratum C. In stratum B, *Savia dyctiocarpa* (30), *Ocotea indecora* (9), *Syagrus romanzoffiana* (6), *Piptadenia gonoacantha* (6), *Centrolobium tomentosum* (6) and *Astronium graveollens* (6) were the most important. As dominant species, *Savia disctyocarpa* (2), *Aspidosperma polyneuron* (2) and *Alchornea triplinervea* (2) were the most important.

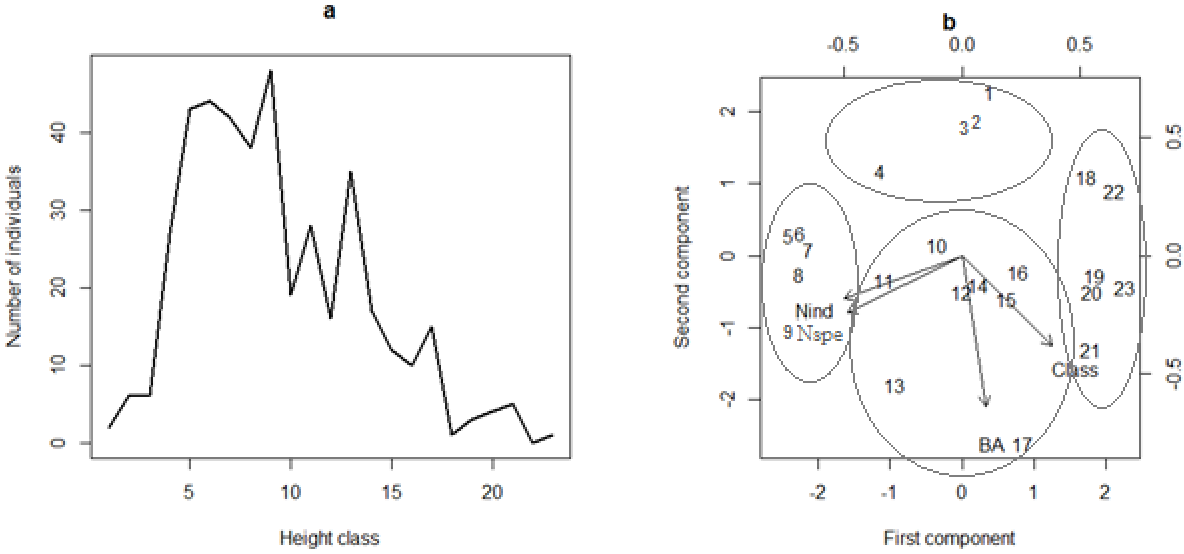

Figure 2.5 - Height classes' distribution and b) Plotted values of the first two components for 23 height classes in Caetetus Ecological Station. Let BA = Basal area, Nind = Number of individuals, Nspe = Number of species and Class = number of the class

Table 2.9 - Principal components analysis of vertical structure: eigenvalues, proportion of variance of each component, cumulative proportion of variance and eigenvectors for four components of variables in Caetetus Ecological Station

Item	**Comp.1**	**Comp.2**	**Comp.3**	**Comp.4**
Standard deviation	1.5145	1.1624	0.5634	0.1937
Proportion of variance	0.5734	0.3378	0.0793	0.0093
Cumulative proportion	0.5734	0.9112	0.9906	1.0000
Class	0.477	-0.474	0.740	-
Number of individuals	-0.623	-0.227	-0.257	0.703
Number of species	-0.607	-0.303	-0.197	-0.708
Basal area	0.124	-0.795	0.590	-

Table 2.10 - Forest structure data for four vertical strata (A, B, C and D) based on height classes of seasonal semideciduous forest in Caetetus Ecological Station. The values represent the median values of each stratum

	Strata			
Variables	**A**	**B**	**C**	**D**
Basal area (m^2)	0.637041	0.67074	0.22673	0.02142
Number of individuals	2	16.5	42.5	6
Number of species	1.5	12	21.5	3

2.3.7 Ombrophilous forest composition and structure

In the "Carlos Botelho" State Park plot inventory, a total of 540 individuals were measured and 165 species were registered. Of the registered species, 8 were described to morphospecies and 6 to family. Stand physical structure in the area is summarized in Table 2.11. The estimated total density was 1,800.00 N/ha and the estimated basal area was 50.29 $m^2.ha^{-1}$ Ecological dominance was substantial: the 10 species with the highest densities accounted for 38.89% of all individuals while the 10 with the highest basal areas accounted for 46.19% of total basal area. The highest density species, *Euterpe edulis*, contained approximately 20% of total number of individuals and *Micropholis crassipedicellata* showed the highest basal area, but contained less than 18% of total basal area.

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(it continues)

SPECIES	N	BA (m^2)	P	RD (%)	RDo (%)	RF (%)	VI (%)
Euterpe edulis Mart.	110	0.71	10	20.37	4.68	3.30	28.35
Micropholis crassipedicellata (Mart. & Eichler) Pierre	12	2.69	4	2.22	17.80	1.32	21.35
Alchornea triplinervia (Spreng.) Müll.Arg.	10	1.48	4	1.85	9.84	1.32	13.01
Guapira opposita (Vell.) Reitz	11	0.55	7	2.04	3.67	2.31	8.02
Cyathea phalerata Mart.	21	0.13	6	3.89	0.87	1.98	6.74
Pouteria bullata (S.Moore) Baehni	7	0.58	4	1.30	3.84	1.32	6.45

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(continuing)

SPECIES	**N**	**BA (m^2)**	**P**	**RD (%)**	**RDo (%)**	**RF (%)**	**VI (%)**
Ocotea catharinensis Mez	9	0.29	5	1.67	1.89	1.65	5.21
Ocotea corymbosa (Meisn.) Mez	9	0.23	6	1.67	1.53	1.98	5.18
Bathysa australis (A.St.-Hil.) Benth. & Hook.f.	10	0.22	3	1.85	1.48	0.99	4.32
Cordiera myrciifolia (K.Schum.) C.Perss. & Delprete	11	0.09	5	2.04	0.59	1.65	4.28
Pterocarpus rohri Vahl	8	0.21	4	1.48	1.42	1.32	4.22
Schefflera angustissima (Marchal) Frodin	4	0.32	4	0.74	2.10	1.32	4.16
Cyathea delgadii Sternb.	11	0.07	4	2.04	0.48	1.32	3.84
Nectandra membranacea (Sw.) Griseb.	2	0.40	2	0.37	2.64	0.66	3.67
Weinmannia paulliniifolia Pohl	4	0.26	3	0.74	1.74	0.99	3.47
Aiouea acaradomatifera Kosterm.	4	0.34	1	0.74	2.25	0.33	3.32
Myrsine umbellata Mart.	6	0.12	4	1.11	0.80	1.32	3.23
Amaioua guianensis Aubl.	6	0.07	5	1.11	0.45	1.65	3.21
Cordiera sp.1	10	0.05	3	1.85	0.36	0.99	3.21
Chionanthus filiformis (Vell.) P.S.Green	7	0.04	5	1.30	0.24	1.65	3.19
Hirtella hebeclada Moric. ex DC.	6	0.11	4	1.11	0.71	1.32	3.14
Nectandra oppositifolia Nees	3	0.28	2	0.56	1.88	0.66	3.10
Marlierea reitzii D.Legrand	5	0.08	5	0.93	0.51	1.65	3.09
Vantanea compacta (Schnizl.) Cuatrec.	3	0.23	3	0.56	1.50	0.99	3.04
Plinia brachybotrya (D.Legrand) Sobral	7	0.04	4	1.30	0.23	1.32	2.85
Rudgea jasminoides (Cham.) Müll.Arg.	7	0.03	4	1.30	0.17	1.32	2.78
Aniba firmula (Nees & Mart.) Mez	7	0.09	2	1.30	0.59	0.66	2.55
Copaifera trapezifolia Hayne	2	0.27	1	0.37	1.80	0.33	2.50
Pouteria gardneriana (A.DC.) Radlk.	2	0.22	2	0.37	1.45	0.66	2.48
Diploon cuspidatum (Hoehne) Cronquist	1	0.29	1	0.19	1.90	0.33	2.41
Lauraceae 1	2	0.21	2	0.37	1.38	0.66	2.41
Neomitranthes glomerata (D.Legrand) D.Legrand	4	0.05	4	0.74	0.30	1.32	2.36
Cryptocarya moschata Nees & Mart. ex Nees	2	0.19	2	0.37	1.24	0.66	2.27
Guarea macrophylla Vahl	4	0.02	4	0.74	0.15	1.32	2.21
Matayba guianensis Aubl.	3	0.09	3	0.56	0.61	0.99	2.15

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(continuing)

SPECIES	**N**	**BA (m^2)**	**P**	**RD (%)**	**RDo (%)**	**RF (%)**	**VI (%)**
Posoqueria latifolia (Rudge) Roem. & Schult.	4	0.06	3	0.74	0.42	0.99	2.15
Protium heptaphyllum (Aubl.) Marchand	3	0.09	3	0.56	0.60	0.99	2.14
Nectandra lanceolata Nees	2	0.17	2	0.37	1.11	0.66	2.14
Cupania oblongifolia Mart.	2	0.16	2	0.37	1.07	0.66	2.10
Ocotea divaricata (Nees) Mez	5	0.02	3	0.93	0.13	0.99	2.04
Mollinedia uleana Perk.	6	0.04	2	1.11	0.25	0.66	2.02
Chrysophyllum viride Mart. & Eichler	1	0.23	1	0.19	1.50	0.33	2.01
Andira anthelmia (Vell.) Benth.	4	0.07	2	0.74	0.47	0.66	1.87
Sorocea bonplandii (Baill.) W.C.Burger et al.	3	0.04	3	0.56	0.28	0.99	1.82
Matayba juglandifolia Radlk.	3	0.07	2	0.56	0.49	0.66	1.71
Mollinedia oligantha Perkins	4	0.04	2	0.74	0.27	0.66	1.67
Myrcia splendens (Sw.) DC.	3	0.07	2	0.56	0.44	0.66	1.65
Guatteria australis A.St.-Hil.	3	0.02	3	0.56	0.10	0.99	1.65
Eugenia cerasiflora Miq.	3	0.01	3	0.56	0.10	0.99	1.64
Alseis floribunda Schott	3	0.01	3	0.56	0.09	0.99	1.64
Persea willdenowii Kosterm.	4	0.08	1	0.74	0.50	0.33	1.57
Eugenia handroana D.Legrand	3	0.05	2	0.56	0.34	0.66	1.56
Cinnamomum triplinerve (Ruiz & Pav.) Kosterm.	2	0.06	2	0.37	0.43	0.66	1.46
Eugenia magnifica Spring ex Mart.	3	0.03	2	0.56	0.17	0.66	1.38
Tapirira guianensis Aubl.	2	0.05	2	0.37	0.34	0.66	1.37
Swartzia acutifolia Vogel	2	0.10	1	0.37	0.66	0.33	1.36
Duguetia lanceolata A.St.-Hil.	3	0.06	1	0.56	0.42	0.33	1.31
Pouteria guianensis Aubl.	1	0.12	1	0.19	0.78	0.33	1.30
Byrsonima ligustrifolia A.Juss.	3	0.01	2	0.56	0.08	0.66	1.29
Couepia venosa Prance	3	0.01	2	0.56	0.07	0.66	1.29
Calyptranthes widgreniana O.Berg	3	0.01	2	0.56	0.07	0.66	1.28
Myrtaceae 1	2	0.03	2	0.37	0.22	0.66	1.25
Chrysophyllum inornatum Mart.	1	0.11	1	0.19	0.71	0.33	1.23
Miconia pusilliflora (DC.) Triana	4	0.02	1	0.74	0.14	0.33	1.21

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(continuing)

SPECIES	**N**	**BA (m^2)**	**P**	**RD (%)**	**RDo (%)**	**RF (%)**	**VI (%)**
Faramea montevidensis (Cham. & Schltdl.) DC.	2	0.03	2	0.37	0.17	0.66	1.20
Ocotea odorifera (Vell.) Rohwer	1	0.10	1	0.19	0.68	0.33	1.20
Morphospecies 1	1	0.10	1	0.19	0.68	0.33	1.19
Tabebuia botelhensis A.H.Gentry	1	0.10	1	0.19	0.64	0.33	1.15
Parinari excelsa Sabine	1	0.10	1	0.19	0.63	0.33	1.15
Ormosia monosperma (Sw.) Urb.	2	0.02	2	0.37	0.10	0.66	1.13
Coussarea contracta (Walp.) Müll.Arg.	2	0.01	2	0.37	0.09	0.66	1.12
Eugenia neoaustralis Sobral	2	0.06	1	0.37	0.41	0.33	1.11
Marlierea tomentosa Cambess.	2	0.01	2	0.37	0.08	0.66	1.11
Randia armata (Sw.) DC.	2	0.01	2	0.37	0.07	0.66	1.10
Ixora francavillana Müll.Arg.	2	0.01	2	0.37	0.07	0.66	1.10
Cordia sellowiana Cham.	2	0.01	2	0.37	0.06	0.66	1.09
Myrsine gardneriana A.DC.	1	0.09	1	0.19	0.57	0.33	1.09
Esenbeckia grandiflora Mart.	2	0.01	2	0.37	0.06	0.66	1.09
Plinia complanata M.L.Kawasaki & B.Holst	2	0.01	2	0.37	0.05	0.66	1.09
Ocotea dispersa (Nees) Mez	2	0.01	2	0.37	0.05	0.66	1.08
Mollinedia schottiana (Spreng.) Perkins	2	0.01	2	0.37	0.05	0.66	1.08
Myrceugenia myrcioides (Cambess.) O.Berg	2	0.01	2	0.37	0.04	0.66	1.07
Roupala sculpta Sleumer	1	0.08	1	0.19	0.55	0.33	1.07
Morphospecies 2	1	0.08	1	0.19	0.54	0.33	1.06
Byrsonima myricifolia Griseb.	2	0.05	1	0.37	0.35	0.33	1.06
Ormosia arborea (Vell.) Harms	1	0.08	1	0.19	0.51	0.33	1.02
Chomelia catharinae (L.B.Sm. & Downs) Steyerm.	3	0.02	1	0.56	0.12	0.33	1.01
Morphospecies 3	1	0.07	1	0.19	0.49	0.33	1.00
Prunus myrtifolia (L.) Urb.	1	0.07	1	0.19	0.47	0.33	0.98
Jacaranda puberula Cham.	1	0.06	1	0.19	0.41	0.33	0.92
Protium kleinii Cuatrec.	1	0.06	1	0.19	0.39	0.33	0.91
Eugenia cambucarana Kiaersk.	1	0.06	1	0.19	0.38	0.33	0.89
Persea venosa Nees	1	0.05	1	0.19	0.34	0.33	0.86

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(continuing)

SPECIES	**N**	**BA (m^2)**	**P**	**RD (%)**	**RDo (%)**	**RF (%)**	**VI (%)**
Myrcia pubipetala Miq.	1	0.05	1	0.19	0.34	0.33	0.85
Miconia cubatanensis Hoehne	2	0.02	1	0.37	0.14	0.33	0.84
Drimys brasiliensis Miers	2	0.02	1	0.37	0.11	0.33	0.81
Campomanesia sp.1	2	0.02	1	0.37	0.10	0.33	0.80
Lonchocarpus cultratus (Vell.) Az.-Tozzi & H.C.Lima	2	0.01	1	0.37	0.10	0.33	0.80
Miconia theaezans (Bonpl.) Cogn.	1	0.04	1	0.19	0.27	0.33	0.79
Endlicheria paniculata (Spreng.) J.F.Macbr.	1	0.04	1	0.19	0.27	0.33	0.79
Buchenavia kleinii Exell	1	0.04	1	0.19	0.26	0.33	0.77
Copaifera langsdorffii Desf.	2	0.01	1	0.37	0.07	0.33	0.77
Rollinia sericea (R.E.Fr.) R.E.Fr.	1	0.04	1	0.19	0.25	0.33	0.76
Pithecellobium langsdorffii Benth.	2	0.01	1	0.37	0.05	0.33	0.76
Myrtaceae 2	2	0.01	1	0.37	0.05	0.33	0.75
Dalbergia frutescens (Vell.) Britton	2	0.01	1	0.37	0.05	0.33	0.75
Eugenia sp.1	1	0.03	1	0.19	0.23	0.33	0.74
Salacia elliptica (Mart. ex Schult.) G.Don	1	0.03	1	0.19	0.18	0.33	0.70
Cupania vernalis Cambess.	1	0.02	1	0.19	0.16	0.33	0.68
Symplocos falcata Brand	1	0.02	1	0.19	0.15	0.33	0.67
Eugenia melanogyna (D.Legrand) Sobral	1	0.02	1	0.19	0.15	0.33	0.66
Nectandra leucantha Nees	1	0.02	1	0.19	0.15	0.33	0.66
Rhodostemonodaphne macrocalyx (Meisn.) Rohwer ex Madriñán	1	0.02	1	0.19	0.14	0.33	0.66
Eugenia santensis Kiaersk.	1	0.02	1	0.19	0.13	0.33	0.64
Campomanesia sp.2	1	0.02	1	0.19	0.13	0.33	0.64
Cordiera sp.2	1	0.02	1	0.19	0.12	0.33	0.64
Myrcia tijucensis Kiaersk.	1	0.01	1	0.19	0.10	0.33	0.61
Myrcia anacardiifolia Gardner	1	0.01	1	0.19	0.09	0.33	0.60
Ocotea silvestris Vattimo-Gil	1	0.01	1	0.19	0.08	0.33	0.60
Morphospecies 4	1	0.01	1	0.19	0.08	0.33	0.60
Calyptranthes obovata Kiaersk.	1	0.01	1	0.19	0.08	0.33	0.59

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(continuing)

SPECIES	**N**	**BA (m^2)**	**P**	**RD (%)**	**RDo (%)**	**RF (%)**	**VI (%)**
Eugenia verticillata (Vell.) Angely	1	0.01	1	0.19	0.08	0.33	0.59
Ocotea velloziana (Meisn.) Mez	1	0.01	1	0.19	0.08	0.33	0.59
Morphospecies 5	1	0.01	1	0.19	0.07	0.33	0.58
Casearia decandra Jacq.	1	0.01	1	0.19	0.06	0.33	0.58
Persea sp.	1	0.01	1	0.19	0.06	0.33	0.58
Citronella paniculata (Mart.) R.A.Howard	1	0.01	1	0.19	0.06	0.33	0.57
Coussapoa microcarpa (Schott) Rizzini	1	0.01	1	0.19	0.06	0.33	0.57
Ocotea aciphylla (Nees) Mez	1	0.01	1	0.19	0.06	0.33	0.57
Ilex taubertiana Loes.	1	0.01	1	0.19	0.05	0.33	0.57
Rollinia dolabripetala (Raddi) R.E.Fr.	1	0.01	1	0.19	0.05	0.33	0.57
Morphospecies 6	1	0.01	1	0.19	0.05	0.33	0.57
Symplocos variabilis Mart. ex Miq.	1	0.01	1	0.19	0.05	0.33	0.56
Coccoloba latifolia Lam.	1	0.01	1	0.19	0.04	0.33	0.56
Miconia petropolitana Cogn.	1	0.01	1	0.19	0.04	0.33	0.56
Eugenia sp.2	1	0.01	1	0.19	0.04	0.33	0.56
Ocotea tabacifolia (Meisn.) Rohwer	1	0.01	1	0.19	0.04	0.33	0.56
Vochysia selloi Warm.	1	0.01	1	0.19	0.04	0.33	0.56
Myrtaceae 3	1	0.01	1	0.19	0.04	0.33	0.56
Nectandra grandiflora Nees	1	0.01	1	0.19	0.04	0.33	0.55
Platymiscium floribundum Vogel	1	0.01	1	0.19	0.04	0.33	0.55
Eugenia involucrata DC.	1	0.01	1	0.19	0.04	0.33	0.55
Myrtaceae 4	1	0.01	1	0.19	0.03	0.33	0.55
Psychotria suterella Müll.Arg.	1	0.01	1	0.19	0.03	0.33	0.55
Aspidosperma olivaceum Müll.Arg.	1	0.00	1	0.19	0.03	0.33	0.55
Heisteria silvianii Schwacke	1	0.00	1	0.19	0.03	0.33	0.54
Eugenia sp.3	1	0.00	1	0.19	0.03	0.33	0.54
Mollinedia oligotricha Perkins	1	0.00	1	0.19	0.03	0.33	0.54
Miconia minutiflora (Bonpl.) DC.	1	0.00	1	0.19	0.02	0.33	0.54
Ocotea brachybotra (Meisn.) Mez	1	0.00	1	0.19	0.02	0.33	0.54

Table 2.6 – Forest structure descriptors of tree species with DBH ≥ 5 cm sampled in 0.3 ha of seasonal semideciduous forest in Caetetus Ecological Station, Southeastern Brazil. N= number of individuals; BA = basal area (m^2); RD = relative density (%); RDo = relative dominance (%); RF = relative frequency (%); VI = value of importance (%)

(conclusion)

SPECIES	**N**	**BA (m^2)**	**P**	**RD (%)**	**RDo (%)**	**RF (%)**	**VI (%)**
Ouratea multiflora (DC.) Baill.	1	0.00	1	0.19	0.02	0.33	0.54
Attalea dubia (Mart.) Burret	1	0.00	1	0.19	0.02	0.33	0.54
Sloanea monosperma Vell.	1	0.00	1	0.19	0.02	0.33	0.54
Myrocarpus frondosus Allemão	1	0.00	1	0.19	0.02	0.33	0.54
Eugenia sp.4	1	0.00	1	0.19	0.02	0.33	0.53
Morphospecies 7	1	0.00	1	0.19	0.02	0.33	0.53
Myrtaceae 5	1	0.00	1	0.19	0.02	0.33	0.53
Ardisia sp.	1	0.00	1	0.19	0.02	0.33	0.53
Cordiera macrophylla Kuntze	1	0.00	1	0.19	0.01	0.33	0.53
Ocotea glaziovii Mez	1	0.00	1	0.19	0.01	0.33	0.53
Trichilia pallida Sw.	1	0.00	1	0.19	0.01	0.33	0.53
Maytenus robusta Reissek	1	0.00	1	0.19	0.01	0.33	0.53
Morphospecies 8	1	0.00	1	0.19	0.01	0.33	0.53
Eugenia umbelliflora O.Berg	1	0.00	1	0.19	0.01	0.33	0.53
Marlierea suaveolens Cambess.	1	0.00	1	0.19	0.01	0.33	0.53

2.3.8 Diameter stratification in ombrophilous forest

In the dense ombrophilous montane forest, nearly all of the measured information on forest pattern was contained in the first two principal components, which explained 90.3% of the variation (Table 2.12). The first principal component explained 62.45% of the variation and was essentially equivalent to the number of individuals and species. The second principal component explained 27.85% of the variation, mainly related to basal area.

The diameter of all trees and species combined showed a reversed-J shape (Figure 2.6 a). Using principal component analysis it was possible to identify 3 groups and define the diameter limits of each class: 5≤ DBH <10cm, 10≤ DBH <55cm and DBH ≥ 55cm (Figure 2.6 b). Most of individuals and species are concentrated in the first group represented by class 1, between 5 and 10 centimeters, characterized by high number of individuals and species. The second group, consisted in classes 2 to 10 had a high total basal area compared to the third and lower number of individuals and species than the first. The third group, comprising classes 11 to 21, as seen in Figure 5.b, is featured by low number of individuals and species, thereby resulting in a small basal area group. Through the median values (Table 2.13), a majority of total basal area is concentrated in the first two classes, up to 35 centimeters. The difference between these 2 groups, confirmed by the principal component graph, is the number of individuals and species, concentrated in the first group. 54 .8% of individuals and 8.3% of basal area are smaller than 10.0cm in diameter, distributed in 107 species, containing 64.8% of the total number of species. On the other hand, 43.7% of the number of individuals and 70.0% of basal area are distributed in group B, including 107 species, which is 64.8% of the total number of species. The greater than 55.0 cm class contains 1.4% of the number of individuals and 21.7% of the basal area. The 9 species presented in this class represents 5.4% of the total number of species. *Chysophyllum viride* were exclusive species in the largest diameter group.

In the dense ombrophilous montane forest, *Euterpe edulis* (79), *Cyathea phallerata* (15) and *Cyathea delgadii* (8) were the most important species in the smallest diameter group. In the medium diameter group, *Euterpe edulis* (31), *Bathysa australis* (9) and *Micropholis crassipedicellata* (8) were the most frequent. As the largest individuals, *Alchornea triplinervea* (3) and *Microphollis crassipedicelata* (3) were the most important species.

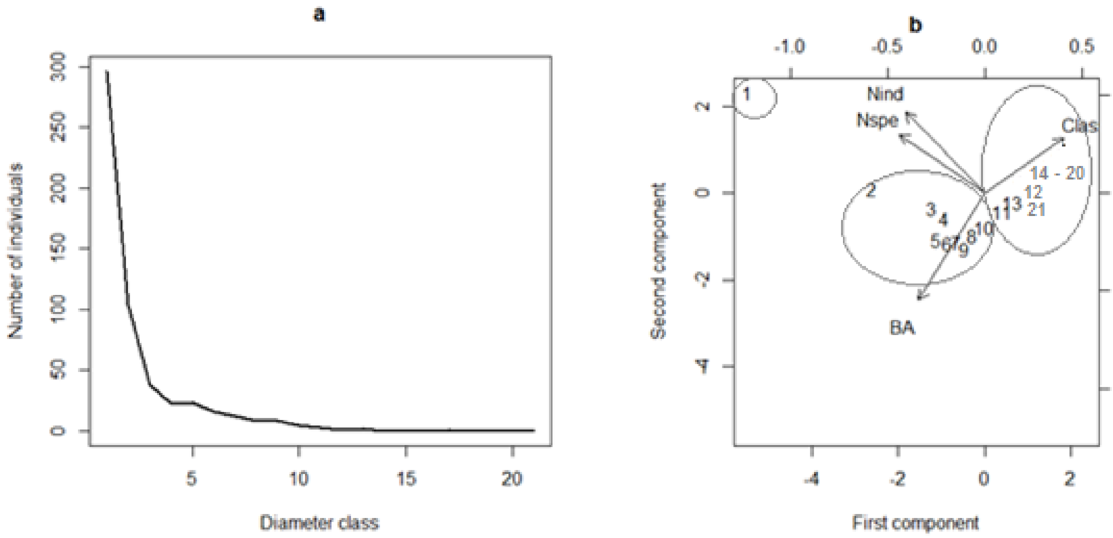

Figure 2.6 - a) Diameter classes' distribution and b) Plotted values of the first two components for 21 diameter classes in "Carlos Botelho" State Park. Let BA = Basal area, Nind = Number of individuals, Nspe = Number of species and Class = number of the class

Table 2.12 - Principal components analysis of horizontal structure: eigenvalues, proportion of variance of each component, cumulative proportion of variance and eigenvectors for four components of variables in "Carlos Botelho" State Park

Item	**Comp.1**	**Comp.2**	**Comp.3**	**Comp.4**
Eigenvalue	1.7090	0.9222	0.4703	0.0871
Proportion of variance	0.7301	0.2126	0.0553	0.0019
Cumulative proportion	0.7301	0.9427	0.9981	1.0000
Class of diameter	0.511	0.354	0.768	-0.154
Number of individuals	-0.509	0.518	0.230	0.648
Number of species	-0.547	0.378	-	-0.746
Basal area	-0.425	-0.681	0.597	-

Table 2.13 - Forest structure data for three horizontal strata (A, B and C) based on diameter classes of dense ombrophilous montane forest in "Carlos Botelho" State Park. The values represent the median values of each stratum

	Strata		
Variables	**A**	**B**	**C**
Basal area (m^2)	1.25513	1.17127	0.18386
Number of individuals	296	16	0
Number of species	107	14	0

2.3.9 Height stratification in ombrophilous forest

In the dense ombrophilous montane forest, nearly all of the measured information on forest pattern was contained in the first two principal components, which explained 89.56% of the variation (Table 2.14). The first principal component explained 58.95% of the variation related to the number of individuals and species. The second principal component explained 30.61% of the variation, mainly associated with basal area.

According to Figure 2.7 b, the principal component analysis (PCA) of individuals' distribution throughout the height classes for all the species surveyed in "Carlos Botelho" State Park presented a gradient in 4 groups or strata: stratum A ($h \geq 18.4$m), B ($13.4 \leq h < 18.4$ m), C ($5.4 \leq h < 13.4$ m) and D ($h < 5.4$ m). The analysis showed similarity between strata A and D, distributed along the axis 1 due to the small number of individuals and species. Class D (< 5.4 m), comprising classes 1 to 4, contained 9.1% of individuals and 1.5% of basal area, distributed in 8 species or, 4.8% of all species. On the other hand, Class A (> 18.4m), involving classes 18 to 25, contained 4.0% of individuals and 32.1% of basal area distributed in 19 species, representing 11.5% of the total number of species. These low densities in stratum A and D resulted in a lower floristic richness (table 2.15). Stratum B, classes 13 to 17, had 43.3% of the basal area and 17.6% of the number of individuals, distributed in 127 species or 77.0% of the total number of species. Stratum C, consisted in classes 5 to 12, had 23.0% of the total basal area and 69.2% of the total number of individuals in 62 species which was 37.6% of the total number of species. *Chrysophyllum viride*, *Diploon cuspidatum*, *Ormosia arborea* and *Roupala sculpta* were exclusive species of the tallest stratum. No species occurs in the 4 strata simultaneously.

Considering height, *Cyathea phallerata* (20), *Euterpe edulis* (18) and *Cyathea delgadii* (6) were the most important in the lowest height stratum. In the stratum C, *Euterpe edulis* (89), *Cordiera myrciifolia* (11) and *Cordiera sp.* (10) were the most frequent. In stratum B, *Alchornea triplinervea* (6), *Micropholis crassipedicellata* (6), *Guapira opposite* (4), *Pouteria bullata* (4) and as the dominant stratum, *Micropholis crassipedicellata* (3) *and Ocotea catharinensis* (2) were the most import species.

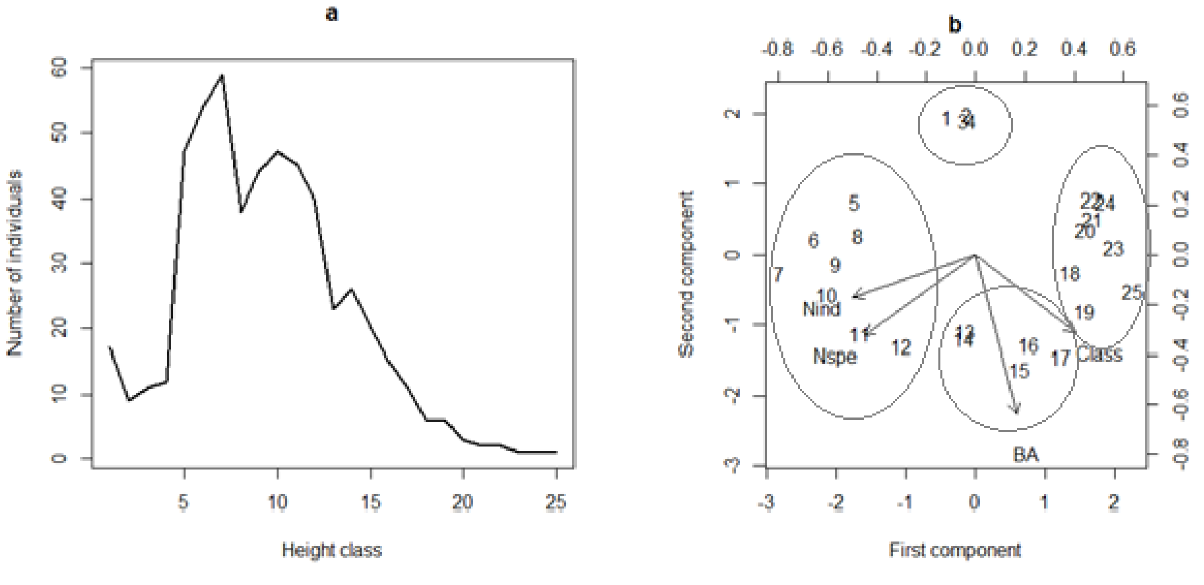

Figure 2.7 - a) Height classes' distribution and b) Plotted values of the first two components for 25 height classes in "Carlos Botelho" State Park. Let BA = Basal area, Nind = Number of individuals, Nspe = Number of species and Class = number of the class

Table 2.14 - Principal components analysis of vertical structure: eigenvalues, proportion of variance of each component, cumulative proportion of variance and eigenvectors for four components of variables in “Carlos Botelho” State Park

Item	**Comp.1**	**Comp.2**	**Comp.3**	**Comp.4**
Standard deviation	1.5356	1.1065	0.6149	0.1983
Proportion of variance	0.5895	0.3061	0.0945	0.0098
Cumulative proportion	0.5895	0.8956	0.9902	1.0000
Class of height	0.501	-0.391	0.762	0.124
Number of individuals	-0.622	-0.213	0.180	0.732
Number of species	-0.565	-0.406	0.272	-0.665
Basal area	0.207	-0.798	-0.560	-

Table 2.15 - Forest structure data for four vertical strata (A, B, C and D) of dense ombrophilous montane forest in “Carlos Botelho” State Park. The values represent the median values of each stratum

	Strata			
Variables	**A**	**B**	**C**	**D**
Basal area (m^2)	0.5552	1.1059	0.2228	0.0526
Number of individuals	2.0	24.5	47.0	11.5
Number of species	2.0	22.0	29.0	3.5

2.4 **Discussion**

2.4.1 Floristic considerations

In the São Paulo state, rain forest showed a more complex structure and diversity compared to semi-deciduous forest, that showed a more complex ecosystem compared to cerrado. According to Huggett (1995), tree species diversity is highly correlated with water consumption and energy uptake, resources that are partitioned among species which limits their number in forest communities. The simpler structure of cerrado is indicated by reduced density of trees, dominance and richness of species compared to the other forest types in Atlantic forests.

The high variation in density and dominance is observable across studies in other cerrado forests. Felfili and Silva Júnior (1993), carrying out 5 cerrado areas in Central Brazil, found tree density varying between 664 N/ha and 1396 N/ha , basal areal between 5.79 $m^2.ha^{-1}$ and 11.30 $m^2.ha^{-1}$ and number of species between 55 and 72. The study in Mogi-Guaçu

Biological Reserve indicates a high density and basal, distributed in a lower number of species.

Durigan (2006), studying 80 localities in São Paulo State, verified the principal species in terms of frequency. Comparing the most 20 frequent species to the 20 most important species in Mogi-Guaçu Biological Reserve, we found *Vochysia tucanorum, Xylopia aromatica, Anadenanthera peregrina, Acosmium suberosum, Copaifera langsdorffi, Siparuna guianensis, Roupala montana* as mutual species to Durigan´s study. According to this author, the species *Ouratea spectabilis* is thought to be endemic to São Paulo State, found in the present study. Brando and Durigan (2004), monitoring the changes in cerrado vegetation after frosts in São Paulo state, concluded that some of the more frost-susceptible species are *Xylopia aromatic, Vochysia tucanorum* and *Caryocar brasiliense*, found in Mogi Guaçu Biological Reserve, whose reproductive processes can be interrupted, thus affecting community structure. Comparing the species found in Ratter and Dargie (1992), in 26 analyzed localities, *Qualea grandiflora* and *Xylopia aromatica* are the only mutual species amongst the main species. These authors found that *Qualea grandiflora* was the most widespread cerrado species of tree encountered (recorded at 23 of 26 sites they compared). This species was the only one found by Felfili and Silva Júnior (1993) in all of the study localities. *Vochysia tucanorum* and *Qualea grandiflora*, both Vochysiaceae, were the most important species in this study site, respectively. Many Vochysiaceae species are typical aluminum accumulators (HARIDASAN; ARAÚJO, 1988) and this probably gives them a competitive advantage to grow successfully on the aluminum toxic cerrado soils. Observing the variation amongst species and its distribution, these authors verify that these differences indicate that the spatial distribution of cerrado species is a mosaic, each mosaic showing a different combination of less than 100 species.

Observing the species we can presuppose that this semideciduous forest is a primary forest constituted by well established species. Analyzing different human disturbance histories in a semideciduous forest, Toniato and Oliveira-Filho (2004) assessed that the most remarkable difference in floristic composition among the studied stands was the absence of *Aspidosperma polyneuron, Metrodorea nigra* and *Holocalyx balansae* from both the arboreal and subarboreal components of the secondary stands. According to Lorenzi (2002), these species are generally found in later succession stages of forests situated on more fertile soils, as were the preserved stands, in which the same species were important constituents of the forest canopy. This area achieved one of the highest basal areas compared with other semideciduous forests (TABANEZ; VIANA, 2000; SOUSA; BATISTA, 2004).

Metrodorea nigra is a sub-canopy, late-secondary species that is extremely abundant in the smaller diameter classes, representing approximately 50% of all individuals with DBH ≥ 5 cm in the sampling area (MARTINI et al., 2008). This author suggests that, however, this species is considerably less abundant in the larger size class analyzed (DBH > 19.1 cm), representing less than 5% of all plants surveyed in Caetetus Ecological Station (MARTINI et al., 2008). *Ocotea indecora* is a very abundant late-secondary species in the study area, and according to Martini et al. (2008), its capacity to resist damage seems to be strongly associated with the maintenance of dense populations in this community in Caetetus.

In dense ombrophilous forest, the relatively high proportion of undetermined species masks the results from quantitative surveys and influences the estimated richness. Determining species level is still a major difficulty in analyses of the Atlantic Ombrophilous Dense Forest. Scudeller, Martins and Shepherd (2001) concluded that the Atlantic Ombrophilous Dense Forest is characterized by the predominance of species with low constancy and restricted distribution.

The Atlantic Ombrophilous Dense Forest in São Paulo state showed great heterogeneity both in distribution and abundance of tree species. Câmara (1996) attributed the great biological diversity in the Atlantic Forest partly to the heterogeneity of soils and relief. Scudeller, Martins and Shepherd (2001) indicated that precipitation and temperature, on one hand, and altitude, on the other, also play significant roles in this diversity.

The vegetation structure is characterized by an abundance of *Euterpe edulis*. The marketable product obtained from this species is the palm heart, which is called palmito locally and is a delicacy throughout the country. Euterpe edulis has a high potential for sustainable management of its natural populations and can contribute to maintaining forest remnants and recovering degraded forest patches (REIS et al., 2000).

2.4.2 Horizontal and vertical stratification

The inverse J-shaped diameter distribution was mutual in three forest types. A large number of small trees in the smaller diameter classes with decreasing frequency as the diameter increases is a typical diameter distribution for an uneven-aged stand, as demonstrated in cerrado, seasonal semideciduous forest and dense ombrophilous montane forest.

According to Richards (1952), if a histogram is made relating height classes to the number of trees in each height class on a given site a distribution approximating a negative exponential curve is usually found. Observing the diameter classes' distribution of every forest type is supposed to have the same diameter distribution pattern of defined groups generated by principal component analyses. The principal component technique allowed us to determining the diameter and height classes' boundaries within the observed data. Principal component analysis permitted detecting groups with similar variability based on their diameter and height distribution.

Principal component analysis can be used considering many aspects of forest structure. Using this multivariate method, Gutierrez-Granados, Perez-Salicrup and Dirzo (2011) determined undesirable characteristics for future forest management by lianas and trees densities and dominances.

Vertical as well as horizontal stratification of trees and its association with differences in attributes of forest structure have been useful in a variety of management or research-oriented applications where definition of strata is desired. The vertical structure of forests is important because increasing height causes structure and microclimate to be more obviously vertically organized. Height of the canopy and tree size are defining characteristics of forests, yet smaller-stature vegetation types all exhibit vertical patterns (MOFFETT, 2001).

Cerrado was characterized by representing a majority of individuals concentrated in the second diameter group, between 8 and 21cm, while most of the species are concentrated in a group lower than 8cm in diameter. Most of species were identified in the shortest trees group, as well as density and dominance. Although the number of trees above 11.7 meters of height is low, they represent trees with high basal area. Observing that 2% of individuals include 25% of the total number of species, this indicates that many species adapted to these specific conditions. It is important to consider this forest had most species distributed amongst smallest diameter individuals. Strata formed in cerrado is characterized by small diameter size-class (5-8cm), medium diameter size-class (8-21cm) and large diameter size class (≥21cm).

In the seasonal semideciduous forest a majority of basal area is distributed in the largest diameter group, distributed in a low number of individuals, as *Carinina estrellensis, Cedrella fissilis, Colubrina glandulosa, Copaifera langsdorffii, Ficus enormis, Ficus* *guaranitica*, *Hymenaea courbaril* and *Maytenus robusta*. According to Tabanez and Viana (2000), Shade tolerant canopy species are slow-growing and reach the canopy, as *Aspidosperma polyneuron*, *Cariniana legalis*, and *Hymenaea courbaril*. Most of the individuals have small diameters. This stratification reflects some characteristics of species, as shade-tolerant species and their succession groups. When the individuals are grouped by height, most of individuals are between 5 and 11 meters. The majority of species were between 11 and 19 meters in height, reflecting a group where species of all succession groups concentrate. Basal area is concentrated mainly in this region, including high diameter individuals. Groups containing dominants and dominated trees have similar characteristics based on number of individuals and species. Cedrella fissilis, *Copaifera langsdorffii*, *Ficus enormis* and *Ficus guaranitica* were exclusive species in the tallest trees region. Strata area formed in semi-deciduous forest is characterized by small diameter size-class (5-10cm), medium diameter size-class (10-35cm) and large diameter size class (≥ 35cm).

Dense ombrophilous montane forest was similar to semideciduous forest comparing the number of individuals in each group. Basal area was concentrated mainly between 10 and 55 cm of diameter. *Chrysophyllum viride* was the only exclusive species in the largest diameter group. Few species are concentrated in the largest diameter group, with individuals larger than 55 cm. Observing the height stratification, it is possible to visualize that most species are concentrated between 13.3 and 18.4 meters, but the highest number of individuals is concentrated between 5.4 and 13.4 meters. These values indicate likely high variability of species in the second highest group, determined by many ecological features, as light, disturbance, soil, water etc. This Atlantic forest type exhibited some exclusive species in the tallest stratum, as Chrysophyllum viride, Diploon cuspidatum, Ormosia arborea and Roupala *sculpta*. *Chrysophyllum viride* was the only mutual species indicated by height and diameter stratification. Strata area formed in ombrophilous forest is characterized by small diameter size-class (5-10cm), medium diameter size-class (10-55cm) and large diameter size class (≥ 55cm).

According to Richards (1996), in a tropical rainforest the number of tree species per unit area is always greater in the smaller diameter classes than in the larger diameter-classes, though less relative to the total number of individuals. This is because there are more trees in the lower strata and because the latter include many young individuals of species that may reach the canopy when mature as well as species that will not do so. Considering diameter-classes, is possible to confirm this pattern in cerrado, seasonal semideciduous and dense ombrophilous montane forests. When diameter classes are separated based on their structural characteristics, Cerrado presented a high proportion of species distributed in the smallest diameter stratum, despite the number of individuals that are concentrated in the intermediary diameter stratum. The shortest height stratum in this forest type is composed of high basal area individuals, indicating a great deal of biomass storage in this stratum, as well as the highest species richness. On the other hand, Atlantic forests, as for semideciduous and ombrophilous forests, store most of biomass and species in the second highest stratum.

Richards (1996) concludes that mixed rain forest can be regarded as having five strata of independent plants. The highest strata of trees are never clearly definable. The lowest stratum represents herbaceous plants. The height of each stratum varies, but not within very wide limits. This author shows the height of the highest stratum, stratum A, is about 30 meters or more in the Guyana forest, about 35 m in Borneo and about 42 m in Nigerian, localities classified as mixed rain forests. Similarly, the height of the B stratum is about 20, 18 and 27 m, respectively, and that of the C stratum 14, 8 and 10, respectively. The author still stresses that each stratum has a different and characteristics floristic composition, but in all the strata, except A and B, young trees of species that reach higher strata when mature form a large proportion of the total number of individuals.

Species composition of the canopy should affect the number of strata in a stand. Shade-tolerant trees typically have longer crowns than their shade-intolerant neighbors (Lorimer, 1983). As longer crowns create a more continuous distribution of foliage throughout the vertical profile of the stand, stands with a greater proportion of shade-tolerant species in the canopy should have fewer strata. Therefore, stratification varies according to the forest type. For communities in which trees are not so competitive for luminosity, as Cerrado, the number of strata is lower than other physiognomies, demonstrated by this present work.

The reason why the trees crowns were rarely clearly stratified in mixed rain forest, as dense ombrophilous montane and seasonal semideciduous forests, is no doubt chiefly because they are composed of very large numbers of tree species each differing in growth potential and in the reactions to light and other factors.

By PCA it is possible to classify individuals according to their structural characteristics to determine horizontal and vertical strata. The horizontal and vertical plane is a simple and convenient way to visualize and organize concepts, and it is a first step in understanding the biotic community in our study forests. Forest stratification might help to prompt the development and implementation of timber harvesting practices generally referred as "reduced-impact logging". This low impact management takes into account, beyond other factors, a minimum diameter cutting limit and the distribution of species. To manage uneven aged tropic forests or for forest studies the vertical and horizontal structure are an important sustainability indicator.

2.5 Conclusion

Comparisons amongst same size sampling in different forest types indicate that Cerrado is characterized by lower density, dominance and number of species, followed by semideciduous and dense ombrophilous forests. Forest structure differences, as suggested by some authors, are influenced by factors interactions as water availability, heterogeneity of soils and relief, temperature, precipitation and altitude. Quantifying and stratifying horizontal and vertical structure play important roles in visualizing concepts, and organizing biotic community in forest studies. By principal component analyses (PCA) it is possible to classify individuals according to their structural characteristics, such as height and diameter at breast height (DBH), and determine which vertical and horizontal stratum some tree belong to. Horizontally, the three forest types are divided into three classes, varying size classes according to the forest. Vertically, Cerrado is divided into 3 strata, while semideciduous and dense ombrophilous forests into 4 different strata. Differences in number of strata seem to be influenced by biotic and abiotic forest characteristics (i.e. light exposure), however factors herein not measured.

References

BRANDO, P.M.; DURIGAN, G. Changes in cerrado vegetation after disturbance by frost (Sao Paulo State, Brazil). **Plant Ecology,** Dordrecht, v. 175, n. 2, p. 205-215, 2004.

BURGER, D.M.; DELITTI, W.B.C. Fitomassa epigéia da Mata ciliar do rio Mogi Guaçu, Itapira, SP. **Revista Brasileira de Botânica**, São Paulo, v. 22, p. 429-435, 1999.

CÂMARA, I.G. **Plano de ação para a Mata Atlântica:** roteiro para a conservação de sua biodiversidade. Recife: Conselho Nacional da Reserva da Biosfera, 1996. 34 p. (Cadernos da Reserva da Biosfera, 4).

DELITTI, W.B.C. Ciclagem de nutrientes em cerrados. In: SEMINÁRIO REGIONAL DE ECOLOGIA, 8., 1998, São Carlos. **Anais...** São Carlos: UFSCar, 1998. p. 1031-1045.

DURIGAN, G. Observations on the Southern Cerrados and their relationship with the core area. In: PENNINGTON, R.T.; LEWIS, G.P.; RATTER, J.A. **Neotropical savannas and seasonally dry forests:** plant diversity, biogeography, and conservation. Boca Raton: CRC Press, 2006. chap. 3, p. 67-77.

EITEN, G. Habitat flora of Fazenda Campininha, São Paulo, Brazil. I--Introduction, species of the" cerrado", species of open wet ground**.** In: SIMPÓSIO SOBRE O CERRADO, 1963, São Paulo. **Anais...** São Paulo: EDUSP, 1963. p. 171-202.

FELFILI, J.M.; DASILVA, M.C. A comparative-study of cerrado (sensu-stricto) vegetation in central Brazil. **Journal of Tropical Ecology,** Cambridge, v. 9, p. 277-289, Aug. 1993.

GUTIERREZ-GRANADOS, G.; PEREZ-SALICRUP, D.R.; DIRZO, R. Differential diameter-size effects of forest management on tree species richness and community structure: implications for conservation. **Biodiversity and Conservation,** London, v. 20, n. 7, p. 1571-1585, June 2011.

HARIDASAN, M.; DEARAUJO, G.M. Aluminum-accumulating species in 2 forest communities in the Cerrado region of Central Brazil. **Forest Ecology and Management,** Amsterdam, v. 24, n. 1, p. 15-26, Apr. 1988.

HOTELLING, H. Analysis of a complex of statistical variables into principal components. **Journal of Educational Psychology,** Arlington, v. 24, p. 417-441, 1933.
HUGGETT, R. **Geoecology:** an evolutionary approach. London: Routledge, 1995. 301 p.

KAISER, H.F. The varimax criterion for analytic rotation in factor-analysis. **Psychometrika,** Williamsburg, v. 23, n. 3, p. 187-200, 1958.

KOÖPPEN, W. **Das geographische System der Klimate-Handbuch der Klimatologie,** Vol. 1, Part C. Berlin**:** Gebr. Borntrager Verl., v. 388, 1936.

LATHAM, P.A. **A process-related quantification of forest structure and understory diversity in inland northwest forests: from stands to landscapes**. 1996. 490 p. Dissertation (PhD in Forestry) - University of Montana, Missoula, 1996.

LATHAM, P.A.; ZUURING, H.R.; COBLE, D.W. A method for quantifying vertical forest structure. **Forest Ecology and Management,** Amsterdam, v. 104, n. 1/3, p. 157-170, May 1998.

LORENZI, H. **Árvores brasileiras**: manual de identificação e cultivo de plantas arbóreas nativas do Brasil. Nova Odessa: Instituto Plantarum, 2002. v. 1, 368 p.

LORIMER, C.G. A test of the accuracy of shade-tolerance classifications based on physiognomic and reproductive traits. **Canadian Journal of Botany,** Ottawa, v. 61, n. 6, p. 1595-1598, 1983.

MACDICKEN, K.G.; WOLF, G.V.; BRISCOE, C.B. **Standard research methods for multipurpose trees and shrubs**. Little Rock: Winrock International Institute for Agricultural Development, Forestry/Fuelwood Research and Development Project, 1991. 93 p.

MANTOVANI, W. **Estrutura e dinâmica da floresta atlântica na Juréia, Iguape, SP**. 1993. 126 p. Tese (Livre-Docência) – Instituto de Biociências, Universidade de São Paulo, São Paulo, 1993.

MARTINI, A.M.Z.; LIMA, R.A.F.; FRANCO, G.; RODRIGUES, R.R. THE need for full inventories of tree modes of disturbance to improve forest dynamics comprehension: An example from a semideciduous forest in Brazil. **Forest Ecology and Management,** Amsterdam, v. 255, n. 5/6, p. 1479-1488, Apr 2008.

MOFFETT, M.W. The nature and limits of canopy biology. **Selbyana**, Sarasota, v. 22, n. 2, p. 155-179, 2001.

MORAES, P.L.R. Dispersão de sementes pelo mono-carvoeiro (*Brachyteles arachnoides* E. Geoffroy, 1806) no Parque Estadual de Carlos Botelho. **Revista do Instituto Florestal,** São Paulo, v. 4, n. 4, p. 1193-1198, 1992.

MUELLER-DOMBOIS, D.; ELLENBERG, H. **Aims and methods of vegetation ecology**. New York: John Wiley, 1974. 547 p.

OLIVEIRA, A.T.; FONTES, M.A.L. Patterns of floristic differentiation among Atlantic forests in southeastern Brazil and the influence of climate. **Biotropica,** Washington, v. 32, n. 4B, p. 793-810, 2000.

PASSOS, F.C. **Padrão de atividades, dieta e uso do espaço em um grupo de mico-leão preto *(Leontopithecus chrysopygus)* na Estação Ecológica de Caetetus, SP**. 1997. 162 p. Tese (Doutorado em Ecologia e Recursos Naturais) – Universidade Federal de São Carlos, São Carlos, 1997.

PEARSON, K. On lines and planes of closest fit to systems of points in space. **Philosophical Magazine,** London, v. 2, n. 7/12, p. 559-572, July/Dec. 1901.

PÉLLICO-NETTO, S.; SANQUETTA, C.R.; MENDES, J.B. Definição dos limites volumétricos em estratifícação de florestas plantadas. **Floresta,** Curitiba, v. 25, n. 12, p. 17-29, 1995.

RADAMBRASIL. **Levantamento de recursos naturais**: Geologia, geomorfologia, solos, vegetação e uso potencial da terra. v. 32, sf. 23/24. Rio de Janeiro/Vitória. Rio de Janeiro: IBGE; Ministério das Minas e Energia, Secretaria Geral, 1983.

RATTER, J.A.; DARGIE, T.C.D. An analysis of the floristic composition of 26 Cerrado areas in Brazil. **Edinburgh Journal of Botany,** Edinburgh, v. 49, n. 2, p. 235-250, 1992.

REIS, M.S.; FANTINI, A.C.; NODARI, R.O.; REIS, A.; GUERRA, M.P.; MANTOVANI, A. Management and conservation of natural populations in Atlantic rain forest: The case study of palm heart (*Euterpe edulis* Martius). **Biotropica,** Washington, v. 32, n. 4B, p. 894-902, 2000.

RICHARDS, P.W. **The tropical rain forest: an ecological study**. Cambridge: Cambridge University Press, 1952. 450 p.

______. **The tropical rain forest:** an ecological study. 2nd ed. Cambridge: Cambridge University Press, 1996. 600 p.

SCUDELLER, V.V.; MARTINS, F.R.; SHEPHERD, G.J. Distribution and abundance of arboreal species in the Atlantic ombrophilous dense forest in Southeastern Brazil. **Plant Ecology,** Dordrecht, v. 152, n. 2, p. 185-199, 2001.

SHARMA, S. **Applied multivariate techniques**. New York: John Wiley, 1995. 512 p.

SMITH, A.P. Stratification of temperate and tropical forests. **American Naturalist,** Chicago, v. 107, n. 957, p. 671-683, 1973.

SOUZA, D.R.; SOUZA, A.L. Estratificação vertical em floresta ombrófila densa de terra firme não explorada, Amazônia oriental. **Revista Árvore,** Viçosa, v. 28, n. 5, p. 691-698, 2004.

SOUZA, F.M.; BATISTA, J.L.F. Restoration of seasonal semideciduous forests in Brazil: influence of age and restoration design on forest structure. **Forest Ecology and Management,** Amsterdam, v. 191, n. 1/3, p. 185-200, Apr. 2004.

TABANEZ, A.A.J.; VIANA, V.M. Patch structure within Brazilian Atlantic forest fragments and implications for conservation. **Biotropica,** Washington, v. 32, n. 4B, p. 925-933, 2000.

R CORE TEAM. **A language and environment for statistical computing**. Vienna: R Foundation for Statistical Computing, 2012.

TONIATO, M.T.Z.; OLIVEIRA-FILHO, A.T. de. Variations in tree community composition and structure in a fragment of tropical semideciduous forest in southeastern Brazil related to different human disturbance histories. **Forest Ecology and Management,** Amsterdam, v. 198, n. 1/3, p. 319-339, Aug. 2004.

3 VOLUME MODELING AND A NEW TAPER EQUATION FOR NATURAL FORESTS IN BRAZIL

Abstract

This work presents two approaches of volume models, one based on diameter at breast height and height and another based on crown area and height, and a trigonometric taper equation to describe the stem form for three natural forest types in São Paulo State, Brazil. The primary use of the taper models is for predicting upper stem diameters as a function of relative height and diameter at the base of the tree. Additionally, these models can be used to create volume tables to any merchantable top diameter. Diameters and volume table resulted by the proposed taper equation was compared to other taper models.

Keywords: Volume tables; Taper equation; Tropical vegetation formations

3.1 Introduction

Accurate information about stem profile and volume is critical for the identification of potential areas for sustainable timber production, carbon estimation and conservation, which attempt to compare forests over time and space. Cerrado and the Atlantic forests in Brazil are included among the 25 hotspots considered as global priorities for biodiversity conservation by Myers et al. (2000). São Paulo state presents different forest landscapes, as cerrado, seasonal semideciduous and ombrophilous forests. This high diversity of formations contributes to a high biodiversity, threatened by changes in land cover and fragmentation.

As with descriptive knowledge, land-management policies and organizational cultures can play a significant role in determining how and which predictive tools are used. Certain mathematical models may be acceptable for land-management planning purposes, but others are not. Conversely, well-grounded procedural knowledge and predictive statistics can inform and change, in some cases, management policies and procedures. With the growing interest in estimating carbon stocks in forests, both to assess the mitigation effect of forests on global change and to predict the potential impact of the mechanisms to reduce carbon emissions, volume equations have recently regained interest as a prediction tool for biomass (PENMAN; KIKAN, 2003).

To have high utility, models must be accurate. According to Burkhart (2003), model accuracy can be improved by increasing the size of a data set, improving the quality of the data obtained, or by applying more sophisticated modeling techniques to existing data. Typical modeling efforts attempt to enhance prediction by amplifying a pattern and discarding noise. The relationship between variables is stochastic and governed by probability theory. Selection of appropriate methodology is central in the calculation of accurate results for biomass estimation. According to Avery and Burkhart (2002), volume equations are used to estimate average content of standing trees of various sizes and species. The reliability of volume estimates depends on the range and extent of the available sample data, and how well volume equations fit this sample data. Considering a remote sensing context, Van Laar and Akça (2007) recommended the construction of aerial stand volume tables based on stand height and crown dimensions as independent variables, estimating volume trees as a function of tree variables measured by photogrammetric methods.

One of the most accurate approaches to estimating stem volume in response to differing silvicultural regimes is to integrate taper equations that reflect subtle stem form responses to the treatments imposed. Construction of taper equations requires the collection of longitudinal data, or multiple measurements on individual trees (LINDSTROM; BATES, 1990). Because trees taper, often irregularly, from stump to top, it is necessary to make some evaluation of stem form in the construction and application of tree volume tables. The rate of tree taper varies not only by species but also by age, DBH, and tree height. If a series of diameter measurements are taken at intervals along the bole, average taper rates may be derived for groups of trees characterized by a particular shape or form category.

The purpose of this study was to develop DBH-based and crown-based volume models for each forest type and a unique taper equation that could accurately and precisely describe stem form when estimating parameters for the three forest types. Volume and diameters estimated by the taper equation herein proposed was compared to the estimated volume and diameters obtained by three other taper equations.

3.2 **Material and methods**

3.2.1 Data collection arrumar a numeração

Before selecting trees for determination of volume, the diameter at breast height (DBH) and total height was measured, as well as identifying all of the species in every forest type and determining the light intensity and stem quality for every scaled tree. Parameters were performed in order to estimate the importance value (IV=Relative Frequency +Relative Density + Relative Basal Area for a species, need a reference). To obtain the representative tree samples, diameter distributions and the species grouping were taken into account during tree selection. The diameter distribution was divided into diameter classes and from these diameter classes selected trees were chosen for taper measurements to determine their individual volumes. The highest IV species and a miscellaneous group, including many species, were selected, choosing individuals proportionately to each diameter class. The number of trees for each class was determined according to the total number of individuals in the class. Based on this method, we determined the volume of 52 trees in Mogi-Guaçu Biological Reserve, whose diameters were grouped into 5 classes, varying between 5.0 to 52.0 cm. Caetetus Ecological Station had 53 individuals measured in order to obtain the volume, with diameters grouped into 5 classes varying between 5.0 to 135.0 cm and "Carlos Botelho" State Park had 55 trees measured, considering diameter varying between 5.1 to 157.0 divided into 5 classes. According to Husch, Beers and Kershaw Jr. (2002), the volume of the stem can also be calculated with good accuracy using Smalian´s formula if the stem is divided into short sections. Measurements included the portion of the stem above 10 cm height and every stem was measured at 0.1, 0.3, 0.7, 1.3 meters and constant intervals of 1 meter above 1.3 m up to a minimum 5 cm stem diameter outside bark. The device used to measure upper stem diameters was the electronic dendrometer Criterion RD 1000 (Laser Technology, Inc., USA), an optical instrument that provides real-time results for calculations of the tree height and diameters along the stem. The dendrometer uses the angular measurement and the horizontal distance to the target tree to calculate the diameter of the tree stem at any height. Above the last point, the tree form was considered as a cone. Thus, the total volume is the sum of the stem volume and cone volume.

Figure 3.1 - Examples of Cerrado, semideciduous forest and dense ombrophilous forest profile trees, respectively

Direct volume determinations of parts of trees were made on sample trees to obtain basic data for the development of relationships between the various dimensions of a tree and its volume, crown and taper. In instance of multi-stemmed trees, Macdicken, Wolf and Briscoe (1991) recommended that all of the stems be measured above the root collar along the axis of each stem and combined with equivalent diameter formula below:

$$D_{combined} = \sqrt{(d_1^2 + d_2^2 + \ldots + d_n^2)}$$

The advantage of this definition is that nearly all potentially useful wood is included, allowing accurate comparisons between trees with single and multiple stems.

To calculate crown area, scaled trees had diameter projections on the ground measured in orthogonal directions (North-South and East-West). The average crown diameter per each tree was used to compute area assuming a circular crown with the area equal to average horizontal crown area.

The definition of light intensity and stem quality was empirically based on the observation during the field work. Light intensity was measured according to the amount of light on the crown, varying amongst 1, 2 and 3. Scaled trees receiving no light were classified as number 1, light in some parts of the crown as number 2 and light on the entire crown as number 3. Stem quality classification was defined as numbers varying amongst 1 and 4, ordering individuals in terms of stem tortuosity and bifurcation height. Number 1 represents straight and not bifurcated stems while number 4 represents the most tortuous and bifurcated trees.

3.2.2 Data analysis

As the first step, Spearman correlation matrices were calculated to assess the relationship between the variables, considering linear models assumptions. After observing values obtained by Spearman correlation, it was possible to define which variables to use in the regression.

The volume modeling was based on two approaches: models using diameter at breast height (DBH) and total height and models using crown area and height. The models were estimated using linear regression techniques. We found optimal transformations to ensure that our data adhered to the linear model assumptions. Akaike Information Criterion (AIC), adjusted coefficient of determination (R^2) and graphic analysis were used to compare and then selected the best models.

Transformations are to achieve a mean function that is linear in the transformed scale. Box and Cox (1964) provided a general method for selecting transformations of the response that is applicable both in simple linear and multiple regressions. The Box-Cox method is not transforming for linearity, but rather it is transforming for normality, making the residuals from the regression as close to normally distributed as possible and so graphical checks are desirable after selecting a transformation. Using this method it was possible determine the best transformation for each model.

The assumptions of linear models predicted using least squares are: Independent observations, homogeneous variance, normally distributed errors and independent explanatory variables. Residual plots are used to examine regression models to see if they fail to match observed data.

The residual sum of squares was minimized by ordinary least squares and weighted least squares and which were used in parameter estimation. Because the least squares technique minimizes the sum of squares of deviations from the regression line, those classes of the dependent variable which have excessively high variance (and thus excessively high deviations from the regression line) will have a disproportionate effect on the estimation of the regression coefficients. According to Munro (1964), one way to remedy the situation is to weight the dependent variable in such a manner that the variance is made homogeneous throughout the range of the independent variable. The simplest way of accomplishing this is to multiply each variable in the equation by the inverse of the variance of the dependent variable. As suggested by Munro (1964), average volumes and volume variances for successive classes of each independent variable were calculated in order to choose the appropriate weight. Correlation analysis was then used in an attempt to find a relationship between volume variance and one or more of the independent variables. Considering diameter at breast height (DBH), total height (HT) and crown area (AC), the relationship of volume variance to DBH, HT, $DBH^{0.5}*HT$, $DBH*HT$ and DBH^2*HT for DBH-based volume models and AC, HT, $AC^{0.5}*HT$, $AC*HT$ and AC^2*HT for crown-based volume models was examined in this manner. Additionally, percent overpredictions, percentage bias and percentage standard errors of the estimate were used to evaluate the goodness of fit for each model in different forest types using different weights. Analyses were performed using R Core Team (2012) software.

3.2.3 Taper equation

This work describes the development of a taper equation for Cerrado and two tropical forests formations in Brazil. These vegetation formations include different many species, described previously (see chapter 1). Data from stem analysis trees were used to characterize the stem profile and develop the equation that accurately describes the stem form. The trees used to estimate the volume and crown size were the same used to develop the taper equation.

Initial plotting of height versus diameter curves for each species using all the data revealed a heterogeneous variance in diameters as height varied, and transformations were considered to allow for an improved model fit. The transformation of the relative diameter improved the stem form, decreasing the residual standard errors of the estimative and obtaining better visual pattern for the residual plots.

General taper equations may be integrated mathematically to produce whole tree cubic meter volume tables. This approach will not lead to volumes identical to those predicted from total tree volume prediction equations. This is because the volume of the tree of average profile for a given height and diameter class is not necessarily equal to the average volume of the trees in that class. The volume obtained by the taper equation herein proposed is one of the objectives of this study that will be forward presented.

The taper equation proposed was compared to three well-established equations in order to verify how predictive the equation is for different parts of the stem: Kozak, Munro and Smith (1969), Demaerschalk (1972) and Biging (1984). In order to estimate the parameter for those three taper equations, diameter at breast height (DBH) was used as in the original manuscripts. Taper equations were leaded in this thesis to Kozak model, Demaerschalk model and Biging model.

$$- \text{Kozak, Munro and Smith (1969) model:} \qquad \left(\frac{\text{Di}}{\text{DBH}}\right)^2 = \beta_0 + \beta_1\left(\frac{\text{Hi}}{\text{HT}}\right) + \beta_2\left(\frac{\text{Hi}}{\text{HT}}\right)^2$$

$$- \text{Demaerschalk (1972) model:} \quad \left(\frac{\text{Di}}{\text{DBH}}\right)^2 = 10^{2*\beta_0} * \text{DBH}^{2*\beta_1-2} * \text{HT}^{2*\beta_2} * \text{HT} - \text{Hi}^{2*\beta_3}$$

$$- \text{Biging (1984) model:} \qquad \frac{\text{Di}}{\text{DBH}} = \beta_0 + \beta_1 \ln\left[1 - \left(\frac{\text{Hi}}{\text{Ht}}\right)^{\frac{1}{3}} * \left(1 - \exp^{\frac{-\beta_1}{\beta_2}}\right)\right]$$

Let Hi = height above ground to some point on the stem, HT = total height, Di = diameter outside bark at height Hi and D_B = diameter at breast height (1.30 meters). β_0, β_1, β_2 and β_3 are the parameters to be estimated from the data.

3.2.4 Criteria of model evaluation

We used the commom statistics of average bias, percent standard error of the estimate (RMSE) and percent overprediction to evaluate the goodness of fit for the DBH-based and crown-based volume modelling and prediction of volume using the taper-based system.

$$- \text{Percent standard error of estimate (\%)} \qquad \frac{\sqrt{\frac{\sum\left(\mathrm{Di}-\widehat{\mathrm{Di}}\right)^2}{\mathrm{n}}}}{\overline{\mathrm{Vobs}}} * 100$$

$$- \text{Bias (\%)} \qquad \frac{\sum\left(\mathrm{Di}-\widehat{\mathrm{Di}}\right)}{\mathrm{n}} * 100$$

$$- \text{Percent overprediction (\%)} \qquad \frac{\widehat{\mathrm{Vol}}-\mathrm{Vobs}}{\mathrm{Vobs}} * 100$$

Where $\widehat{\mathrm{Di}}$ is predicted diameter at height Hi and Di is the actual measurement at point i on the bole; n = number of individuals; Vobs = Scaled volume; $\overline{\mathrm{Vobs}}$ = Average scaled volume; and $\widehat{Vol}$ = Predicted volume.

3.3 **Results**

3.3.1 Correlation analysis

In order to model volume, crown area and taper in the cerrado, the correlation amongst primary variables was examined (Table 3.1). Volume was highly correlated to DBH (r=0.98) and total height (r=0.74). Crown area is correlated to volume strongly (r=0.88), diameter (r=0.87) and total height (r=0.66). In order to model volume, crown area and taper in semideciduous forest, the correlation amongst primary variables was examined (Table 3.2). Volume was highly and positively correlated to DBH (r=0.99), total height (r=0.84), and luminosity (r=0.78). Crown area was related to DBH (r=0.83), height (r=0.71), volume (r=0.83) and light intensity (0.69). In order to modeling volume, crown area and taper in dense montane ombrophilous forest the correlation amongst primary variables was examined s (Table 3.3). The DBH was highly correlated to total volume (r=0.99), as well as the height (r=0.87). Crown area was highly correlated to DBH (r=0.92), volume (r=0.82) and total height (r=0.82) as well. Stem quality was measured in order to model taper, separating individuals according to the shape of trees, but there was no correlation between stem quality and any variable.

Table 3.1 - Spearman correlation among Diameter at Breast Height (DBH), Height, Crown area (Crown), Stem quality (Quality), Light intensity (Light) and Volume (V) in Mogi Guaçu Biological Reserve

Correlation analysis - Mogi Guaçu Biological Reserve						
Variables	**DBH**	**Height**	**Crown**	**Quality**	**Light**	**V**
DBH	1					
Height	0.64	1				
Crown	0.87	0.66	1			
Quality	0.24	-0.29	0.18	1		
Light	-0.09	-0.08	-0.18	0.16	1	
V	0.98	0.74	0.88	0.16	-0.09	1

Table 3.2 - Spearman correlation among Diameter at Breast Height (DBH), Height, Crown area (Crown), Stem quality (Quality), Light intensity (Light) and Volume (V) in Caetetus Ecological Station

Correlation analysis - Caetetus Ecological Station						
Variables	**DBH**	**Height**	**Crown**	**Quality**	**Light**	**V**
DBH	1					
Height	0.84	1				
Crown	0.83	0.71	1			
Quality	-0.21	-0.45	-0.06	1		
Light	0.76	0.7	0.57	-0.39	1	
V	0.99	0.88	0.83	-0.26	0.78	1

Table 3.3 - Spearman correlation among Diameter at Breast Height (DBH), Height, Crown area (Crown), Stem quality (Quality), Light intensity (Light) and Volume (V) in “Carlos Botelho” State Park

Correlation analysis - "Carlos Botelho" State Park

Variables	**DBH**	**Height**	**Crown**	**Quality**	**Light**	**V**
DBH	1					
Height	0.87	1				
Crown	0.92	0.82	1			
Quality	0.11	-0.11	0.18	1		
Light	0.9	0.85	0.84	0.04	1	
V	0.99	0.92	0.92	0.06	0.92	1

3.3.2 Volume modeling with Diameter at Breast Height (DBH)-based system

Linear model were developed to estimate volume as described in the methodology. Let HT= total height of the tree in meters, DBH = diameter at breast height in centimeters. β_0, β_1, β_2,…, β_n are parameters to be estimated from the data, considering n parameters in the model.

$$V = \beta_0 + \beta_1 \ln \text{DAP} + \beta_2 \ln \text{HT} + \beta_3 \frac{1}{\text{HT}^{0.5}\,\text{DAP}} \qquad (3.1)$$

The best-fit equation for volume based on combinations of diameter at breast height (DBH) and total height (HT) as independent variables after data transformation, met the linear model assumptions reasonably well. A logarithmic transformation was indicated by Box-Cox method as the best data transformation, in order to transform for normality, making residuals from the regression on independent variables as close to normally distributed as possible. This model predicted the volume reasonably well, indicated by the coefficients of determination (Table 3.4) compared to other possible HT and DBH combinations. By different combinations in order to choose the best weight when using weighted least squares to estimate coefficients in the linear models, DBH in Cerrado and $\text{DBH}^{0.5}\text{HT}$ in semideciduous and ombrophilous forests resulted in the best percent overprediction, percentage bias and percentage standard error of the estimate, as well as most correlated independent variables to volume variance.

Table 3.4 - Coefficients for multiple linear models fitted and adjusted coefficient of determination for volume prediction based on height and diameter at breast height (see equation 3.1) for Cerrado, semideciduous forest and dense ombrophilous forest. Weight is specified when using weighted least squares to estimate parameters

Item	Cerrado	Semideciduous	Ombrophilous
β_0	-7.3801	-8.8534	-9.2271
β_1	1.6502	1.7353	1.6185
β_2	0.4164	0.9149	1.2020
β_3	-15.7022	-11.2397	-10.1938
adj. R^2	0.9786	0.9869	0.9745
Weight	DBH	$DBH^{0.5}$ HT	$DBH^{0.5}$ HT

A number of models based on diameter at breast height (DBH) and total height (HT) were tested for their suitability in estimating volume. Figure 3.2 shows the relationship between estimated volume and DBH that could be modeled as indicated in the fitted line. Therefore, the lines represent the multiple linear regression models for the three forest types until maximum observed values of DBH. According to the lines representation, we can observe different behaviors in terms of DBH and estimated volume. Volume in dense ombrophilous forest resembles volume in semideciduous forest according to various DBH sizes. On the other hand, trees in Cerrado have a different pattern, which we can observe a lower volume for larger trees comparing to the other two forest types.

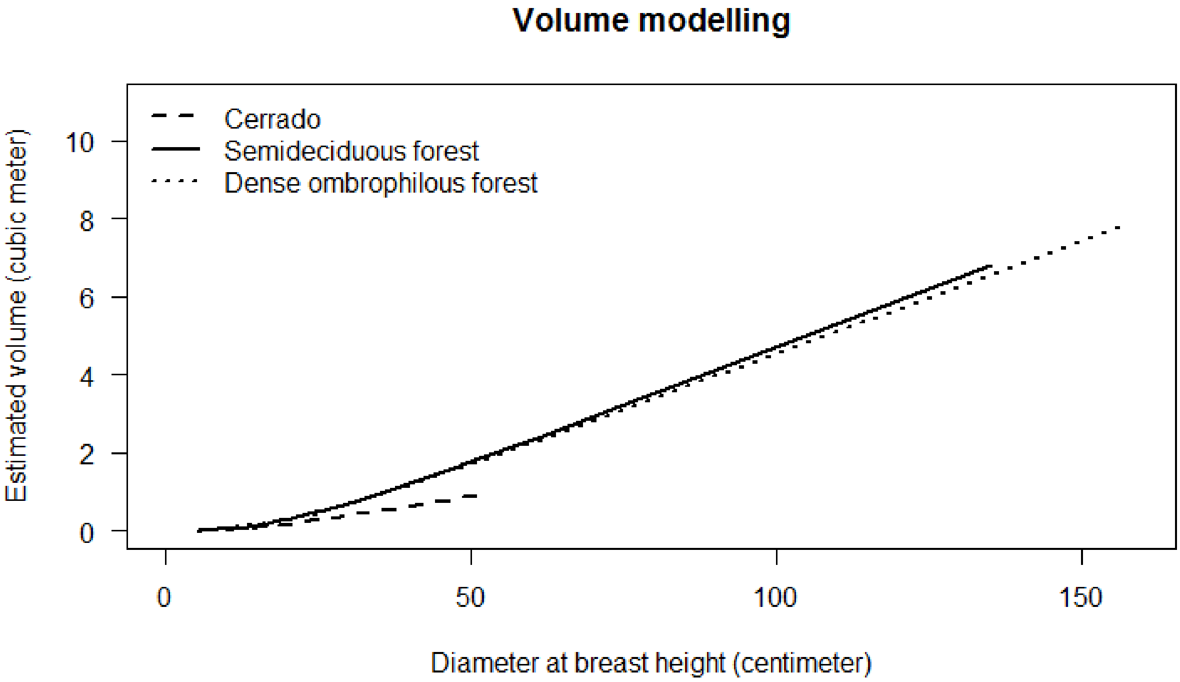

Figure 3.2 - Representation of the volume modeling based on diameter at breast height (DBH) and total height (see equation 3.1) on the DBH versus estimated volume plot

The average percent overpredictions, standard error of estimate and average bias by forest type (cerrado, semideciduous and dense ombrophilous forests) were calculated (Table 3.5, 3.6 and 3.7). The diameter classes were divided according to the principal component analysis performed (see chapter 1) to separate classes according to the number of individuals, number of species and basal area. The volume prediction results were better for some forest types than for others. In general, the models showed low overall percent overprediction values and low values per class. For example, in Cerrado (Table 3.5), for smaller trees in the first class the model underpredicted volume in -10.02%, resulting in 1.92% overall overprediction though. In semideciduous forest (Table 3.6), the model for volume did not varied substantially by diameter classes, resulting in an overall overprediction of the volume by 1.32%. In dense ombrophilous forest (Table 3.7), the percent overprediction values tended to underpredict for larger individuals.

The calculations of bias showed that the highest bias in volume obtained by the model 3.1 using total height and DBH occurred for larger diameters in ombrophilous forest, 20.55%, considering every forest type herein studied. In general, the overall bias using the model 3.1 were low, resulting in an accurate model for estimating volume in the three forest types, even though the directions of bias can vary by diameter class.

The percentage standard error of the estimate had no pattern according to the diameter class and forest type in terms of values. The overall percentage standard error of the estimate was lower for the Cerrado, probably indicating a high precision of the model in obtaining the volume in this forest type, as weel as an accurate method as shown by the bias values. Moreover, more precise results were obtained in the smaller diameter classes for semideciduous and ombrophilous forests.

Table 3.5 - Number of individuals (n), percent overpredictions, standard error of the estimate (RMSE) and average bias in the Mogi Guaçu Biological Reserve in Cerrado for DBH class and overall

DBH class (cm)	n	Overprediction (%)	RMSE (%)	Bias (%)
5 ≤ DBH < 8	9	-10.02	26.75	-0.16
8 ≤ DBH < 20	25	9.11	12.43	0.09
DBH ≤ 20	18	-2.11	21.15	-0.65
Overall	52	1.92	28.63	-0.21

Table 3.6 - Number of individuals (n), percent overpredictions, standard error of the estimate (RMSE) and average bias in the Caetetus Biological Reserve in semideciduous forest for DBH class and overall

DBH class (cm)	n	Overprediction (%)	RMSE (%)	Bias (%)
5 ≤ DBH < 10	19	1.09	22.30	-0.08
10 ≤ DBH < 35	23	2.14	19.59	0.08
DBH ≤ 35	11	-0.01	34.29	-2.42
Overall	53	1.32	63.27	-0.49

Table 3.7 - Number of individuals (n), percent overpredictions, standard error of the estimate (RMSE) and average bias in the Carlos Botelho" State Park in ombrophilous forest for DBH class and overall

DBH class (cm)	n	Overprediction (%)	RMSE (%)	Bias (%)
5 ≤ DBH < 10	16	0.11	28.04	-0.05
10 ≤ DBH < 55	32	6.45	32.11	-1.58
DBH ≤ 55	7	-10.30	37.95	20.55
Overall	55	2.47	68.24	1.68

Incoherent points in the standardized residuals-based plot (Figure 3.3) were identified to infer about the quality of the DBH-based volume model. In Cerrado, *Ficus citrifolia* was overestimated by using the model 3.1, caused by a bifurcation at several heights along the stem, including 1.30 meters, and influencing the volume prediction that takes into account only DBH and total height. *Ficus enormis* in semideciduous forest and *Alchornea triplinervea* in dense ombrophilous forest semideciduous had the volume overestimated as well, caused by buttressing, which probably influenced measurement of DBH.

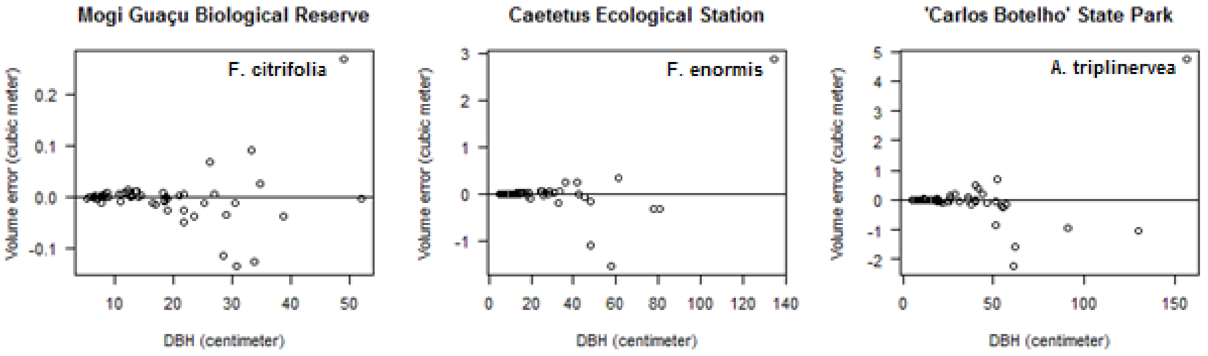

Figure 3.3 - Volume error estimation versus diameter at breast height (DBH) obtained by the volume modeling (see equation 3.1) for the three forest types

3.3.3 Volume modeling with crown area-based system

Linear models were developed to estimate volume as described in the methodology. Let HT= total height of the tree in meters, AC = crown area in meters. β_0, β_1, β_2,…, β_n are parameters to be estimated from the data, considering n parameters in the model.

$$\ln V = \beta_0 + \beta_1 \ln AC + \beta_2 \ln HT + \beta_3 \frac{1}{HT^{0.5} * AC} \qquad (3.2)$$

$$\ln V = \beta_0 + \beta_1 \ln AC + \beta_2 \ln HT + \beta_3 \frac{1}{HT * AC} \qquad (3.3)$$

$$\ln V = \beta_0 + \beta_1 \ln AC + \beta_2 \ln HT \qquad (3.4)$$

The best-fit equation for volume based on combinations of crown area (AC) and total height (HT) as independent variables after data transformation, met the linear model assumptions reasonably well. A logarithmic transformation was indicated by Box-Cox method as the best data transformation, in order to transform for normality, making residuals from the regression on independent variables as close to normally distributed as possible. This model predicted the volume reasonably well, indicated by the coefficients of determination (Table 3.8) compared to other possible HT and AC combinations. By different combinations in order to choose the best weight when using weighted least squares to estimate coefficients in the linear models, AC^2HT in ombrophilous forest resulted in the best percent overprediction, percentage bias and percentage standard error of the estimate, as well as most correlated independent variables to volume variance. In Cerrado and semideciduous forest the use of ordinary least squares resulted in better goodness of fit.

Table 3.8 - Coefficients for multiple linear models fitted and adjusted coefficient of determination for volume prediction based on height and crown area (see equations 3.2, 3.3 and 3.4) for Cerrado, semideciduous forest and dense ombrophilous forest. Weight is specified when using weighted least squares to estimate parameters.

Item	**Cerrado**	**Semideciduous**	**Ombrophilous**
β_0	-7.0419	-11.2692	-9.1574
β_1	0.9242	0.6696	1.4693
β_2	1.0793	2.946	1.0222
β_3	1.6033	1.9655	..
adj. R^2	0.8049	0.8425	0.78
Weight	..	..	AC^2 HT

A number of models based on crown area (AC) and total height (HT) were tested for their suitability in estimating volume. Figure 3.4 shows the relationship between estimated volume and crown area that could be modeled as indicated in the fitted line. Therefore, the lines represent the multiple linear regression models for the three forest types until observed values of crown area. According to the lines representation, we can observe different behaviors in terms of crown area and estimated volume. Until a certain crown area the volume values are similar, and after varying according to the forest type. In dense ombrophilous forest, larger crown area trees have higher volume values comparing to same crown area trees in semideciduous forest. On the other hand, Cerrado showed lower wood volume for same crown area sizes in the other two forest types.

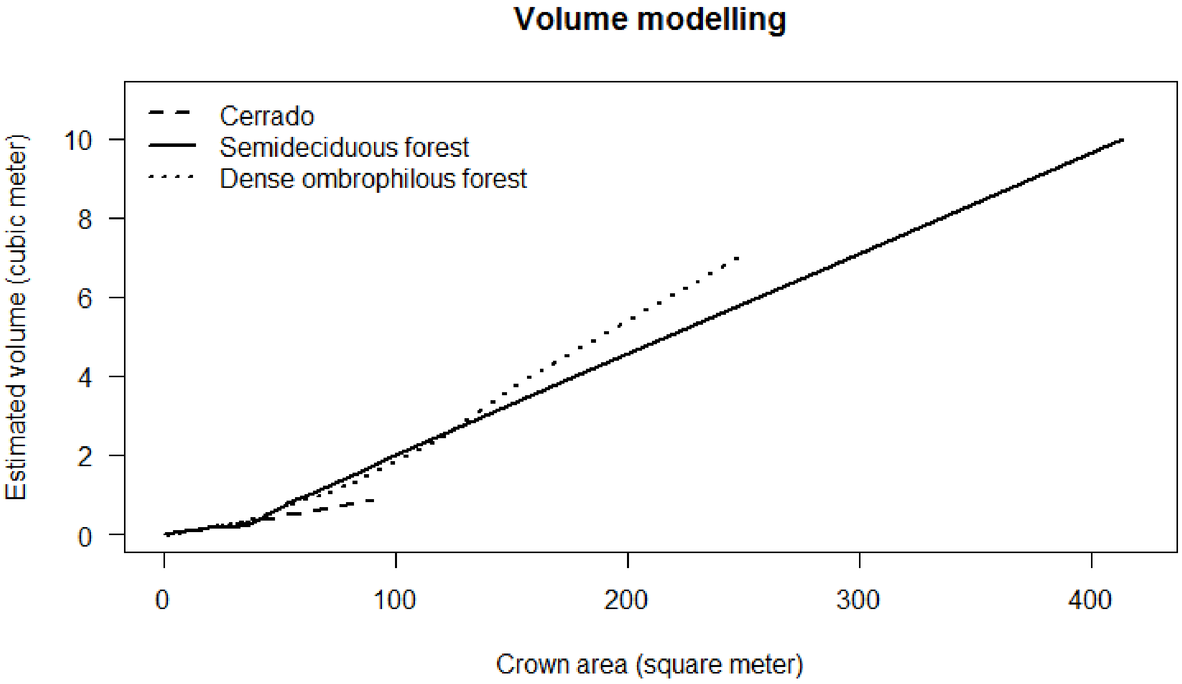

Figure 3.4 - Representation of the volume modeling based on crown area and total height (see models 3.2, 3.3 and 3.4) on the crown area versus estimated volume plot

The average percent overpredictions, standard error of estimate and average bias by forest type (cerrado, semideciduous and dense ombrophilous forests) were calculated (Table 3.9, 3.10 and 3.11). The height classes were divided according to the principal component analysis performed (see chapter 1) to separate classes according to the number of individuals, number of species and basal area. In semideciduous forest (Table 3.10) and ombrophilous forest (Table 3.11) the two lowest height classes were merged to provide one class more representative in terms of number of individuals. The volume prediction results were better for some forest types than for others. In general, the models showed higher percent overprediction values in the lower height classes and more biased for higher height classes in the three forests types. For example, in Cerrado (Table 3.9), for shorter trees up to 11.7 meters the models overpredict volumes, while for taller trees the model for volume estimation tends to underpredict the volume, resulting in 10.6% overall overprediction. In semideciduous forest, the model for volume estimation underpredicted for taller individuals than 11 meters, resulting in an overall overprediction of the volume by 30.06%. In dense ombrophilous forest, the percent overprediction values tended to overpredict more for the individuals taller than 13.4 meters of height. In general, the method resulted in an overall underprediction of the volume for the dense ombrophilous forest, while the method overpredicts the volume for the other two forest types. Dense ombrophilous forest showed the lowest values of percent overprediction.

The calculations of bias showed that the highest bias in volume obtained by the models 3.2, 3.3 and 3.4 using total height and crown area occurred in the highest height classes in the three forest types. Cerrado and semideciduous forest showed low overall percentage bias, even though the directions of bias can vary by height class. On the other hand, dense ombrophilous forest showed a higher overall percentage bias, resulting in 15.05% overall bias.

Using total height and crown area to estimate volume, the percentage standard error of the estimate had no pattern according to the height class and forest type in terms of values. The overall percentage standard error of the estimate was higher for the semideciduous forest, indicating a low precision of the model in obtaining the volume in this forest type, even though this method is an accurate method as shown by the bias values. On the other hand, more precise results were obtained in the highest height class for the ombrophilous forests, however this model is a biased as shown by the bias values.

Table 3.9 - Number of individuals (n), percent overpredictions, standard error of the estimate (RMSE) and average bias in the Mogi Guaçu Biological Reserve in Cerrado for DBH class and overall

Class HT (cm)	n	Overprediction (%)	RMSE (%)	Bias (%)
HT < 7.7	24	52.03	46.58	1.12
7.7 ≤ HT < 11.7	19	0.87	54.74	0.67
11.7 ≤ HT	9	-27.34	48.01	-13.06
Overall	52	19.60	62.64	-1.50

Table 3.10 - Number of individuals (n), percent overpredictions, standard error of the estimate (RMSE) and average bias in the Caetetus Biological Reserve in semideciduous forest for DBH class and overall

Class H (cm)	n	Overprediction (%)	RMSE (%)	Bias (%)
HT < 11	24	70.22	63.81	-1.31
11≤ HT < 19	21	-4.65	57.68	5.52
19 ≤ HT	8	-3.45	84.24	-33.11
Overall	53	30.06	141.02	-2.83

Table 3.11 - Number of individuals (n), percent overpredictions, standard error of the estimate (RMSE) and average bias in the Caetetus Biological Reserve in semideciduous forest for DBH class and overall

Class H (cm)	**n**	**Overprediction (%)**	**RMSE (%)**	**Bias (%)**
HT < 13.4	25	-12.10	116.59	0.21
13.4 ≤ HT < 18.4	21	0.19	75.89	22.58
18.4 ≤ HT	9	6.00	48.82	38.71
Overall	55	-4.44	86.48	15.05

Incoherent points in the standardized residuals-based plot (Figure 3.5) were identified to infer about the quality of the geometric form method. In semideciduous, the species *Copaifera langsdorffii* presented overestimated volume, because its crown area measured was much larger compared to other trees in the community. On the other hand, the individual of the species *Alchornea tripinervea* in ombrophilous forest was underestimated using the crown-based model, because this individual had a small crown area compared to other individuals with the same volume.

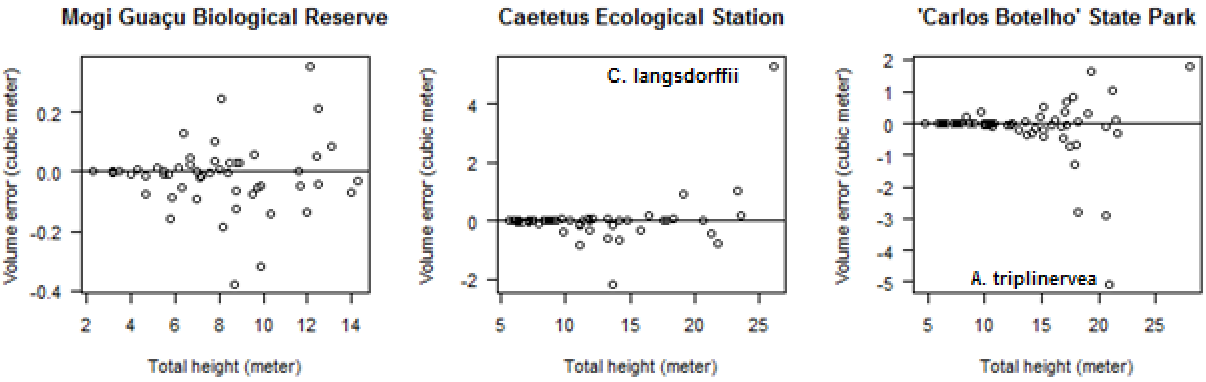

Figure 3.5 - Volume error estimation versus total height obtained by the volume modeling (see equations 3.2, 3.3 and 3.4) for the three forest types

3.3.4 Taper Equation

3.3.4.1 Equation development

The developed taper equation was fitted to the data for the tree community using nonlinear regression technique. The equation was based on the CRC Handbook of Mathematical Curves and Surfaces (VON SEGGERN, 1989), using surfaces models and respective parameter coefficients for each sort of surface form. Cosine transformation of the relative diameter (Di/ $D_{0.1}$) established surfaces that provided a good model fit. For the forest types studied, the diameter at the base (10 centimeter of height) estimated the relative diameter more precisely compared to the DBH, broadly used to estimate relative diameters in other taper equations.

$$\mathrm{Di} = \mathrm{D_B} \cos^{-1}\left[(1-\beta_0)\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{\beta_1} + \beta_0\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{0.05\beta_0}\right]^2 \tag{3.5}$$

Let Hi = height above ground to some point on the stem, HT = total height, Di = diameter outside bark at height Hi and D_B = diameter at 10 centimeters of height. β_0 and β_1 are the parameters to be estimated from the data.

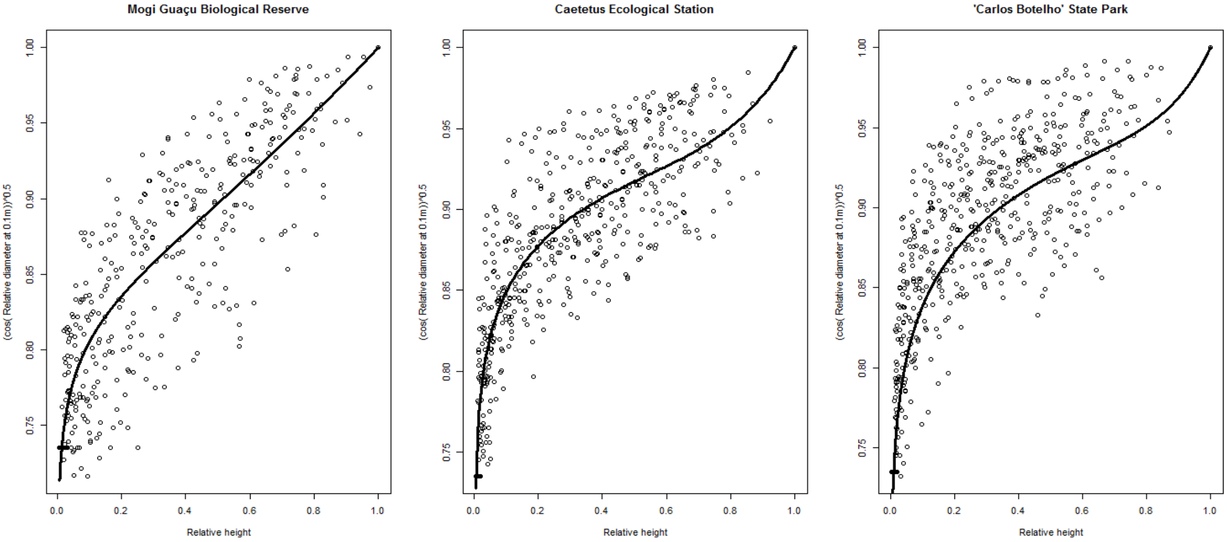

Figure 3.6 - Fitted trigonometric taper equations separately according to the respective data set for the three forest types

This model was fitted using least squares regression for each species. Coefficients and fit statistics are presented in Table 3.12. In general the models fitted quite well as demonstrated in the fitted values versus observed values plot.

Table 3.12 - Coefficients and fit statistics for the trigonometric taper equation in each forest type. β_0 and β_1 are the parameters, $S_{\beta 1}$and S_{β} the standard error of the parameters, n the sample size

Item	**Forest type**		
	Cerrado	**Semideciduous**	**Ombrophilous**
$\boldsymbol{\beta_0}$	0.8895	0.9470	0.9569
$\boldsymbol{\beta_1}$	1.6889	6.1531	8.5931
$\mathbf{S}_{\boldsymbol{\beta 0}}$	0.1754	1.7291	5.1733
$\mathbf{S}_{\boldsymbol{\beta 1}}$	0.0040	0.0017	0.0018
n	460	595	622

At the top of the tree, the relative height (h/H) is equal to one and the diameter (Di) should be zero. Considering the cosine of a 0 value is equal one, we can conclude that equation 3.5 is forced to go through the tip of the tree, being a constrained form of the taper equation.

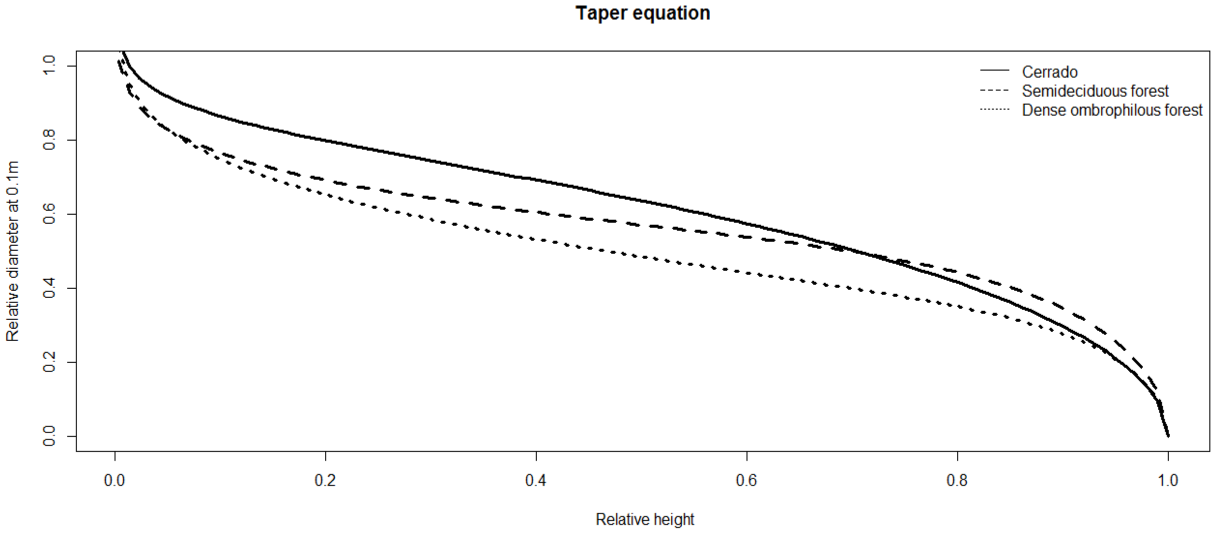

Figure 3.7 - Relative diameters versus height diameters plot fitted to the data in the three forest types

From the equation 3.5 we can obtain:

$$\cos\left(\frac{\mathrm{Di}}{\mathrm{D_B}}\right)^{1/2} = (1-\beta_0)\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{\beta_1} + \beta_0\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{0.05\beta_0} \tag{3.6}$$

$$\cos\left(\frac{\mathrm{Di}}{\mathrm{D_B}}\right) = \left[(1-\beta_0)\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{\beta_1} + \beta_0\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{0.05\beta_0}\right]^2 \tag{3.7}$$

$$\frac{\mathrm{Di}}{\mathrm{D_B}} = \cos^{-1}\left[(1-\beta_0)\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{\beta_1} + \beta_0\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{0.05\beta_0}\right]^2 \qquad (3.8)$$

$$\mathrm{Di} = \mathrm{D_B} * \cos^{-1}\left[(1-\beta_0)\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{\beta_1} + \beta_0\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{0.05\beta_0}\right]^2 \qquad (3.9)$$

Integrating the expression 3.10 for area in square centimeters over the length desired in meters gives the volume in cubic meters for that segment, after multiplying by a constant $= {}^{\pi}/_{40000}$. Using equation 3.11 it is possible to determine the volume from the taper equation.

$$Vol = \int_{0.1}^{HT} K * (Di)^2 \; dx \qquad (3.10)$$

$$Vol = \int_{0.1}^{HT} K * \left(\mathrm{D_B} * \cos^{-1}\left[(1-\beta_0)\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{\beta_1} + \beta_0\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{0.05\beta_0}\right]^2\right)^2 dHi \qquad (3.11)$$

3.3.4.2 Comparisons of diameter predictions by taper equations

Evaluation of trigonometric equation 3.5 against Kozak, Demaerschalk and Biging models was performed for each forest type on the same data set used to estimate coefficients. Coefficients and fit statistics for the four models are presented in Tables 3.13, 3.14 and 3.15. Coefficients in the semideciduous are quite similar to the dense ombrophilous forest. Cerrado showed a different pattern in terms of form modeling when observing parameters.

Table 3.13 - Coefficients for the Kozak, Demaerschalk and Biging in Cerrado in the Mogi Guaçu Biological Reserve.

Item	**Kozak**	**Demaerschalk**	**Biging**
β_0	*1.3106*	0.1345	1.2414
β_1	*-1.5956*	0.9544	0.3125
β_2	*0.3173*	0.5327	..
β_3	..	-0.5622	..

Table 3.14 - Coefficients for the Kozak, Demaerschalk and Biging in semideciduous forest in the Caetetus Ecological station

Item	**Kozak**	**Demaerschalk**	**Biging**
β_0	1.4958	0.1629	1.2345
β_1	-2.7943	1.0225	0.3382
β_2	1.4375	0.6885	..
β_3	..	-0.8086	..

Table 3.15 - Coefficients for the Kozak, Demaerschalk and Biging in dense ombrophilous forest in the “Carlos Botelho” State Park

Item	**Kozak**	**Demaerschalk**	**Biging**
β_0	1.4429	0.1808	1.2898
β_1	-2.4965	0.9665	0.3703
β_2	1.1939	0.7484	..
β_3	..	-0.8003	..

In predicting diameters along the stem, the standard error of estimate and average bias to overall and various portions of height in the three forest types were calculated (Tables 3.16, 3.17 and 3.18). Diameter prediction results were better for some forest types than for others. In general, all of the taper equations overpredicted diameters, resulting in negative bias. However, trigonometric model resulted in more negative bias along the stem in various portions of height in ombrophilous and semideciduous forests. On the other hand, Cerrado showed an opposite pattern with more positive bias in predicting diameters at different heights of the stem.

Demaerschalk taper equation predicted diameters more precise to various portions of height for stems in Cerrado, as well as a more precise overall standard error of estimate. Trigonometric model resulted in a lower overall bias for this forest type comparing to other taper equations, nonetheless no pattern of bias in terms of values and directions to various height portions can be determined observing results of diameter predictions. In semideciduous forest, trigonometric model resulted in a lower overall standard error of estimate, as well as better diameter predictions for lower portions of the stem up to 40% of the total height and upper diameters above 70%. Kozak taper equation showed more precise predictions in the midrange portion of the stem. Additionally, trigonometric model resulted in more accurate in lower (up to 40%) and upper (above 70%) portions of the stem in term of bias, and showed the lowest overall bias comparing the four taper equations each other. In dense ombrophilous forest, trigonometric taper equation had the lowest overall standard error of the estimate. Even though this general result was better at all in this forest type, Biging´s model presented a good fit on the midrange and upper portions in terms of precision. On the other hand, Biging's model presented a more overall accurate prediction, while trigonometric model resulted in good fit on various portions of the stem in terms of accuracy.

The residuals plots can be observed in order to analyze the residuals pattern (Figure 3.8, 3.9 and 3.10). From the visual plots and comparisons on the stem portions is possible to visualize good predictions of the trigonometric model in terms of tendency, accuracy and precision. Observing plots for the three forest types, diameter predictions by the trigonometric model resulted in good fit especially of lower stems, that is, larger relative heights.

Table 3.16 - Comparisons of standard error of the estimate (RMSE (cm)) and bias (cm) for diameter predictions to stem portions of height for Kozak, Demaerschalk, Biging and trigonometric taper equations in the Mogi Guaçu Biological Reserve in Cerrado

Height	**n**	**Kozak**		**Demaerschalk**		**Biging**		**Trigonometric**	
		RMSE	**Bias**	**RMSE**	**Bias**	**RMSE**	**Bias**	**RMSE**	**Bias**
0.0H—0.1H	187	2.84	-0.1707	2.59	0.4474	2.81	-0.255	2.08	-0.3701
0.1H—0.2H	83	1.48	-0.8649	0.91	-0.3942	1.05	-0.3431	3.20	0.3911
0.2H—0.3H	72	4.08	-1.1267	3.63	-0.8129	3.79	-0.6332	3.81	0.0187
0.3H—0.4H	68	4.60	-0.4821	4.30	-0.2906	4.44	-0.1783	4.59	0.5683
0.4H—0.5H	67	4.07	-0.5298	3.81	-0.3921	3.96	-0.4237	4.13	-0.1189
0.5H—0.6H	53	5.29	-0.2969	5.03	-0.1661	5.25	-0.3892	4.75	0.1191
0.6H—0.7H	40	4.21	-1.206	3.93	-0.9492	4.28	-1.4339	4.29	-1.3218
0.7H—0.8H	19	5.46	-1.1773	5.17	-0.864	5.44	-1.3465	5.22	-0.8537
0.8H—0.9H	8	5.30	0.8659	5.55	1.4236	5.05	1.0937	5.29	1.3799
0.9H—0.10H	55	4.72	-2.7721	2.83	0.3578	2.85	0.3921	2.76	0.3356
Overall	652	3.77	-0.8014	3.28	-0.0899	3.52	-0.3438	3.49	-0.0682

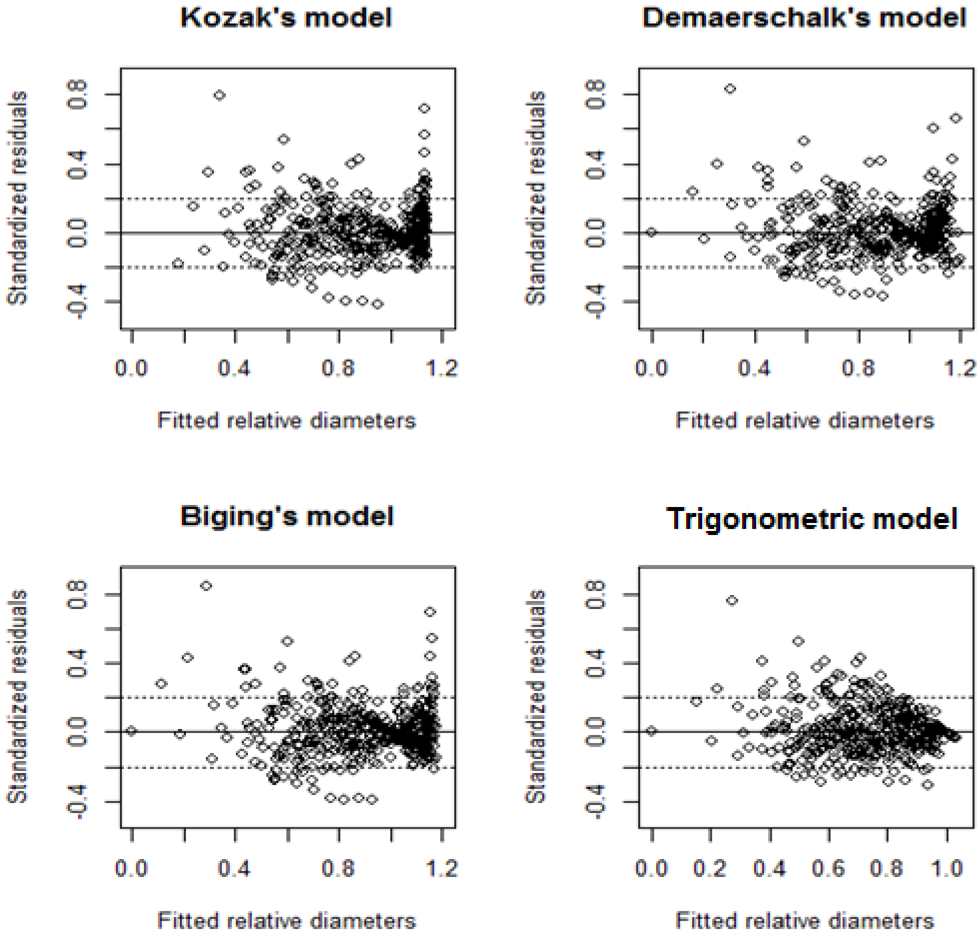

Figure 3.8 - Standardized residuals of relative diameter prediction versus fitted relative diameter values (cm) for the Kozak, Demaerschalk, Biging and the trigonometric taper equations in Cerrado in the Mogi Guaçu Biological Reserve. Dotted lines only represent a tool for visualizing plots

Table 3.17 - Comparisons of standard error of the estimate (RMSE (cm)) and bias (cm) for diameter predictions to stem portions of height for Kozak, Demaerschalk, Biging and trigonometric taper equation in the Caetetus Ecological Station in semideciduous forest

Height	n	Kozak		Demaerschalk		Biging		Trigonometric	
		RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias
0.0H—0.1H	175	5.30	-0.8937	5.16	1.3045	4.72	1.0008	3.69	-0.4679
0.1H—0.2H	73	13.91	-5.7242	11.97	-4.3617	11.48	-3.8188	9.64	-2.9839
0.2H—0.3H	65	10.93	-3.9623	10.25	-3.3103	9.92	-3.0402	9.00	-2.2131
0.3H—0.4H	62	7.82	-1.7861	7.74	-1.8476	7.95	-2.1411	6.99	-1.3997
0.4H—0.5H	55	7.47	-0.3644	7.83	-0.9424	8.47	-1.9242	7.82	-2.1351
0.5H—0.6H	51	6.70	1.4846	6.81	0.8038	7.33	-0.9509	7.67	-2.3338
0.6H—0.7H	46	8.03	2.4082	8.29	2.054	8.26	-0.2193	9.78	-3.2464
0.7H—0.8H	23	9.23	4.163	10.18	4.9879	8.25	2.8411	8.54	-1.3764
0.8H—0.9H	8	13.10	6.4062	20.09	9.1015	13.21	7.334	7.81	2.3052
0.9H—0.10H	53	13.15	-8.6994	0.84	0.1078	0.76	0.0994	0.37	0.0486
Overall	611	8.85	-1.8024	7.63	-0.2371	7.53	-0.7673	6.87	-1.5114

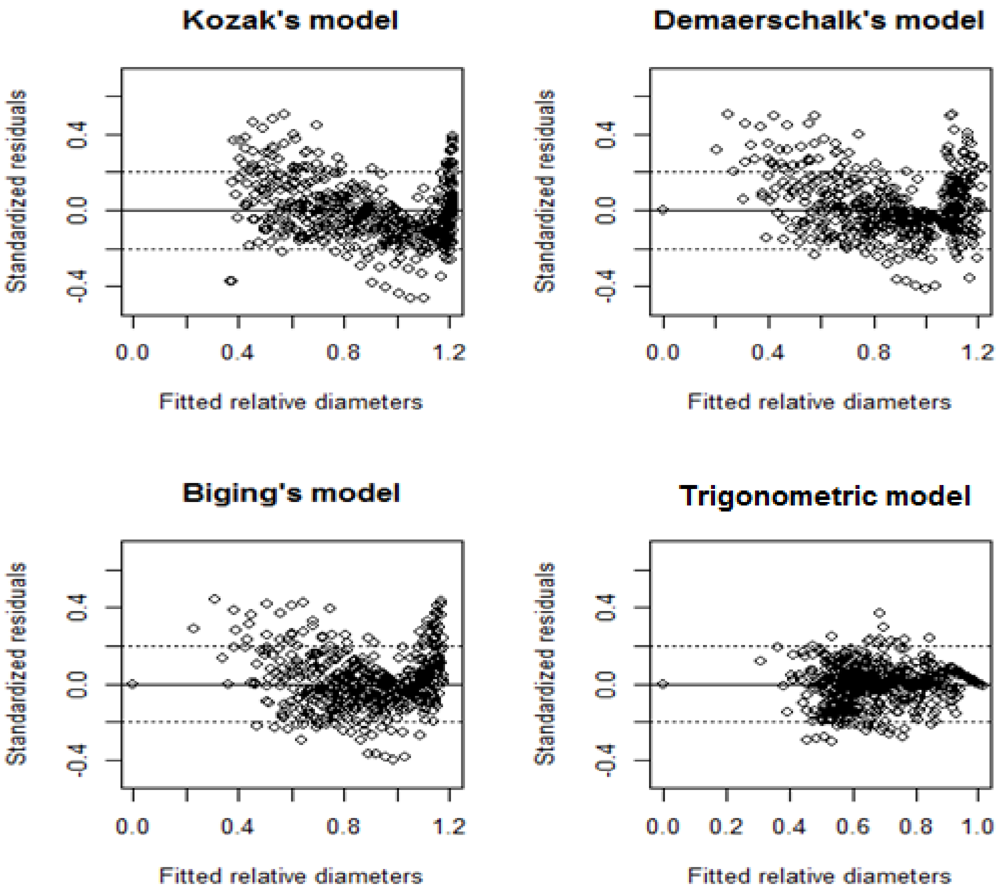

Figure 3.9 - Standardized residuals of relative diameter prediction versus fitted relative diameter values (cm) for the Kozak, Demaerschalk, Biging and the trigonometric taper equations in semideciduous forest in the Caetetus Ecological station. Dotted lines only represent a tool for visualizing plots

Table 3.18 - Comparisons of standard error of the estimate (RMSE (cm)) and bias (cm) for diameter predictions to stem portions of height for Kozak, Demaerschalk, Biging and trigonometric taper equations in the "Carlos Botelho" State Park in dense ombrophilous forest

Height	**n**	**Kozak**		**Demaerschalk**		**Biging**		**Trigonometric**	
		RMSE	**Bias**	**RMSE**	**Bias**	**RMSE**	**Bias**	**RMSE**	**Bias**
0.0H—0.1H	187	8.49	1.1673	9.41	3.2984	8.51	2.8127	7.28	-0.9892
0.1H—0.2H	83	12.06	-6.0048	10.42	-4.485	9.66	-3.8855	11.57	-4.3816
0.2H—0.3H	72	16.03	-6.0086	15.28	-5.1207	14.51	-4.7552	12.48	-3.9212
0.3H—0.4H	68	11.89	-2.7518	11.76	-2.3799	11.47	-2.561	10.53	-2.5902
0.4H—0.5H	67	9.30	0.8532	9.52	1.0699	9.14	0.0853	9.61	-1.0244
0.5H—0.6H	53	9.06	3.6126	9.58	3.9361	8.23	2.4443	9.33	0.104
0.6H—0.7H	40	7.37	3.8419	8.38	4.7429	6.50	2.5918	8.88	-1.4513
0.7H—0.8H	19	8.95	4.0656	11.13	5.9619	8.52	3.6763	11.07	-1.9638
0.8H—0.9H	8	9.10	4.0187	13.98	6.7426	9.01	5.1031	12.42	-3.5775
0.9H—0.10H	55	16.43	-11.3969	0.00	0	0.00	0	0.00	0
Overall	652	10.97	-1.5401	9.93	0.5569	9.27	0.0673	9.15	-1.8312

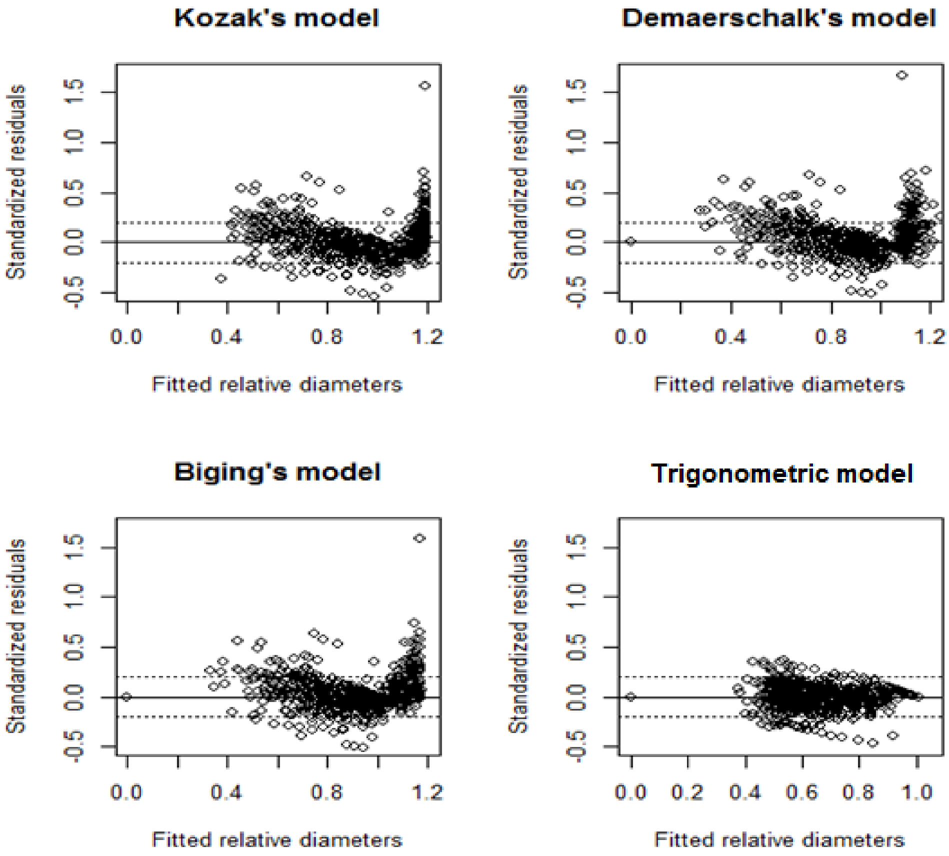

Figure 3.10 - Standardized residuals of relative diameter prediction versus fitted relative diameter values (cm) for the Kozak, Demaerschalk, Biging and trigonometric taper equations in "Carlos Botelho" State Park in the dense ombrophilous forest. Dotted lines only represent a tool for visualizing plots

3.3.4.3 Comparison of volume predictions by taper equations

Estimating the volume for the three forest types, we can observe the percent overpredictions, per diameter class and overall, as well as overall standard error of the estimative and bias for the trigonometric equation, Kozak, Demaerschalk and Biging´s models (Tables 3.19, 3.20 and 3.21). Diameters classes were separated according to the principal component analysis performed in the first chapter to separate classes according to the number of individuals, number of species and basal area. The results were better for some forest types than for others. The four taper equations tested fitted quite well and similar for Cerrado, even though the trigonometric model seems to fit a little more precisely and accurately volume compared to the other equations, observing overall percent overprediction, standard error of the estimative and bias. By percent overpredictions for diameter classes, we can observe that smaller diameter trees had higher percent overprediction than larger trees in Cerrado. For the forest types presented, the standard error of the estimate showed lower values for trigonometric model compared with other taper models. However there are some differences in overpredictions and directions of percent overprediction according to the diameter class, as well as the biases obtained for each taper equation. In cerrado, the taper-based model showed lower overall percent overpredictions, bias and standard error of the estimate in the volume prediction (Table 3.19). In semideciduous forest, the model proposed presented the lower overall percent overprediction and standard error of the estimative for volume prediction (Table 3.20). The percent overpredictions are in different directions according to the DBH class. In the dense ombrophilous forest, trigonometric equation showed the lower standard error of the estimate (Table 3.21). On the other hand, the model showed the higher bias and percent overpredictions amongst the tested models.

It is important to consider the benefit of using the trigonometric model in predicting volume of large trees observing residual plots versus DBH, which is possible evaluate lower errors in prediction (Figure 3.11, 3.12 and 3.13).

Table 3.19 - Average percent overpredictions (%) by DBH class (cm), overall percent overprediction (%), standard error of the estimate (RMSE (m^3)) and bias (m^3) for Kozak, Demaerschalk, Biging and trigonometric taper equations in the Mogi Guaçu Biological Reserve in Cerrado

DBH Class (cm)	**n**	**Kozak**	**Demaerschalk**	**Biging**	**Trigonometric**
5 ≤ DBH < 7.9	9	-9.9857	-0.7176	-13.3734	5.8223
8 ≤ DBH < 19.9	25	-1.9614	0.6727	-4.7437	-2.9071
20 ≤ DBH	18	0.4862	0.4464	0.4740	0.4171
Overall overprediction (%)	52	0.2048	0.1913	0.1996	0.1824
Overall RMSE (m^3)	52	0.11352	0.08646	0.10589	0.08266
Overall bias (m^3)	52	-0.02180	-0.00833	-0.01661	0.00058

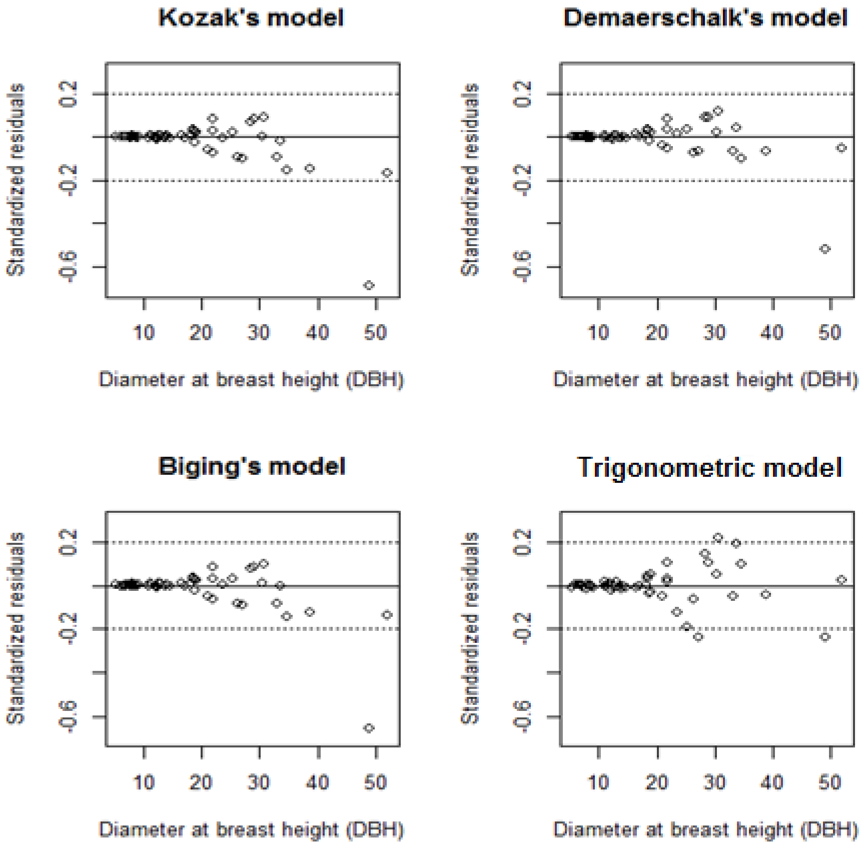

Figure 3.11 - Standardized residuals of volume prediction (m^3) versus Diameter at Breast Height (cm) for the Kozak, Demaerschalk, Biging and trigonometric taper equations in Cerrado in the Mogi-Guaçu Biological Reserve. Dotted lines only represent a tool for visualizing plots

Table 3.20 - Average percent overpredictions (%) by DBH class (cm), overall percent overprediction (%), standard error of the estimate (RMSE (m^3)) and bias (m^3) for Kozak, Demaerschalk, Biging and trigonometric taper equations in the Caetetus Ecological Station in semideciduous forest

DBH Class (cm)	n	Kozak	Demaerschalk	Biging	Trigonometric
5 ≤ DBH < 9.9	19	11.0484	10.2176	-2.2464	-18.2968
10 ≤ DBH < 34.9	23	1.0848	-2.4359	-2.9047	5.8322
35 ≤ DBH	11	21.4785	11.7800	17.4800	24.5075
Overall overprediction (%)	53	8.8893	5.0507	1.5621	1.0582
Overall RMSE (m^3)	53	1.29783	1.09761	1.19389	0.96652
Overall bias (m^3)	53	-0.21107	-0.13101	-0.17632	-0.18091

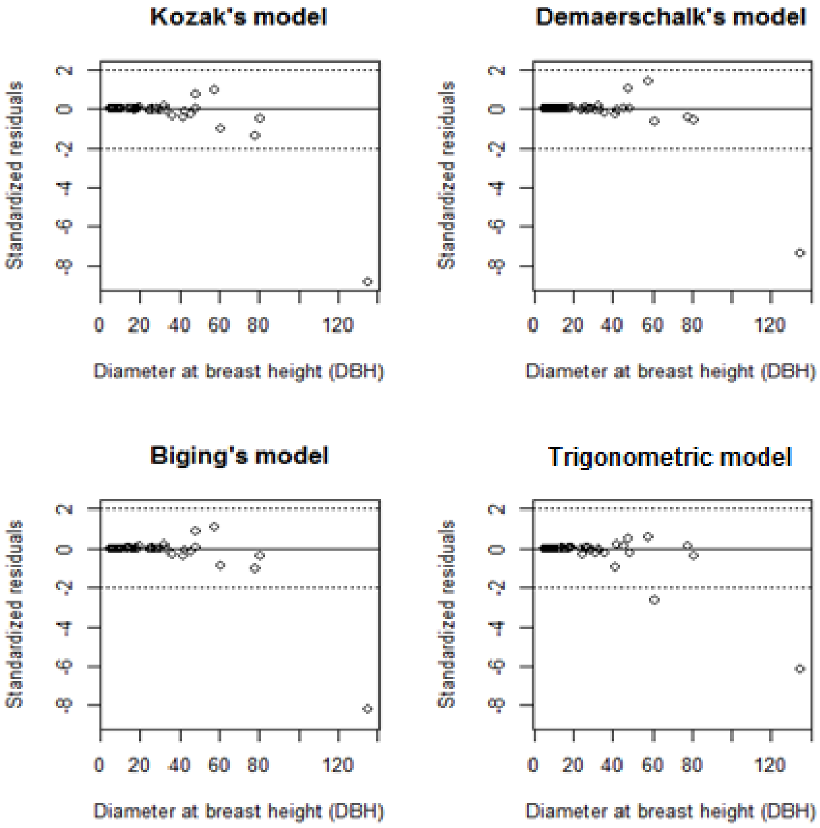

Figure 3.12 - Standardized residuals of volume prediction (m^3) versus Diameter at Breast Height (cm) for the Kozak, Demaerschalk, Biging models and trigonometric equation in the semideciduous forest in Caetetus Ecological Station. Dotted lines only represent a tool for visualizing plots

Table 3.21 - Average percent overpredictions (%) by DBH class (cm), overall percent overprediction (%), standard error of the estimate (RMSE (m^3)) and bias (m^3) for Kozak, Demaerschalk, Biging and trigonometric taper equations in the "Carlos Botelho" State Park in dense ombrophilous forest

DBH Class (cm)	n	Kozak	Demaerschalk	Biging	Trigonometric
5 ≤ DBH < 9.9	16	-12.5522	0.2827	-9.4563	-1.5709
10 ≤ DBH < 54.9	32	-2.1332	1.2999	3.4043	16.4147
55 ≤ DBH	7	10.6183	13.8750	15.6670	18.9341
Overall overprediction (%)	55	0.9038	4.8495	6.2987	16.1450
Overall RMSE (m^3)	55	1.51323	1.65750	1.56758	1.02191
Overall bias (m^3)	55	-0.18280	-0.21847	-0.24658	-0.27352

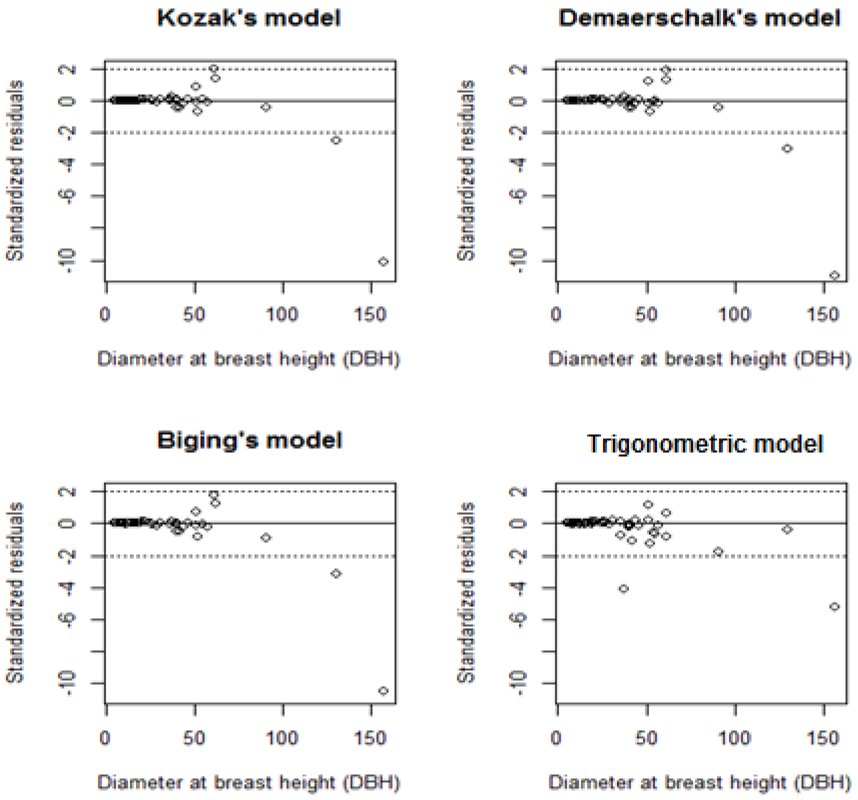

Figure 3.13 - Standardized residuals of volume prediction (m^3) versus Diameter at Breast Height (cm) for the Kozak, Demaerschalk, Biging models and trigonometric taper equations in dense ombrophilous forest in the "Carlos Botelho" State Park. Dotted lines only represent a tool for visualizing plots

3.4 **Discussion**

3.4.1 Volume modeling

Each forest type required a different model to predict the tree volume and different combinations were performed in order to obtain the lowest residual standard error and to conform to the linear model assumptions. Residuals of the models were studied and no dependency of residuals was found in the three forest types. Logarithmic transformation resulted in the best transformation and better estimation. Our regressions were not improved by the inclusion of light intensity or quality of the stem.

The volume of trees in a forest is one of the most important statistics in forest management. The individual tree volume is usually considered to be a function of tree DBH, tree height, and an expression of tree form (CLUTTER et al., 1983), but most practitioners prefer using volume equations that involve only DBH and height. Diameter at breast height for the DBH-based model and crown area for crown-based model to estimate volume, including the total tree height in the models, were important variables in predicting the stem volume. Segura and Kanninen (2005) developed allometric models based only on DBH for the estimation of tree volume in a tropical humid forest in Costa Rica, considering the simplicity in obtaining the tree volume. Chave et al. (2005) show that in tropical forests the most important predictors of above ground volume of trees in order of decreasing importance are diameter and total height. The total height was an important variable in predicting the volume for the three forest types in the present study, judged by the importance of each parameter. It is suggested that tree height, HT, for a given diameter (DBH) may vary significantly among species (KING, 1996) and across regions (NOGUEIRA et al., 2008). Considering that individual volume is determined by diameter and height and excluding the hipothesis that form variations is likely a factor influencing volume, we can suppose that trees in Cerrado are shorter for a given DBH, compared to the other two forest types, so resulting in lower volume. Ombrophilous and semideciduous have similar HT:DBH relationships, probably indicating that similar models would predict volume reasonably well. Ketterings (2001) suggested that site-specific HT:DBH relationships were required for accurate biomass estimates of mixed secondary forests in Indonesia. There are also indications that climatic regime can influence HT:DBH allometry. Hydraulic limitation theory predicts that tree height is ultimately limited by water availability, and thus gradients in maximum tree height may be expected to coincide with rainfall distribution (RYAN; PHILLIPS; BOND, 2006). Such differences in volume estimation caused by HT:DBH relationship observed could hold important implications for carbon storage potential of tropical formations. Relationships between architecture and forest structure were stronger than those with climatic variables (BANIN et al., 2012). Other studies have also shown that forest structural characteristics can improve the estimation of height–diameter curve parameters (FANG; BAILEY, 1998).

Even though intensity light has not been used as an independent variable in the linear models, volume is strongly influenced by this variable in the semideciduous and ombrophilous forests. Light exposure was an important factor influencing variables such as DBH, total height, crown size and volume considering this two forest types. Cerrado, even though height classes were divided into different strata (see chapter 1), did not show strong relationship between light exposure and structure variables. Overall, light availability cannot be said to have been an important selection force acting on architectural changes with tree height (STERCK; BONGERS, 2001). However, Biging and Dobbertin (1992), for example, demonstrated that the competition can have a considerable impact on height growth. The ombrophilous forest, as seen in the chapter 1, showed the highest tree density and dominance which is likely related to tree competition, ruling as an important reason determining the forest structure and dynamic. This forest type, probably as a result of genetic pattern of the species, site conditions and competition, showed higher trees volume at a given crown area when compared to the other two forest types, as well as the strongest relationship Height:Crown area. On the other hand, Cerrado had lower volume at any given crown size, indicating a different potential to allocate resources compared to the wet forests formations.

Remote-sensing techniques offer the most practical approach to estimating forest biomass and monitoring changes in forest structure over large heterogeneous areas (CHAMBERS et al., 2007). Gering and May (1995), for example, have used the crown diameter/DBH relationship of a species for estimating DBH or basal area from crown diameters measured from aerial photographs or other methods of remote sensing. Suitable and feasible models were achieved to determine volume based on crown size and total height, indicating a potential approach on predicting volume in natural tropical vegetation formations using remote sensing techniques. This allometric relationship is of practical significance since volume can be easily predicted from crown size.

If systematic failures in residual plots to examine regression models are found, then models may need to be reformulated to find a better fitting model. Residuals that seem to increase or decrease in average magnitude with the fitted values might indicate non-constant residual variance. A few relatively large residuals may be indicative of outliers, cases for which the model is somehow inappropriate (WEISBERG, 2005). Also, as a direct consequence of the heterogeneity of the variance it is not possible to attach the usual meaning to the statements of tests of significance or confidence limits.

The least squares method of regression analysis is valid only if the assumptions of conditional normality, homogeneity of variance, and randomness in sampling are fulfilled. According to Munro (1964), in tree volume table construction the most important assumption is probably the homogeneity of variance. A way of correcting for the non-homogeneity of the variance, and apparently a better one since it is unbiased is to estimate the regression coefficients by the method of weighted least squares. However, there is few formal treatment of the method of weighted least squares in today's literature of forest mensuration, showing why and when it is better than the least squares method and what is the best set of weights to use in each particular case, specially applied to tropical natural formations.

It should be kept in mind when using allometric equations that many sources of errors are possible. The sources of bias which can create additional errors are the range of observations, the bias of logarithm transformation and data source (BIGING, 1988; DJOMO, 2010).

In summary, our results illustrate the importance of complexity in modeling. To achieve good predictive ability, it is important to use a parsimonious model. Model selection techniques can aid in the selection of the most parsimonious model but consideration should be given to using the most appropriate model selection criterion. Additionally, model selection does not prevent a poor model or the combination of a strong data-specific effect. To assess predictive ability we maintain that as often as possible models should be tested against independent data. This was not possible with the current study because of the cost of collecting additional data. There is a growing tendency for simulation models to become more complex. It is important for both model developers and models users to remember that more complex models do not always result in better predictive models.

These DBH-based and crown-based volume equations should be used for the forest type which data were performed in. We are hoping that these will improve the quality in predicting the stem volume, and contributes to the conservation and management to the São Paulo State forests.

3.4.2 Taper equation

A well behaved taper equation should not only give unbiased estimates of diameter with a minimum variance, but also have flexibility to adapt to a wide variety of species and give accurate predictions of stem volume (KOZAK; SMITH, 1993). The trigonometric taper equation herein proposed presented good fit to estimate the diameter at any height, especially at the base and lower stem. The different stem shape observed in natural forests in Brazil varies considerably from the stem form in European and North American trees, commonly used to describe the stem form in forests in other studies. This is partly due to species differences and also due to the fact that multi-stemmed trees are common in our study areas. The taper equation developed in this manuscript, using the relative diameter at the base, permitted estimating more precisely this diameter (of all stem segments at a given relative height) than other taper equations, especially observing residuals plots. It is a two-parameter model, as is Biging's taper equation, so it is parsimonious as well. It is important to emphasize that Kozak, Demaerschalk and Biging models were developed to describe single stem profiles for conifer species. On the other hand, the model herein proposed was developed to predict directly multi-stemmed profiles, estimating equivalent diameters of all stem segments at a given relative height in the case of multiple stems tree. Therefore, a likely reason for using the equation for multi-stemmed trees is to estimate volume until a determined height.

For Thomas and Parresol (1991) studying bole forms, trigonometric functions provide impressive flexibility, parsimony and potential utility and for these reasons it is suggested that trigonometric functions may be considered for developing and applying taper functions for many species. According to Bi (2000), a trigonometric variable-form taper model has overcome the weakness of unstable specification in the variable form taper models introduced by some other authors. The construction of the base function from trigonometric volume-ratio equations follows the geometry of a tree stem and is also constrained to pass through a certain point of the stem. It has three trigonometric variables for depicting changes in stem form along the stem and three other variables for taking into account differences in stem form between trees of different sizes. These characteristics have provided the flexibility observed in the model in fitting data without resorting to variable selection for species and trees from a range of growth conditions and with varying stem forms. This flexibility is particularly useful for minimizing local bias and improving global prediction accuracy.

The relative height of the inflection point (where the taper curve changes from neiloidal to paraboloidal) on the predicted stem profile changed according to the forest type. The inflection point decreased in cerrado, while semideciduous and ombrophilous inflection points occurred on increased heights. Considering trees of same total height and diameter at the base, the mean shape of the individuals in Cerrado have larger diameters than in other forest types studied up to about 70% of the height. On the other hand, these individuals have the highest decreasing rate of diameter along the stem. In semideciduous forest and dense ombrophilous are more similar each other, but we can note how constant the rate of change is in the midrange portion of the stem for the semideciduous forest. Above approximately 70%

of the total height, the individuals in general in this forest type presented more volume in the upper stem compared to the other forests, and they exhibit an abrupt decrease in taper next to the tip.

Various factors are needed to judge which model is more accurate and precise. By graphics plotted we can see that the model herein proposed estimated more precisely the taper of the largest diameter trees compared with the other taper-based models, moreover this equation showed better values of standard error of the estimate.

Whole tree volume model might provide better estimates of whole tree volume, but cannot be used to predict volume by section (BIGING, 1984). A 2 parameter model developed can be considered as a parsimonious model that can be used to predict to directly yield cubic meter volume estimates to any height. Thus, it appears that for this data set the taper-based volume estimates can be used in lieu of whole tree volume equations with little or no loss in accuracy for this set of data. Therefore, it is necessary and beneficial to further study the characteristics of taper profile equations and extend their use to other species besides the ones for which they were originally developed. Monitoring the status of all species and assessing their viability is impossible from a practical standpoint. Therefore, is important to consider that only one model for each forest type was generated in order to become accessible the volume determination in natural forests. As the management of native forests becomes increasingly intensive, accurate estimates of stem volume and taper will be needed for complex vegetation structures.

3.5 **Conclusion**

Suitable models were fitted to modeling volume in the three forest types based on two approaches: DBH-based models and crown-based models. Weighted least squares were used in order to decrease heteroskedasticity problems when necessary and combinations of high-correlated variables not used to avoid multicollinearity effect.

The trigonometric taper equation proposed in this chapter enhanced diameter and volume predictions when observing visual plots, percent overpredictions, standard error of the estimate and bias compared to other taper equations. The taper equation is not integrable, however whole-volume can be obtained by determining volume sections. The equation has been the first proposed to estimate taper in natural vegetation formations in Brazil. Models parameters were estimated for communities instead of species, aiming at unbiased estimations in each forest type. Taking into consideration the advantages and limitations of the taper equation, the determination of the proper volume depends on the requisite accuracy, the complexity and the effort in the field.

References

AVERY, T.E.; BURKHART, H.E. **Forest measurements**. New York: McGraw-Hill, 2002. 408 p.

BANIN, L.; FELDPAUSCH, T.R.; PHILLIPS, O.L.; BAKER, T.R.; LLOYD, J.; AFFUM-BAFFOE, K.; ARETS, E.; BERRY, N.J.; BRADFORD, M.; BRIENEN, R.J.W.; DAVIES, S.; DRESCHER, M.; HIGUCHI, N.; HILBERT, D.W.; HLADIK, A.; IIDA, Y.; ABU SALIM, K.; KASSIM, A.R.; KING, D.A.; LOPEZ-GONZALEZ, G.; METCALFE, D.; NILUS, R.; PEH, K.S.H.; REITSMA, J.M.; SONKE, B.; TAEDOUMG, H.; TAN, S.; WHITE, L.; WOLL, H.; LEWIS, S.L. What controls tropical forest architecture? Testing environmental, structural and floristic drivers. **Global Ecology and Biogeography,** Oxford, v. 21, n. 12, p. 1179-1190, Dec. 2012.

BI, H.Q. Trigonometric variable-form taper equations for Australian eucalypts. **Forest Science,** Washington, v. 46, n. 3, p. 397-409, Aug. 2000.

BIGING, G.S. Taper equations for second growth mixed conifers of northern California. **Forest Science,** Washington, v. 30, n. 4, p. 1103-1117, 1984.

______. Estimating the accuracy of volume equations using taper equations of stem profile. **Canadian Journal of Forest Research,** Ottawa, v. 18, n. 8, p. 1002-1007, Aug. 1988.

BIGING, G.S.; DOBBERTIN, M. A comparison of distance-dependent competition measures for height and basal area growth of individual conifer trees. **Forest Science,** Washington, v. 38, n. 3, p. 695-720, Aug. 1992.

BOX, G.E.P.; COX, D.R. An analysis of transformations. **Journal of the Royal Statistical Society Series B-Statistical Methodology,** Oxford, v. 26, n. 2, p. 211-252, 1964.

BURKHART, H.E. Suggestions for choosing an appropriate level for modelling forest stands. In: AMARO, A.; REED, D.; SOARES, P. **Modelling forest systems**. Cambridge: CABI Publ., 2003. chap. 1, p. 3-10.

CHAMBERS, J.Q.; ASNER, G.P.; MORTON, D.C.; ANDERSON, L.O.; SAATCH, S.S.; ESPIRITO-SANTO, F.D.B.; PALACE, M.; SOUZA, C. Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests. **Trends in Ecology & Evolution,** Amsterdam, v. 22, n. 8, p. 414-423, Aug. 2007.

CHAVE, J.; ANDALO, C.; BROWN, S.; CAIRNS, M.A.; CHAMBERS, J.Q.; EAMUS, D.; FOLSTER, H.; FROMARD, F.; HIGUCHI, N.; KIRA, T.; LESCURE, J.P.; NELSON, B.W.; OGAWA, H.; PUIG, H.; RIERA, B.; YAMAKURA, T. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. **Oecologia,** Berlin, v. 145, n. 1, p. 87-99, Aug. 2005.

CLUTTER, J.L.; FORTSON, J.C.; PIENAAR, L.V.; BRISTER, G.H.; BAILEY, R.L. **Timber management:** a qualitative approach. New York: John Wiley, 1983. 333 p.

DEMAERSCHALK, J.P. Converting volume equations to compatible taper equations. **Forest Science,** Washington, v. 18, n. 3, p. 241-245, 1972.

DJOMO, A.N.; IBRAHIMA, A.; SABOROWSKI, J.; GRAVENHORST, G. Allometric equations for biomass estimations in Cameroon and pan moist tropical equations including biomass data from Africa. **Forest Ecology and Management,** Amsterdam, v. 260, n. 10, p. 1873-1885, Oct. 2010.

FANG, Z.X.; BAILEY, R.L. Height-diameter models for tropical forests on Hainan Island in southern China. **Forest Ecology and Management,** Amsterdam, v. 110, n. 1/3, p. 315-327, Oct. 1998.

GERING, L.R.; MAY, D.M. The relationship of diameter at breast height and crown diameter for four species groups in Hardin County, Tennessee. **Southern Journal of Applied Forestry,** Washington, v. 19, n. 4, p. 177-181, 1995.

HUSCH, B.; BEERS, T.W.; KERSHAW JR., J.A. **Forest mensuration**. 4th ed. New Jersey: John Wiley, 2002. 433 p.

KETTERINGS, Q.M.; COE, R.; VAN NOORDWIJK, M.; AMBAGAU, Y.; PALM, C.A. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. **Forest Ecology and Management,** Amsterdam, v. 146, n. 1/3, p. 199-209, June 2001.

KING, D.A. Allometry and life history of tropical trees. **Journal of Tropical Ecology,** Cambridge, v. 12, p. 25-44, Jan. 1996.

KOZAK, A.; SMITH, J.H.G. Standards for evaluating taper estimating systems. **Forestry Chronicle,** Ottawa, v. 69, n. 4, p. 438-444, Aug. 1993.

KOZAK, A.; MUNRO, D.D.; SMITH, J.H.G. Taper functions and their application in forest inventory. **Forestry Chronicle,** Ottawa, v. 45, n. 4, p. 278-283, 1969.

LINDSTROM, M.J.; BATES, D.M. Nonlinear mixed effects models for repeated measures data. **Biometrics,** Washington, v. 46, n. 3, p. 673-687, Sept. 1990.

MACDICKEN, K.G.; WOLF, G.V.; BRISCOE, C.B. **Standard research methods for multipurpose trees and shrubs**. Little Rock: Winrock International Institute for Agricultural Development, Forestry/Fuelwood Research and Development Project, 1991. 93 p.

MUNRO, D.D. Weighted least squares solutions improve precision of tree volume estimates. **The Forestry Chronicle,** Ottawa, v. 40, n. 3, p. 400-401, 1964.

MYERS, N.; MITTERMEIER, R.A.; MITTERMEIER, C.G.; FONSECA, G.A.B. da; KENT, J. Biodiversity hotspots for conservation priorities. **Nature,** London, v. 403, n. 6772, p. 853-858, 2000.

NOGUEIRA, E.M.; NELSON, B.W.; FEARNSIDE, P.M.; FRANCA, M.B.; OLIVEIRA, A.C.A. Tree height in Brazil's 'arc of deforestation': shorter trees in south and southwest Amazonia imply lower biomass. **Forest Ecology and Management,** Amsterdam, v. 255, n. 7, p. 2963-2972, Apr. 2008.

PENMAN, J.; KIKAN, C.K.S.K. **Definitions and methodological options to inventory emissions from direct human-induced degradation of forests and devegetation of other vegetation types**. Kanagawa: Institute for Global Environmental Strategies for the IPCC, 2003. 32 p.

R CORE TEAM. **A language and environment for statistical computing**. Vienna: R Foundation for Statistical Computing, 2012.

RYAN, M.G.; PHILLIPS, N.; BOND, B.J. The hydraulic limitation hypothesis revisited. **Plant Cell and Environment,** Oxford, v. 29, n. 3, p. 367-381, Mar. 2006.

SEGURA, M.; KANNINEN, M. Allometric models for tree volume and total aboveground biomass in a tropical humid forest in Costa Rica. **Biotropica,** Washington, v. 37, n. 1, p. 2-8, Mar. 2005.

STERCK, F.J.; BONGERS, F. Crown development in tropical rain forest trees: patterns with tree height and light availability. **The Journal of Ecology,** Oxford, v. 89, n. 1, p. 1-13, Feb. 2001.

THOMAS, C.E.; PARRESOL, B.R. Simple, flexible, trigonometric taper equations. **Canadian Journal of Forest Research,** Ottawa, v. 21, n. 7, p. 1132-1137, July 1991.

VAN LAAR, A.; AKÇA, A. **Forest mensuration**. Dordrecht: Springer, 2007. 377 p.

VON SEGGERN, D.H. **CRC handbook of mathematical curves and surfaces**. Boca Raton: CRC Press, 1990. 388 p.

WEISBERG, S. **Applied linear regression**. 3rd ed. New Jersey: John Wiley, 2005. 283 p.

4 A GEOMETRIC FORM METHOD FOR TAPER PROFILES TO DETERMINE STEM VOLUME WITHOUT LOGGING TREES

Abstract

This work presents the geometric method to estimate volume in tropical natural forests. Proposed by Andrade and Leite (1998) for *Eucalyptus* commercial forests, the methodology is based on analytic geometric principles, permitting the volume determination without logging trees. From the volume results obtained by minimizing the error, lower section and upper section diameters were defined and heights of the upper diameters were modeled based on total height. By measuring the diameters at the base, at breast height, at lower section and upper section diameters and total height, it becomes possible to obtain the slope coefficients between those measured points and estimate any other diameters along the stem. Comparing to the observed volume by percent overpredictions, bias and standard error of estimate, those estimated values described positively the method to create volume tables.

Keywords: Geometric form modeling; Volume tables; Analytic geometry

4.1 Introduction

The development of more efficient techniques of mensuration in tropical forests is an important mechanism for conservation, management and production advancement. Difficult access and the cost of obtaining a large number of samplesneeded for accurate wood volume and biomass determination due to high variability, are often barriers for carrying out inventories and studies in natural forests in Brazil. The absence of knowledge of the tropical forests conditions and storages are another obstacle for profitable and non-profit organizations in planning Cerrado and Atlantic forest management, hotspots in terms of biodiversity and endemism. Moreover, difficulties in assessing data quality in forest inventories lead to continuing debate on the functional response of tropical forests to global change (BAKER et al., 2004).

The geometric method originally proposed by Andrade and Leite (1998) in *Eucalyptus* commercial forests in Brazil, is one alternative to obtain individual tree volume precisely and accurately without harvesting trees. In natural forests the method has never been carried out in inventories for prediction, however it would be a method whose aim is a reduction in expenses and time of data acquistion for volume determination. According to Scolforo and Thiersh (2004), the geometric method is advantageous for permitting measurement of the diameters of stand of trees using dendrometers.

According to Andrade and Leite (1998), between the diameter at breast height (DBH) and total height exists a point that creates two intervals above DBH, which can be measured and which minimize the error of taper estimation. It is a result of matching sections of the tree whose taper can be well represented by a straight line approximation. In general, this method should be appropriate for all sections except for the base of trees with excessive basal flare.

In this chapter we explore the possibility of using this geometric method in tropical natural forests. Our general objective is to evaluate this methodology to estimate wood volume in cerrado, semideciduous and dense ombrophilous forests. As specific objective we intend determine and model the lower section and and upper section diameters and interval slopes along the stem which minimize the error in volume prediction by using the geometric method.

4.2 Material and methods

4.2.1 Sample tree selection and measurement arrumar a numeração

The same individual trees selected for estimating the taper equation were used in this chapter to develop a volume prediction using the geometric method and test its applicability (see chapter 2). In essence the geometric method develops a taper approximation that can be used to estimate volume using solid of revolution technique. Therefore, 52 stems in Mogi Guaçu Biological Reserve (cerrado), 53 in Caetetus Ecological Station (semideciduous forest) and 55 in "Carlos Botelho" State Park (dense ombrophilous forest) were measured for volume using the electronic dendrometer Criterion RD 1000 (Laser Technology, Inc., USA), an optical instrument that provides real-time results for calculations of the tree height and diameters along the stem. The dendrometer uses the angular measurement and the horizontal distance to the target tree to calculate the diameter of the tree stem at any height. According to Husch, Beers and Kershaw Jr. (2002), the volume of the stem can also be calculated with good accuracy using Smalian´s formula if the stem is divided into short sections. Measurements included the portion of the stem above 0.1 meters height, herein defined as the base, and every stem was measured at 0.1, 0.3, 0.7, 1.3 meters and constant intervals of 1 meter above 1.3 m up to a minimum 5 cm stem diameter outside bark. Above the last point, the volume was computed using a cone formula. Thus, the total volume is the sum of the stem volume sections and the tip cone volume.

4.2.2 Geometric form method development

In order to determine lower section (between the base of the tree and diameter at breast height) and upper section (between the diameter at breast height and total height) diameters to minimize volume estimation errors, we calculated diameters using the taper formula proposed in the second chapter, defined by the following equation:

$$\mathrm{Di} = \mathrm{D_B}\cos^{-1}\left[(1-\beta_0)\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{\beta_1} + \beta_0\left(\frac{\mathrm{Hi}}{\mathrm{HT}}\right)^{0.05\beta_0}\right]^2 \qquad (4.1)$$

Considering individual trees, diameters were predicted by trigonometric taper equation (4.1) along the stem at each 0.1 meters in height. To calculate volume we first identified portions of the tree with various geometric shapes, as frustums of neiloids and paraboloids, according to the Figure 4.1.

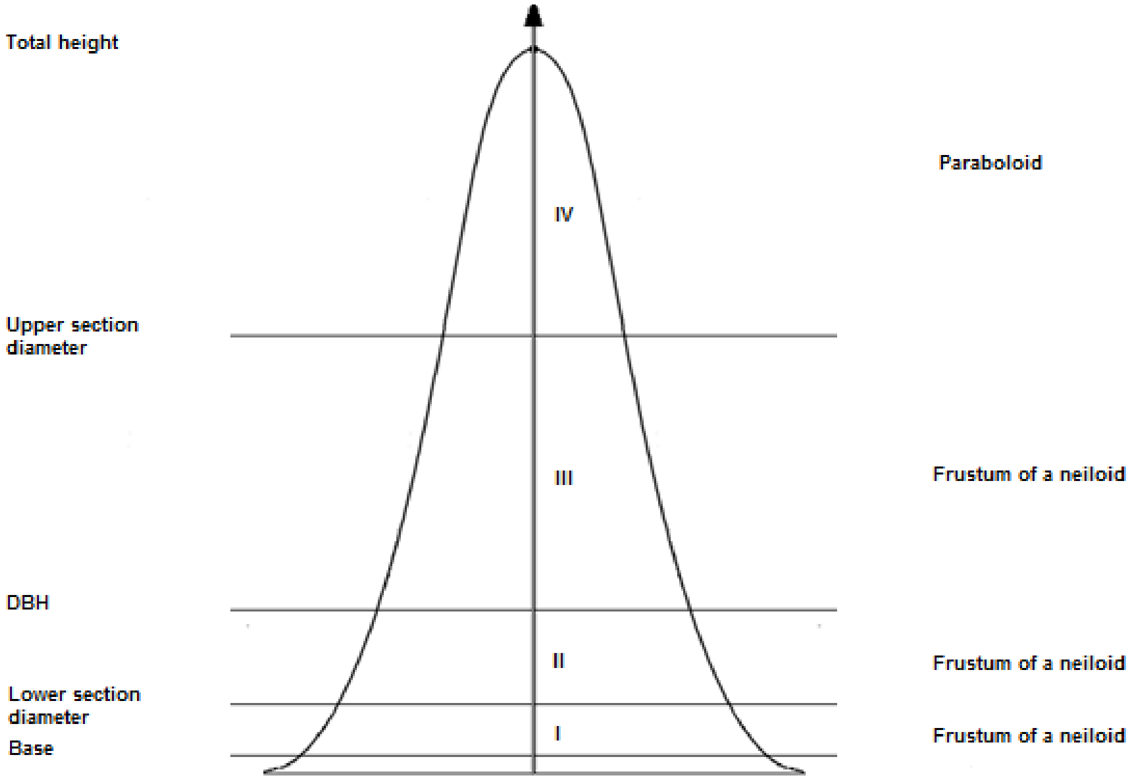

Figure 4.1 - A tree stem profile representing the points to be measured and intervals of lines interseccion

To determine the lower portion diameter, we can obtain the lower stem volume using equation 4.2. Is important to emphasize that intervals I and II in the Figure 4.1 may be considered as frustums of neiloids, therefore lower portion volume must be calculated using a frustum of neiloid's formula. Using the method of Andrade and Leite (1998) we minimize the error in volume estimation for the individual tree. We do this by finding the "best" location (i.e. relative height) of the upper section diameter and lower section diameter (see Figure 4.1) that minimizes the error in volume estimation for the tree. These two diameter measurements are augmented with DBH, base diameter and tip diameter to create a quintuplet of relative height and diameter meausrements. From this collection of measurements we can then create a taper equation by using linear equations of tree form for sections I to IV (Figure 4.1).

$$\mathrm{V_{LP}} = \frac{\mathrm{BA_B} + \mathrm{BA_{LD}} + \sqrt[3]{\mathrm{BA_B} * \mathrm{BA_{LD}}^2} + \sqrt[3]{\mathrm{BA_B}^2 * \mathrm{BA_{LD}}}}{4}(\mathrm{H_{LD}} - \mathrm{H_B}) + \frac{\mathrm{BA_{LD}} + \mathrm{BA_{DBH}} + \sqrt[3]{\mathrm{BA_{LD}} * \mathrm{BA_{DBH}}^2} + \sqrt[3]{\mathrm{BA_{LD}}^2 * \mathrm{BA_{DBH}}}}{4}(\mathrm{H_{DBH}} - \mathrm{H_{LD}}) \qquad (4.2)$$

Let V_{LP} = Lower portion volume, BA_B = Basal area at the base, BA_{LD} = Basal area at the lower section diameter, BA_{DBH} = Basal area at diameter at breast height (DBH), H_B = Height of the tree base (0.1 meters was used as the base height), H_{LD} = Height of the lower section diameter, H_{DBH} = 1.30 meters.

In Figure 4.1, interval III may be considered as a frustum of a neiloid, and the interval IV as a paraboloid when estimating volume, therefore equation 4.3 calculates volume according to the frustum of a neiloid and a paraboloid formulae. We have a number of candidate upper section diameters from which we select the optimum location (relative height) that minimizes the volume estimation error of the upper stem segments.

$$\mathrm{V_{UP}} = \frac{\mathrm{BA_{DBH}} + \mathrm{BA_{UD}} + \sqrt[3]{\mathrm{BA_{DBH}} * \mathrm{BA_{UD}}^2} + \sqrt[3]{\mathrm{BA_{DBH}}^2 * \mathrm{BA_{UD}}}}{4}(\mathrm{H_{UD}} - \mathrm{H_{DBH}}) + \frac{\mathrm{BA_{UD}}}{2}(\mathrm{HT} - \mathrm{H_{UD}}) \qquad (4.3)$$

Let V_{UP} = Upper portion volume, BA_{DBH} = Basal area at the diameter at breast height (DBH), BA_{UD} = Basal area at the upper portion diameter, H_{DBH} = Height of the diameter at breast height (1.30 meters), H_{UD} = Height of the upper portion diameter, HT = total tree height.

In order to calculate the slope between those points, we can use equations 4.4, 4.5, 4.6, 4.7 and 4.8 for each portion of the stem. The diameter at the base, DBH and lower section and upper section diameters used to calculate slopes were the observed values. After determining the heights of the lower section and upper section diameters, we can estimate the diameters at those points using linear interpolation technique in order to approximate to the observed values.

$$S_{I} = \frac{2\ H_{LD} - 2\ H_{B}}{D_{LD} - D_{B}} \qquad (4.4)$$

$$S_{II} = \frac{2\ H_{DBH} - 2\ H_{LD}}{D_{DBH} - D_{LD}} \qquad (4.5)$$

.

$$S_{III} = \frac{2\ H_{UD} - 2\ H_{DBH}}{D_{UD} - D_{DBH}} \qquad (4.6)$$

$$S_{IV} = \frac{2\ HT - 2\ H_{UD}}{0 - D_{UD}} \qquad (4.7)$$

Let S_{I} = slope between the base (H_{B}) and lower section diameter (H_{LD}), S_{II} = slope between the lower section diameter (H_{LD}) and DBH(H_{DBH}), S_{III} = slope between DBH (H_{DBH}) and upper section diameter ((H_{UD}) and S_{IV} = slope between the upper section diameter (H_{UD}) and total height (HT).

Is important to consider that S_I and S_{II} is uniquely necessary to be calculated when the volume is minimized by measuring a lower section diameter. In this context, using a lower section diameter for predictions in Cerrado and semideciduous forest enhanced the volume estimation, as described in the Table 4.1. In the dense ombrophilous forest no intermediate diameter point was able to improve the volume prediction. Therefore, the lower portion slope can be calculated using the following formula:

$$S_{I-II} = \frac{2\ H_{DBH} - 2\ H_{B}}{DBH - D_{B}} \qquad (4.8)$$

Let S_{I-II} = slope between the base (H_B) and DBH (H_{DBH}).

After calculating slopes along the stem, we can determine the diameter at any height using transformations of the slope formulae. For any height, diameters can be calculated using the slope of some portion of the stem that a determined point is part of. The formulae 4.9, 4.10, 4.11, 4.12 and 4.13 describe how diameters are calculated.

$$\mathrm{D_I} = \mathrm{D_B} + \frac{2\ \mathrm{H_{LD}} - 2\ \mathrm{H_B}}{\mathrm{S_I}} \qquad (4.9)$$

$$\mathrm{D_{II}} = \mathrm{DBH} + \frac{2\ \mathrm{H_{DBH}} - 2\ \mathrm{H_{LD}}}{\mathrm{S_{II}}} \qquad (4.10)$$

$$\mathrm{D_{III}} = \mathrm{DBH} + \frac{2\ \mathrm{H_{UD}} - 2\ \mathrm{H_{DBH}}}{\mathrm{S_{III}}} \qquad (4.11)$$

$$\mathrm{D_{IV}} = -\frac{2\ \mathrm{HT} - 2\ \mathrm{H_{UD}}}{\mathrm{S_{IV}}} \qquad (4.12)$$

In “Carlos Botelho” State Park, dense ombrophilous forest, in the interval between the base and DBH, diameters at height can be calculated using:

$$\mathrm{D_{I-II}} = \mathrm{D_B} + \frac{2\ \mathrm{H_{DBH}} - 2\ \mathrm{H_B}}{\mathrm{S_{I-II}}} \qquad (4.13)$$

With form modeling approach in this chapter we can determine the volume of sections of the tree using frustums of paraboloids after obtainning diameters at any height. Smalian’s equation, which was derived for fustrums of paraboloids, is appropriate when taper is linear in a given section. Comparisons of the geometric method based-volume with the observed volume were performed using RCore Team (2012) software.

4.2.3 Criteria of model evaluation

We used the commom statistics of average bias and percent standard error of the estimate (RMSE) to evaluate the goodness of fit for the system.

− Percent standard error of estimate (%) $$\frac{\sqrt{\frac{\sum\left(\mathrm{Di}-\widehat{\mathrm{Di}}\right)^2}{\mathrm{n}}}}{\overline{\mathrm{Vobs}}} * 100$$

− Bias (%) $$\frac{\sum\left(\mathrm{Di}-\widehat{\mathrm{Di}}\right)}{\mathrm{n}} * 100$$

− Percent overprediction (%) $$\frac{\widehat{\mathrm{Vol}}-\mathrm{Vobs}}{\mathrm{Vobs}} * 100$$

Where $\widehat{\mathrm{Di}}$ is predicted diameter at height Hi and Di is the actual measurement at point i on the bole; n = number of individuals; Vobs = Scaled volume; $\overline{\mathrm{Vobs}}$ = Average scaled volume; and $\widehat{Vol}$ = Predicted volume.

4.3 **Results**

4.3.1 Lower section and upper section diameters estimation

Optimal heights for measuring the lower stem diameter were calculated for each forest type (Table 4.1). In the lower portion of the stem, between the base and DBH, the measurement that minimizes the estimation error in the lower stem varies according to the site. In cerrado, for individuals less than 3.2 meters in height, the best point to obtain the metric is at 0.4 meters. For individuals higher than 3.2 meters in total height, the best point is at 0.5 meters. In Caetetus Ecological Station, the semideciduous forest, the point between the base and DBH was 0.5 meters of height for all of the trees. For ombrophilous forest in Carlos Botelho State Park DBH and diameter at the base of the tree are used to minimize the error in the lower stem.

Table 4.1 - Heights of the lower section diameter of the stem to be measured in order to minimize the volume prediction error by the use of the geometric method for Cerrado, semideciduous and dense ombrophilous forests. Let H_{LD} = Height of the lower section diameter, and HT = total height

Item	**Forest type**		
	Cerrado	**Semideciduous**	**Ombrophilous**
H_{LD}	0.4m (HT < 3.2m) 0.5m (HT $\geq$ 3.2m)	0.5m	No lower section diameter

Heights of the upper section diameter between DBH and total height were calculated in order to minimize the error of estimation (Figure 4.2) for upper stem volumes. The plot of upper section diameter location (h(m)) versus total height follows the same relationship for the semideciduous and dense ombrophilous forests. Cerrado had a different curve slope indicating that the locations (h(m)) of the upper stem diameters were larger for trees of a given total height than in the semideciduous and dense ombrophilous forests.

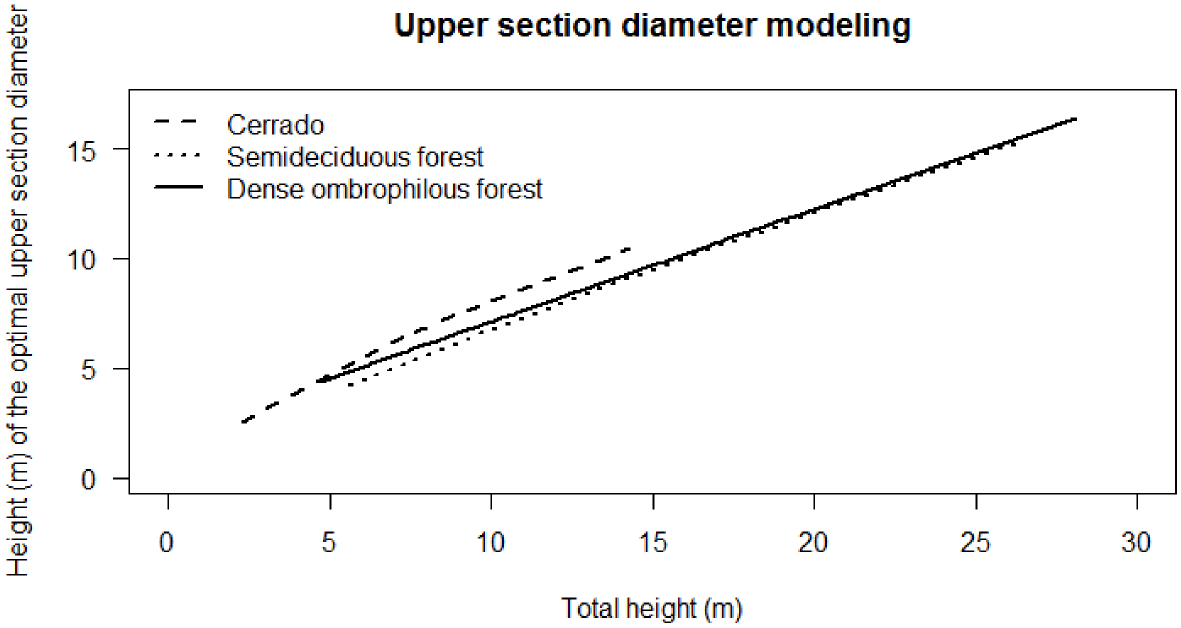

Figure 4.2 - Relationship between the optimal location of heights (m) for measuring the upper section diameter locations and total tree height for the three forest types

After determining the best point in the upper stem, simple linear models were developed to estimate the height of the upper diameter stem using total height as the explanatory variable (Table 4.2). The models below represent the equations to predict the point necessary to have the diameter measured in order to minimize the error volume prediction using the geometric method in each forest type. Equation 4.14 was developed for Cerrado to estimate the height of the upper section diameter, equation is 4.15 for semideciduous forest and equation 4.16 is for dense ombrophilous forest. Statistics and estimated coefficients are presented in the Table 4.2.

$$H_R = \beta_0 + \beta_1\sqrt{HT} \qquad (14)$$

$$\ln H_R = \beta_0 + \beta_1 \ln HT \qquad (15)$$

$$H_R = \beta_0 + \beta_1 HT \qquad (16)$$

Table 4.2 - Coefficients and fit statistics for Cerrado, semideciduous and dense ombrophilous forests to estimate the optimal height of the upper section diameter by using total height as the explanatoy variable. Let: n= number of individuals; and adj.R^2= adjusted coefficient of determination

	Forest type		
Item	**Cerrado**	**Semideciduous**	**Ombrophilous**
β_0	-3.3907	-0.0118	1.9885
β_1	3.6348	0.8356	0.5133
n	52	53	55
adj.R^2	0.9898	0.9996	0.9985

4.3.2 Comparisons of scaled versus predicted volumes

Figure 4.3 is a graph of the estimated volume versus actual volume in the three forest types. The volumes derived from the geometric form models estimated the actual volume quite well. Estimated values are similar to the observed volume, even though the variance tends to increase for larger diameter individuals, as evaluated by the standard residuals plot (Figure 4.4). Incoherent points in the standardized residuals-based plot were identified to infer about the quality of the geometric form method. In Cerrado, the species *Ficus citrifolia* presented overpredicted volume, because its upper section diameter had the diameter measured exactly on a widened portion of the stem due to bifurcation. On the other hand, the individual of the species *Copaifera langsdorffii* was underpredicted using the geometric form method. In the field work this individual was identified as having four stems, which probably interfered with in its growth and presented a different behavior in comparison to other individuals of the same species. In the semideciduous forests, *Ficus enormis* had an overprediction caused by buttressing. In the dense ombrophilous forest, a specific individual belonging to the species *Alchornea triplinervea* was overpredicted using the geometric form method to estimate volume. Due to a high steep surface, the tree developed a structure in the lower portion of the stem to support its growth, whose behavior was similar to buttresses found in Ficus enormis in the semideciduous forest.

Figure 4.5 shows the percent overprediction of the geometric form method based volume plotted with the DBH. The species that had high standardized residuals also showed high percent overpredictions.

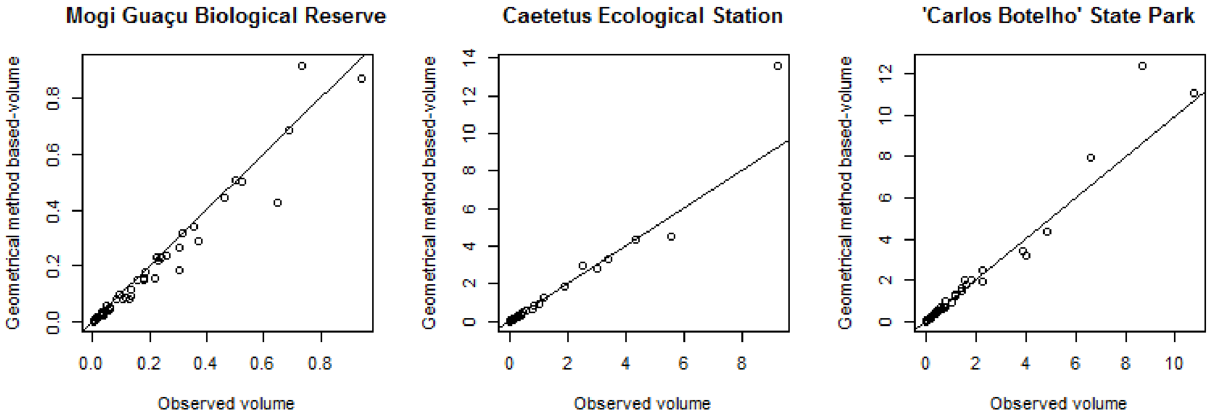

Figure 4.3 – Volume (m^3) based on the geometric form method versus observed volume (m^3) for the three forest types

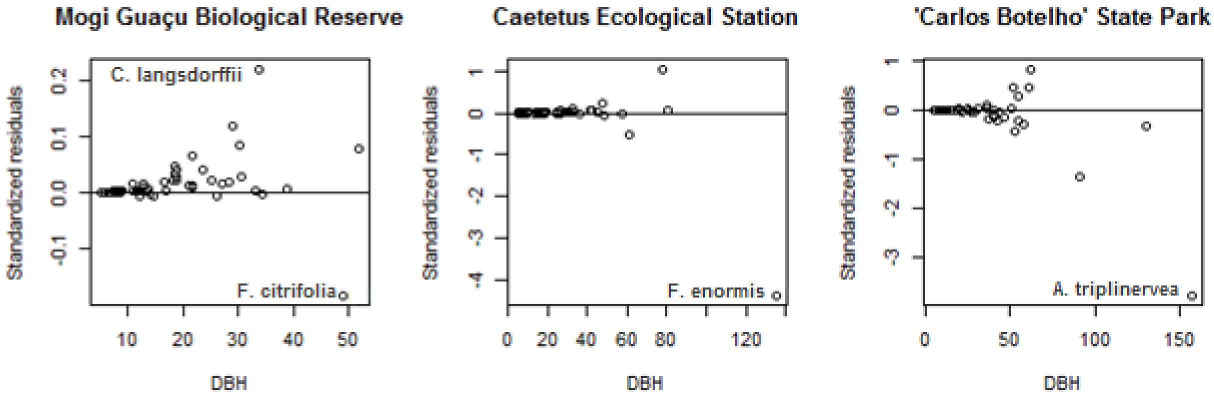

Figure 4.4 – Standardized residuals of volume prediction (m^3) by the use of the geometric form method versus DBH (cm) for the three forest types

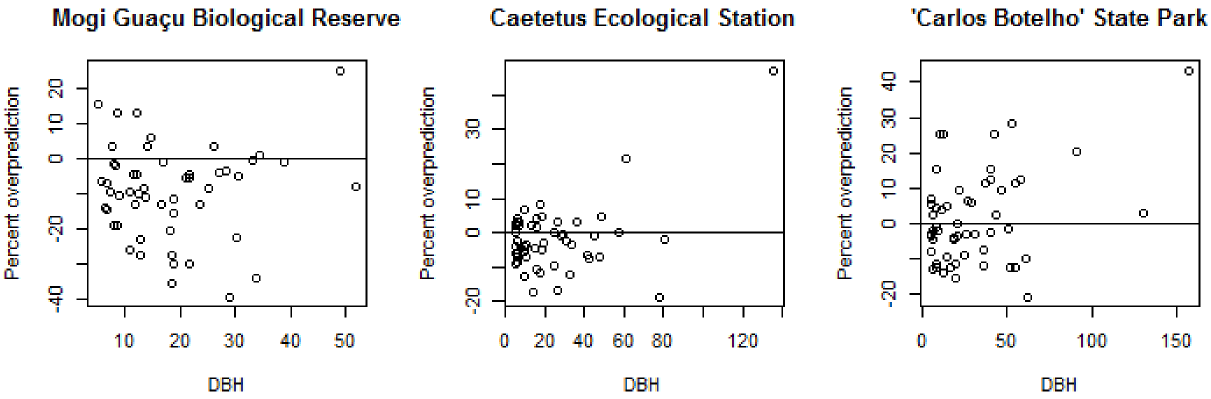

Figure 4.5 - Percent overpredictions (%) by the use of the geometric form method versus DBH (cm) for the three forest types

The average percent overpredictions, standard error of estimate and average bias by forest type (cerrado, semideciduous and dense ombrophilous forests) were calculated (Tables 4.3, 4.4 and 4.5). The classes were divided according to the principal component analysis performed in the first chapter to separate classes according to the number of individuals, number of species and basal area. The results were better for some forest types than for others. The percent overpredictions have no fixed pattern among the three study sites. For example, in Cerrado (Table 4.3), for every diameter class the geometric form method for volume estimation tends to underpredict the volume, maintaining constantly the percentage among the diameter class, resulting in -9.59% overall overprediction. In semideciduous forest (Table 4.4), the geometric form method for volume estimation overpredicted only for the largest individuals, but did not vary by diameter class, resulting in an underprediction of the volume by 1.87%. In dense ombrophilous forest (Table 4.5), the percent overprediction values increase by the DBH class, tending to overpredict more for the largest individuals. In general, the method resulted in an overall overprediction of the volume only for the dense ombrophilous forest, especially considering larger diameter individuals, while the method underpredicts the volume for the other two forest types. Cerrado showed the highest values of overprediction.

The calculations of bias showed that the highest bias in volume obtained by the geometric form method occurred in the largest diameter classes in the dense ombrophilous forest. Large diameters in the semideciduous forest also presented highly biased estimation. In general, the three forest types showed low overall percentage bias, even though the directions of bias can vary by diameter class. Overall bias was lower in cerrado, aproximating the volume' expectation to the observed values while, in terms of direction and values, the semideciduous and dense ombrophilous forests had similar trends. Similar to the results of the overall bias by species, the percent standard error of the estimate in the semideciduous and ombrophilous forests had a similar pattern, in comparison to the Cerrado. Using the geometric form method to estimate volume, the percentage standard error of the estimate was higher for larger individuals, exceptly for Cerrado with similar values in the middle class size to larger diameter class. The overall percentage standard error of the estimate was high for all of the three forest types in larger diameter classes, indicating a low precision of the method in obtaining the volume in large diameter individuals, even though this method is an accurate method as shown by the bias values. As presented previously, a factor that contributed to lowering the precision in the geometric method is due to different structures in some stems, including butressing and widened stem caused by bifurcations, influencing the geometric form method for estimating volume.

Table 4.3 – Overall and per DBH class number of individuals (n), average observed volume (V_m), average percent overpredictions (%), standard error of the estimate (RMSE (%)) and average bias (%) in the Mogi Guaçu Biological Reserve in cerrado

DBH class (cm)	**n**	**V_m (m^3)**	**Overprediction (%)**	**RMSE (%)**	**Bias (%)**
5 ≤ DBH < 7.9	9	0.014192	-5.92	10.17	0.07
8 ≤ DBH < 19.9	25	0.074821	-11.56	22.98	1.04
20 ≤ DBH	18	0.417688	-8.67	19.28	2.96
Overall	52	0.183012	-9.59	26.70	1.54

Table 4.4 - Overall and per DBH class number of individuals (n), average observed volume (V_m), average percent overpredictions (%), standard error of the estimate (RMSE (%)) and average bias (%) in the Caetetus Ecological Station in semideciduous forest

DBH class (cm)	**n**	**mean (m^3)**	**Overprediction (%)**	**SSE (%)**	**Bias (%)**
5 ≤ DBH < 9.9	19	0.013437	-1.81	6.08	0.03
10 ≤ DBH < 34.9	23	0.272980	-4.25	9.76	1.09
35 ≤ DBH	11	3.078036	3.03	44.32	-31.67
Overall	53	0.762117	-1.87	81.59	-6.09

Table 4.5 - Overall and per DBH class number of individuals (n), average observed volume (V_m), average percent overpredictions (%), standard error of the estimate (RMSE (%)) and average bias (%) in the "Carlos Botelho" State Park in semideciduous forest

DBH class (cm)	n	mean (m^3)	Overprediction (%)	SSE (%)	Bias (%)
5 ≤ DBH < 9.9	16	0.016997	-0.06	11.42	0.01
10 ≤ DBH < 54.9	32	0.741846	1.51	18.88	-2.03
55 ≤ DBH	7	5.626514	5.15	27.83	-58.76
Overall	55	1.160273	1.52	49.44	-8.78131

4.4 Discussion

In order to reduce the dependence on destructive measurements or to speed field measurements of stem form, the geometric form method developed in this chapter can be used in conjunction with a dendrometer to provide height and diameter measurments at specific locations that define critical points on the stem taper curve which we term the geometric form model. Individual tree volume estimates can then be derived from the geometric form models. Using the geometric form method, forest mensurationists have a simpler (i.e. more cost effective) technique to obtain lower section and upper section diameters since only a quintuplet of diameter-height measurements need to be taken to define taper and derive volume for individual trees. A large fraction of a tree's total wood volume is concentrated in the lower stem, where the diameters tend to be larger. For some forests, measuring both DBH and a diameter below 1.3 meters and the diameter at the base can minimize the error in volume estimation.

The taper equation used to estimate the volume and find the lower section and upper section diameters was estimated to minimize the error for the entire forest community, not for specific species. According to Fang and Bailey (1999), it is important to evaluate the bias of the volume estimates. Large positive and negative biases at different classes may cancel and give zero bias for the forest community. The stem form differs according to the species, varying in terms of height and diameters along the height. However, the geometric form method does not focus on a specific species, but on the community, seeking unbiased estimation of taper-based volume. Moreover, some considerations should be made. Chave et al. (2004) consider imprecision of the measurements and some structures in the stem as sources of error. The primary source of error in volume estimation is due to diameter measurement error of natural forest trees when using dendrometers. This is especially true when measuring tortuous and multi-stemmed individuals. Another source of error is measurements on bifurcations, which probably have diameter overestimates when measuring above those structures. *Ficus citrifolia* in Cerrado is an example of this problem in the volume prediction.The geometric form method for volume estimation requires an accurate taper equation and approximation to it using a quintuplet of height-diameter points. For hard to model trees such as those with basal flare (butressing) or multi-stems, the inaccuracies in the taper equation for these trees can lead to biased volume estimation using the taper equation proposed in the second chapter.

Trees with low amounts of buttressing are easier to model than those with significant butressing. Tree butressing occurs in specific species of tall trees and it is generally believed that buttressing serves as tension support for tree boles. There is also a tendency for trees on steep slopes to produce buttresses on their slope side (YOUNG; PERKOSHA, 1994). The issue of estimating the biomass of large buttressed trees cannot be solved by simply replacing diameters (NGOMANDA, 2012). First, large trees are prone to hollows that detract from the cross-sectional area (NOGUEIRA; NELSON; FEARNSIDE, 2006). Second, using to predict biomass will depend on how trees were measured to derive the biomass equations. Because biomass data sets most often mix buttressed trees that are measured above the buttresses and non-buttressed trees that are measured at breast height (CHAVE et al., 2005), the uncertainty on the height of measurement is included in the prediction error of the biomass equation. Reducing this uncertainty would require clear documentation of the measurement and appropriate allometric relationships (SILLETTET et al., 2010).

The geometric form method is not equally accurate in estimating volume of all species, as can be visualized for some species in the three forest types. The two *Ficus* species and *Alchornea triplinervea* identifyed in the study had a high overprediction problem, not being well estimated by the method, as well as the species *Copaifera langsdorffii,* which were underpredicted using this method.

Percent overprediction shows that the method does not vary greatly by DBH size, with the exeception of butressed individuals. Good estimates of volume and carbon stocks in natural forests mean that they have low uncertainty and do not overestimate, according to the IPCC guidelines (PEARSON et al., 2008). Overall bias and percent overpredictions for all forest types suggest a high suitability in the use of the geometric method in estimating total tree volume, and might be considered as a “conservative” methodology in estimating volume by IPCC guidelines. This method can be used to predict volume above a specified height, including branches up to 5 cm of diameter. The excessive number of branches in almost every trees in Cerrado, semideciduous and dense ombrophilous forests can be an obstacle for measuring the trees correctly. Thus, the geometric method which needs a small number of diameter measurements at specific lower and upper sections heights is faster (more efficient in time and money) in comparison to taking diameter measurents at fixed intervals of heights.

This chapter of the thesis develops a relatively accurate and precise method for determining total tree volume in tropical natural forests. Many trees in the forests studied are multi-stemmed. To date, there is no effective way to model the taper profile of multi-stemmed trees. That is why the method developed in this thesis uses the geometric average of the diameters of the multi-stems at fixed heights (see Chapter 2). Then the geometric average diameter at lower section and upper section diameters, along with DBH, base diameter and diameter at the tip are used in estimating volume.

This study has determined the optimal lower section and upper section diameters for minimizing errors in volume estimation. With this method, in future studies a larger number of trees can be measured with standard volume estimation methods which require measuring diameters at fixed intervals of height. According to Chave et al. (2004), with larger samples we can reduce the sampling uncertainty, and with a larger number of plots it is possible to reduce allometric uncertainty. Nonetheless, larger trees should be carefully estimated using the methodology herein explored due to buttressing and bifurcation structures, and especially if the diameter exceeds the range for which the use of the method is valid.

4.5 **Conclusions**

There are at least two weaknesses of the geometric form method of volume estiamation: (1) the geometric method depends on the precision and accuracy of the taper equation used to estimate the point that is characterized by the minimum error of the volume using the method. Some species present a biased volume estimation using the taper equation, even though we have obtained an unbiased estimation for the community, as observed in the second chapter; (2) the method needs to be avoided in trees that have excessive butressing or are widened along the stem. Those structures are factors that cause an overestimation of the diameter along the stem, modifying primarily the prediction of the height for measuring the lower section and upper section diameters important in estimating volume with this method.

Nonetheless the geometric form method of volume estimation is accurate and precise when measured over all trees and is recommended for the forest types studied.

References

ANDRADE, V.C.L.; LEITE, H.G. Uso da geometria analítica para descrever o taper e quantificar o volume de árvores individuais. **Revista Árvore,** Viçosa, v. 25, n. 4, p. 481-486, 1998.

BAKER, T.R.; PHILLIPS, O.L.; MALHI, Y.; ALMEIDA, S.; ARROYO, L.; DI FIORE, A.; ERWIN, T.; HIGUCHI, N.; KILLEEN, T.J.; LAURANCE, S.G.; LAURANCE, W.F.; LEWIS, S.L.; MONTEAGUDO, A.; NEILL, D.A.; VARGAS, P.N.; PITMAN, N.C.A.; SILVA, J.N.M.; MARTINEZ, R.V. Increasing biomass in Amazonian forest plots. **Philosophical Transactions of the Royal Society of London Series B-Biological Sciences,** London, v. 359, n. 1443, p. 353-365, Mar. 2004.

CHAVE, J.; CONDIT, R.; AGUILAR, S.; HERNANDEZ, A.; LAO, S.; PEREZ, R. Error propagation and scaling for tropical forest biomass estimates. **Philosophical Transactions of the Royal Society of London Series B-Biological Sciences,** London, v. 359, n. 1443, p. 409-420, Mar. 2004.

CHAVE, J.; ANDALO, C.; BROWN, S.; CAIRNS, M.A.; CHAMBERS, J.Q.; EAMUS, D.; FOLSTER, H.; FROMARD, F.; HIGUCHI, N.; KIRA, T.; LESCURE, J.P.; NELSON, B.W.; OGAWA, H.; PUIG, H.; RIERA, B.; YAMAKURA, T. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. **Oecologia,** Berlin, v. 145, n. 1, p. 87-99, Aug. 2005.

FANG, Z.X.; BAILEY, R.L. Compatible volume and taper models with coefficients for tropical species on Hainan Island in southern China. **Forest Science,** Washington, v. 45, n. 1, p. 85-100, Feb. 1999.

HUSCH, B.; BEERS, T.W.; KERSHAW JR., J.A. **Forest mensuration**. 4th ed. New Jersey: John Wiley, 2002. 433 p.

NGOMANDA, A.; MAVOUROULOU, Q.M.; OBIANG, N.L.E.; IPONGA, D.M.; MAVOUNGOU, J.F.; LEPENGUE, N.; PICARD, N.; MBATCHI, B. Derivation of diameter measurements for buttressed trees, an example from Gabon. **Journal of Tropical Ecology,** Cambridge, v. 28, p. 299-302, May 2012.

NOGUEIRA, E.M.; NELSON, B.W.; FEARNSIDE, P.A. Volume and biomass of trees in central Amazonia: influence of irregularly shaped and hollow trunks. **Forest Ecology and Management,** Amsterdam, v. 227, n. 1/2, p. 14-21, May 2006.

PEARSON, T.; BROWN, S. Estimation of above ground carbon stocks. In: NATURAL RESOURCES CANADA**. GOFC-GOLD:** reducing greenhouse gas emissions from deforestation and degradation in developing countries: a sourcebook of methods and procedures for monitoring, measuring and reporting GOFC-GOLD. Report version COP13-2, GOFC-GOLD Project Office. Alberta, 2008. chap. 2, p. 40-62.

R CORE TEAM. **A language and environment for statistical computing**. Vienna: R Foundation for Statistical Computing, 2012.

SCOLFORO, J.R.S.; THIERSCH, C.R. **Biometria florestal:** medição, volumetria e gravimetria. Lavras: UFLA; FAEPE, 2004. 285 p.

SILLETT, S.C.; VAN PELT, R.; KOCH, G.W.; AMBROSE, A.R.; CARROLL, A.L.; ANTOINE, M.E.; MIFSUD, B.M. Increasing wood production through old age in tall trees. **Forest Ecology and Management,** Amsterdam, v. 259, n. 5, p. 976-994, Feb. 2010.

YOUNG, T.P.; PERKOCHA, V. Treefalls, crown asymmetry, and buttresses. **Journal of Ecology**, Oxford, v. 82, n. 2, p. 319-324, 1994.

APPENDIX

Useful R scripts:

##Principal Component Analysis to height or diameter stratification

```
dados=cbind(Ind,Spe,BA)#Ind=number of individuals;Spe=number of species;BA=basal area
PC1=princomp(dados,cor=TRUE);PC1
summary(PC1, loadings=TRUE)
plot(PC1, main=” Principal components variance proportion”)
biplot(PC1,choices = 1:2,scale = 0,var.axes=TRUE,cex = rep(par("cex"),1),
expand=1,pc.biplot = FALSE,col = c("black", "black"),main="First component versus second
component", xlab="First component",ylab="Second component" )
biplot(PC1,choices = 2:3,scale = 0,var.axes=TRUE,cex = rep(par("cex"),2),
expand=1,pc.biplot = FALSE,col = c("grey", "red"),main="Componente 2 versus
Componente 3", xlab="Second component",ylab="Third component")
```

##Volume modeling using weighted least squares

```
library(MASS) # package for evaluating the best transformation using box-cox
boxcox(model)

model=lm(log(Volume)~log(DBH)+log(HT)+I(1/(DBH*(HT^0.5))),weights=(DBH))
summary(model)
AIC(model) #Akaike information Criterion

plot(Volume,exp(fitted(model))) #plotting observed versus predicted volume
abline(0,1)
plot(DBH,(exp(fitted(model))-V),ylab = "Volume error (cubic meter)",
   xlab = "DBH (centimeter)",las=1) #plotting volume error prediction versus DBH
abline(h=0)
plot(DBH,((exp(fitted(model))-V)*100)/Volume,ylab = "Percent overprediction (%)",
   xlab = "DBH (centimeter)", col="black") #plotting percent overprediction versus DBH
```

```
abline(h=0)

v_RMSE <- (sum((exp(fitted(model))-V)^2)/length(Volume))^(1/2);v_RMSE*100/mean(Volume) #standard error of the estimate
bias <- ((sum(exp(fitted(model))-Volume))/length(Volume))*100; bias #percent bias

plot(DBH,Volume,xlim=c(0,160),ylim=c(0,11),"n",xlab="Diameter at breast height (centimeter)", ylab="Estimated volume (cubic meter)", main="Volume modeling")
lines(lowess(exp(fitted(model))~DBH),lwd=2,lty=3) #plotting the model
```

##Prediction and confidence intervals for evaluating models

```
f <- predict(model,interval = "confidence", level = 0.95)
ff <- predict(model,interval = "prediction", level = 0.95)
fit <- f[,1] #
lower <- f[,2] # lower limit
upper <- f[,3] # upper limit
y <- (Volume) # dependent variable
plot(fit, y,main="Intervals",xlab="fitted log(Volume)",ylab="log(Colume)")
abline(0, 1, lty = 2)
ord <- order(fit)
lines(fit[ord], lower[ord])
lines(fit[ord], upper[ord])
fit <- ff[,1] #
lower <- ff[,2] # Lower limit
upper <- ff[,3] # Upper limit
abline(0, 1, lty = 2)
ord <- order(fit)
lines(fit[ord], lower[ord],lty=3) # dotted lines
lines(fit[ord], upper[ord],lty=3) # dotted lines
legend("topleft",legend=c("Confidence","Prediction"),lty=c(1,3),bty="n")
```

##Taper modeling

```
#Demaerschalk relative diameter estimation
reldiameter=nls((d/dbh)^2~(10^(2*b1))*(dbh^(2*b2-2))*((ht-h)^(2*b3))*(ht^(2*b4)), start=c(b1=0.09,b2=0.94,b3=0.42,b4=-0.44))
summary(reldiameter)

# Volume estimation by Demaerschalk taper equation
#Hi=Height at any position on the stem
#bn=parameter n
ombroDemaer_v = function(DBH, HT, Hi){
  b1 = 0.13446
  b2 = 1.02004
  b3 = 0.69421
  b4 = -0.78206
  (pi/40000) * 10^(2*b1) * DBH^(2*b2) * HT^(2*b4) * ((HT-0.1)^(2*b3+1)-(HT-Hi)^(2*b3+1))/(2*b3+1)
}
```