INSTITUTO NACIONAL DE PESQUISAS DA AMAZÔNIA - INPA
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COMPREENDENDO OS EFEITOS DE CARACTERÍSTICAS TOPOEDÁFICAS SOBRE A PRODUTIVIDADE DO SÍTIO EM PLANTIOS DE *Bertholletia excelsa* Bonpl. NO AMAZONAS

ALEX SOARES DE SOUZA

Manaus, Amazonas
Março, 2020

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Orientador: Dr. Marciel José Ferreira

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Sinopse

Confirmou-se a aplicabilidade de modelos não lineares para classificação de sítios em plantios de *B. excelsa*, com maior precisão e estabilidade obtida pelo modelo Chapman-Richards. A variação na produtividade do sítio foi influenciada principalmente pela textura do solo, topografia, concentrações de K^+, Mn^{2+} e pH_{KCl}. Os resultados encontrados deverão subsidiar o planejamento adequado das atividades operacionais relacionadas às etapas de implantação e condução dos povoamentos de *B. excelsa* no Amazonas, além de contribuir para identificação de áreas potenciais para a expansão de plantios desta espécie.

Palavras chave: Castanheira da amazônia, plantios de produção, índice de sítio, altura dominante.

Dedico aos meus queridos pais

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RESUMO

A classificação de sítios florestais é pré-requisito para a seleção de espécies e definição de estratégias de manejo de povoamentos florestais. No entanto, mesmo para as espécies florestais nativas mais plantadas na região amazônica, a exemplo da Castanheira da amazônia (*Bertholletia excelsa* Bonpl.), a variação na qualidade dos sítios é pouco conhecida. O objetivo geral deste estudo foi verificar se a variação na qualidade do solo e topografia influencia a produtividade do sítio em plantios de *B. excelsa*. Foram comparados diferentes modelos não-lineares para classificar a capacidade produtiva de povoamentos de *B. excelsa* de diferentes idades (14 a 21 anos) localizados no município de Itacoatiara, Amazonas. Para tanto, utilizamos o método da diferença algébrica aplicado a um banco de dados oriundo de 75 parcelas temporárias e da análise completa de tronco de 30 árvores. Em campo, foram feitas medições de resistência do solo à penetração e coletadas amostras de solo nas profundidades de 0-20 cm e 20-40 cm para análises química e física do solo. As informações topográficas foram obtidas a partir de GPS e processamento de imagens de modelo digital de elevação da Shuttle Radar Topography Mission (SRTM). Os modelos Schumacher, Chapman-Richards, Bailey-Clutter, Logístico, Gompertz e Hossfeld IV foram comparados usando estatísticas de erro padrão da estimativa em porcentagem, critério de Informação de Akaike, critério de Informação Bayesiano, análise gráfica dos resíduos e estabilidade entre as curvas polimórficas e anamórficas de cada modelo. As classes de sítio foram espacializadas na área de estudo usando o método de interpolação geoestatística por krigagem ordinária pontual. As relações entre as variáveis topoedáficas e os índices de sítio foram testadas por matriz de correlação e análise de componentes principais para identificar as características mais limitantes à produtividade do sítio. Modelos de regressão múltipla foram ajustados para avaliar se características topoedáficas explicam a variação de crescimento nos povoamentos florestais de *B. excelsa*. O modelo Chapman-Richards apresentou bom desempenho estatístico, boa distribuição de resíduos e resultou em curvas polimórficas que melhor representaram o comportamento da variável altura dominante em função da idade dos plantios. A avaliação do polimorfismo indicou padrão de crescimento diferenciado entre os sítios. As diferenças na capacidade produtiva dos sítios foram relacionadas principalmente à textura do solo e topografia. A variação na qualidade do sítio em povoamentos de *B. excelsa* foi explicada principalmente por características físicas do solo como teor de areia, altitude e, em menor magnitude, por características químicas como K^+, Mn^{2+} e pH_{KCl}. Os resultados encontrados deverão subsidiar futuras ações de planejamento de atividades operacionais relacionadas às etapas de implantação e condução dos povoamentos de *B. excelsa* no Amazonas, além de contribuir para a identificação de áreas potenciais à expansão de plantios desta espécie.

Palavras chave: Castanheira da amazônia; plantios de produção; índice de sítio; altura dominante.

ABSTRACT

Forest site classification is a crucial prerequisite for species selection and definition of management strategies in productive plantations. However, even for the most widely planted native forest species in Amazonia, such as Brazil nut (*Bertholletia excelsa* Bonpl.), the site quality still is little known. Here, we ask if the variation in soil quality and topography influences the site productivity in *B. excelsa* plantations. Nonlinear models were tested to classify the productive capacity of *B. excelsa* stands of different ages (14 to 21 years), from the algebraic difference method. We used a database of 75 temporary plots allocated on field and complete stem analysis of 30 trees. Chemical and physical soil analysis were realized at depths of 0-20 cm and 20-40 cm. Topographic information was obtained by GPS and digital elevation model image processing provided by Shuttle Radar Topography Mission (SRTM). Site classes were spatialized in the study area using the geostatistical interpolation method by ordinary point kriging. The relationships between topoedaphic variables and site index were evaluated by correlation matrix to identify the major characteristics limiting the site quality. In addition, regression models were adjusted to evaluate whether edaphic and topographical characteristics explain the growth variation in *B. excelsa* stands, with the identification of the best predictors by principal component analysis and stepwise backward method. The Chapman-Richards model presented a good statistical performance, a good distribution of residues and resulted in polymorphic curves that best represented the behavior of the dominant height variable over time. The polymorphism evaluation indicated a differentiated growth patterns among the sites. Soil texture (sand content) and topography (altitude) were the main drivers of site productivity. However, some chemical variables of the soil (K^+, Mn^{2+} and pH_{KCl}) also contributed to explaining the variation in the site productivity. The results can support the best planning of operational activities related to installation and management of *B. excelsa* stands in the Amazon, besides to identification of potential areas to expand the plantations of this important commercial tree species.

Keywords: Brazil nut; productive plantations; site index; dominant height.

SUMÁRIO

LISTA DE FIGURAS

LISTA DE TABELAS

INTRODUÇÃO

Bertholletia excelsa Bonpl. (Lecythidaceae), conhecida como Castanheira da amazônia, possui importância econômica, ecológica e social na região Amazônica (Salomão, 2014). O principal produto dessa espécie é a amêndoa, onde o extrativismo e o beneficiamento da castanha estão entre as principais fontes de renda de populações Amazônicas (Cronkleton et al., 2012). Entretanto, a espécie pode fornecer madeira de boa qualidade (Borém et al., 2009), quando proveniente de reflorestamentos para produção de madeira (Locatelli et al., 2015), apresentando crescimento relativamente rápido, com rotações estimadas entre 30 e 40 anos (Yared et al., 1993).

B. excelsa tem sido a espécie florestal mais utilizada em sistemas agroflorestais, se destacando entre as mais comuns por pequenos agricultores na região Amazônica (Hoch et al., 2009) e em projetos de reflorestamento de áreas degradadas (Costa et al., 2009; Ferreira et al., 2012; Scoles et al., 2011), à exemplo dos extensos plantios comerciais da espécie pertencentes à empresa Agropecuária Aruanã LTDA localizados na Amazônia Central (Ferreira et al., 2016).

Variações de crescimento da espécie têm sido registradas em plantios homogêneos ou consorciados na região Amazônica (Fernandes and Alencar, 1993; Costa et al., 2009; Ferreira and Tonini, 2009; Locatelli et al., 2015), que podem estar relacionadas em parte à qualidade diferenciada dos sítios, uma vez que, a combinação inadequada entre espécie e sítio pode acarretar baixa produtividade (Ferreira, 1990). Entretanto, a variação na qualidade dos sítios em plantios de *B. excelsa* ainda é pouco conhecida. E, para definir um melhor regime de gestão integrado, é necessário conhecer a qualidade dos sítios, pois dele depende a quantidade e qualidade da produção e a adaptabilidade da espécie a determinados locais (Caldeira et al., 1996).

O sítio florestal pode ser definido como o somatório dos fatores abióticos e bióticos que influenciam a produtividade de uma espécie florestal em um local ou região (Scolforo, 2006). Por sua vez, a qualidade do sítio florestal, é tida como a capacidade produtiva, podendo ser entendida como potencial de produção de madeira de determinada espécie com base em fatores ambientais (edáficos, climáticos e fisiográficos), bióticos, genótipo e práticas silviculturais (Silva et al., 2018).

A avaliação da qualidade de sítio é imprescindível para identificar o potencial produtivo da propriedade e fornecer base de referência para o diagnóstico e prescrição silvicultural (Burkhart & Tomé, 2012). O sítio, definido como menor unidade de planejamento, pode subsidiar estratégias mais específicas de manejo dos plantios, servindo de base para estratificação dos povoamentos para fins de inventário florestal e planejamento sustentável da exploração (Machado et al., 1997).

A classificação da capacidade produtiva ou qualidade de sítio pode ser realizada por métodos indiretos a partir de fatores ambientais ou por métodos diretos por meio do crescimento da floresta (volume, área basal e altura) (Scolforo, 1997). Dentre os métodos diretos, a altura dominante (H_d) é a variável universalmente utilizada, uma vez que possui alta correlação com a produção volumétrica de madeira, além de ser uma variável que não é muito influenciada pela densidade dos povoamentos e tratamentos silviculturais (Burkhart & Tomé, 2012; Ortega & Monteiro, 1988; Silva et al., 2018).

A capacidade produtiva pode ser expressa de forma quantitativa pelo índice de sítio, que é representada pela altura dominante do povoamento em uma idade referência (Ortega & Monteiro, 1988), onde a classificação direta por meio da altura dominante é realizada usando as curvas de índice de sítio (Silva et al., 2018). Essas curvas são construídas a partir de equações de índice de sítio, derivadas da relação funcional H_d = f(idade), sendo comumente utilizados modelos exponenciais ou sigmóides (Campos & Leite, 2013). Essas variáveis podem ser provenientes de parcelas permanentes, temporárias e/ou de análise completa de tronco, sendo as parcelas permanentes consideradas mais eficientes para detectar a variação de crescimento ao longo de várias idades, porém o uso de dados provenientes de análise completa de tronco pode ser uma boa alternativa em espécies com anéis de crescimento anuais visíveis (Carmean, 1996; Burkhart & Tomé, 2012), a exemplo da espécie *B. excelsa* (Brienen & Zuidema, 2005; Schöngart et al., 2015).

Existem vários métodos para construção de curvas de índice de sítio, como o método da curva guia e diferença algébrica (Scolforo, 1997). O primeiro gera apenas curvas anamórficas com distância proporcional entre as curvas e inclinação comum, assumindo que a tendência de crescimento para todos os sítios é a mesma (Campos & Leite, 2013). Entretanto, quando verificado indícios de polimorfismo, é apropriado o uso de curvas polimórficas (Silva et al., 2018), podendo ser utilizado o método da diferença algébrica para gerar curvas anamórficas ou polimórficas (Scolforo, 1997).

Diversos autores como Scolforo (1992), Cunha Neto et al. (1996), Palahí et al. (2004), Bravo-Oviedo et al. (2004), Carvalho & Parresol (2005), Kitikidou et al. (2011) e Silva et al. (2016), utilizaram o método da diferença algébrica para gerar curvas de índice de sítio e obtiveram bons resultados. Alguns destes estudos têm demonstrado a importância de realizar o teste de anamorfismo e verificar a estabilidade das curvas geradas para comprovar a eficiência dos modelos.

A classificação de sítios é fundamental para o planejamento florestal. Após definidas as classes de sítio, é mais importante ainda conhecer os principais fatores limitantes do crescimento dos plantios. Em relação aos fatores ambientais, as características edáficas e topográficas podem ser importantes indicadores da variação de produtividade dos povoamentos florestais (Scolforo, 1997; Corona et al., 1998). Estudos sobre a influência das propriedades edáficas no crescimento das árvores têm sido direcionados principalmente para definição de espécies a serem plantadas, indicações de práticas adequadas de manejo dos solos e de povoamentos florestais (Carvalho et al., 1999). Muitos estudos que descrevem a relação entre solo e índice de sítio, também têm utilizado características associadas ao solo como a topografia, não apenas indicando características importantes ao sítio, mas as utilizando para estimativa indireta da qualidade de sítio em áreas independentemente da cobertura vegetal existente (Carmean, 1971; Carmean 1975; Johnson et al., 2019). Diversos autores como Bila et al. (2012), Farrelly et al. (2011), Corona et al. (1998), Curt et al. (2001), McKenney & Pedlar (2003), Rigatto et al. (2005) e Louw & Scholes (2006) demonstraram que variáveis edáficas e topográficas como profundidade do solo, teor de argila, níveis de nutrientes, capacidade de retenção de água e inclinação explicaram a qualidade do sítio, conforme a espécie e o tipo de solo.

O conhecimento dos sítios de plantio e a definição de condições limitantes ao crescimento das espécies constituem pré-requisitos necessários para a implantação de reflorestamentos (Pancel, 2015). Apesar de *B. excelsa* ser uma das espécies nativas mais plantadas na região amazônica, não existem estudos de classificação de sítios para povoamentos desta espécie. Em países tropicais e subtropicais, dificilmente as espécies nativas são selecionadas para reflorestamento, devido principalmente à escassez de informações sobre ecologia e silvicultura dessas espécies (Costa et al., 2009). A falta de conhecimento técnico sobre a silvicultura e o manejo de espécies arbóreas nativas constituíram fatores limitantes para as empresas florestais e agricultores de pequena escala em quatro estados da Amazônia brasileira iniciarem novas experiências silviculturais (Walters et al., 2005).

Dessa forma, considerando que a qualidade do sítio é um fator importante para orientar práticas mais adequadas de manejo dos plantios, a classificação de sítios em povoamentos de espécies nativas pode contribuir para a expansão e aumento da produtividade dos plantios com objetivos de produção industrial na região Amazônica. O objetivo principal deste estudo foi avaliar a influência da qualidade do solo e topografia na produtividade do sítio em plantios de *B. excelsa*. Para isso, formulamos as seguintes questões: i) Modelos não lineares são capazes de classificar com precisão a capacidade produtiva de povoamentos de *B. excelsa* em diferentes idades? ii) Características edáficas (químicas e físicas) e topográficas explicam a variação no crescimento de povoamentos florestais de *B. excelsa*? Quais as características mais limitantes?

CAPÍTULO ÚNICO

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Understanding the effects of topoedaphic characteristics on site productivity in a *Bertholletia excelsa* Bonpl. plantation in Amazonas

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Title: Understanding the effects of topoedaphic characteristics on site productivity in a *Bertholletia excelsa* Bonpl. plantation in Amazonas

Abstract

Forest site classification is a crucial prerequisite for species selection and definition of management strategies in productive plantations. However, even for the most widely planted native forest species in Amazonia, such as Brazil nut (*Bertholletia excelsa* Bonpl.), the site quality still is little known. Here, we ask if the variation in soil quality and topography influences the site productivity in *B. excelsa* plantations. Nonlinear models were tested to classify the productive capacity of *B. excelsa* stands of different ages (14 to 21 years), from the algebraic difference method. We used a database of 75 temporary plots allocated on field and complete stem analysis of 30 trees. Chemical and physical soil analysis were realized at depths of 0-20 cm and 20-40 cm. Topographic information was obtained by GPS and digital elevation model image processing provided by Shuttle Radar Topography Mission (SRTM). Site classes were spatialized in the study area using the geostatistical interpolation method by ordinary point kriging. The relationships between edaphic variables and site index (SI) were evaluated by the correlation matrix to identify the major characteristics limiting the site productivity. In addition, regression models were adjusted to evaluate whether edaphic and topographical characteristics explain the growth variation in *B. excelsa* stands, with the identification of the best predictors by principal component analysis and *stepwise backward* method. The Chapman-Richards model presented a good statistical performance, a good distribution of residues and resulted in polymorphic curves that best represented the behavior of the dominant height variable over time. The polymorphism evaluation indicated a differentiated growth patterns of *B. excelsa* among the sites. Soil texture (sand content) and topography (altitude) were the main drivers of site productivity. However, some chemical variables of the soil (K^+, Mn^{2+} and pH_{KCl}) also contributed to explaining the variation in the site productivity. The results can support the best planning of operational activities related to installation and management of *B. excelsa* stands in the Amazon, besides to identification of potential areas to expand the plantations of this important commercial tree species.

Keywords: Brazil nut; productive plantations; site index; dominant height.

1. Introduction

Bertholletia excelsa Bonpl. (Lecythidaceae), known as Brazil nut, has high economic, ecological and social importance in the Amazon region (Salomão, 2014). The main product of this species is the nut, where the extraction and processing of nuts are among the main sources of income of Amazonian populations (Cronkleton et al., 2012). However, the species can provide good quality wood (Borém et al., 2009), when coming from reforestation for wood production (Locatelli et al., 2015), showing relatively fast growth, with estimated rotations between 30 and 40 years (Yared et al., 1993). *B. excelsa* has been the most widely used tree species in agroforestry systems, standing out among the most common by small farmers in the Amazon region (Hoch et al., 2009) and in reforestation projects for recovering degraded areas (Costa et al., 2009; Ferreira et al., 2012; Scoles et al., 2011), as an example the extensive commercial plantations of the species, the largest of the world, belonging to the Company Agropecuária Aruanã LTDA located in the Central Amazon (Ferreira et al., 2016).

Variations of growth of the species have been registered in homogeneous or intercropping plantations in the Amazon region (Fernandes and Alencar, 1993; Costa et al., 2009; Ferreira and Tonini, 2009; Locatelli et al., 2015), which may be related in part with the site quality. The appropriate species-site matching represents the greatest immediate gains in yield from forest plantations. However, the variation in site quality for *B. excelsa* plantations is still little known. Forest site can be defined as the sum of abiotic and biotic factors that influence the productivity of a forest species in a specific locality or region (Scolforo, 2006). The quality of the forest site is taken by the managers as a factor of production, *i. e.*, the potential for wood production of a given species based on environmental factors (edaphic, climatic, biotic and physiographic) (Silva et al., 2018).

The site quality evaluation is essential to identify the productive potential of the property and to provide a baseline for silvicultural diagnosis and prescription (Burkhart and Tomé, 2012). The site, when defined as the smallest planning unit in a plantation, can subsidize more specific stands management strategies, serving as a basis for stratification of stands for forest inventory and sustainable logging planning (Machado et al., 1997). The classification of productive capacity or site quality can be performed by indirect methods based on environmental factors or by direct methods through forest growth (volume, basal area and height) (Scolforo, 1997). Among the direct methods, the dominant height (H_d) is the universally used variable, since it has a high correlation with the volumetric production of wood, besides being a variable that is not much influenced by the density of stands and silvicultural treatments (Burkhart and Tomé, 2012; Ortega and Monteiro, 1988; Silva et al., 2018).

The productive capacity can be expressed quantitatively by the site index (SI), which is represented by the H_d of the stand at a reference age (Ortega and Monteiro, 1988; Silva et al., 2018). Site index curves are constructed from site index equations, derived from the H_d = f(age) functional relationship and exponential or sigmoid models are commonly used (Campos and Leite, 2013). The measurements can be obtained from permanent, temporary plots and/or the complete stem analysis, being that permanent plots are considered more efficient for detecting growth variation over various ages, but the use of data derivate of complete stem analysis may be a good alternative in species with visible annual growth rings (Carmean, 1996; Burkhart and Tomé, 2012), such as *B. excelsa* (Brienen and Zuidema, 2005; Schöngart et al., 2015).

There are several methods for constructing site index curves, such as the guide curve and algebraic difference (Scolforo, 1997). The first method generates only anamorphic curves with a proportional distance between curves and similar slope, assuming that, the growth trend for all sites is the same (Campos and Leite, 2013). However, when evidence of polymorphism is found, the use of polymorphic curves is more appropriate (Silva et al., 2018). The algebraic difference method has been widely used in the literature (Scolforo, 1992; Cunha Neto et al., 1996; Palahí et al., 2004; Bravo-Oviedo et al., 2004; Carvalho and Parresol, 2005; Kitikidou et al., 2011 and Silva et al., 2016). Some of these studies have demonstrated the importance of performing the anamorphism test and verify the stability of the generated curves to ensure the efficiency of the models.

Site classification is crucial for forest planning. After defining the site classes, it is even more important to know the main limiting factors for plant growth. Topoedaphic characteristics may be important indicators of forest productivity (Scolforo, 1997; Corona et al., 1998). Many studies that describe the relationship between edaphic characteristics and SI have also used the topography, to indirectly estimate the quality of the site in areas regardless of vegetation cover existing (Carmean, 1971; Carmean 1975; Johnson et al., 2019). In this sense, topoedaphic variables such as soil depth, clay content, nutrient concentration, water retention capacity and slope have been important drivers of site quality (Bila et al., 2012; Farrelly et al., 2011; Corona et al., 1998; Curt et al., 2001; McKenney and Pedlar, 2003; Rigatto et al., 2005; Louw and Scholes, 2006).

Thus, considering that site quality is an important factor in guiding more appropriate stands management practices, the classification of sites for commercial Amazonian tree species can contribute to the expansion and increase of yield from industrial plantations in the region. Our specific objectives were: i) analyze if nonlinear models accurately predict the productive capacity of *B. excelsa* plantations and, ii) identify what topoedaphic characteristics are more linked to the growth variation of *B. excelsa* plantations.

2. Materials and methods

2.1. Study site

The study was realized in a forest plantation of Brazil nut (*B. excelsa*) belong to the Agropecuária Aruanã LTDA Company located in Itacoatiara, Amazonas, Brazil (3° 0'30.63” S and 58° 50'1.50” W). The company has the largest commercial plantation of *B. excelsa* around the world. The climate of the region according to Köppen classification system (Köppen 1948) is Am, with annual precipitation greater than 2,000 mm and an average temperature of 27.4 °C. The average precipitation regime from 1998 to 2019 was characterized by two distinct periods, the first with high precipitation, with a monthly average of 340 mm (January to May) and the second with low precipitation, with a monthly average of 70 mm (August to September) (Figure 1). The predominant soil is clayey yellow Latosol (Oxisol) (Kato, 1995), with a predominance of very clayey texture (Ferreira et al., 2016).

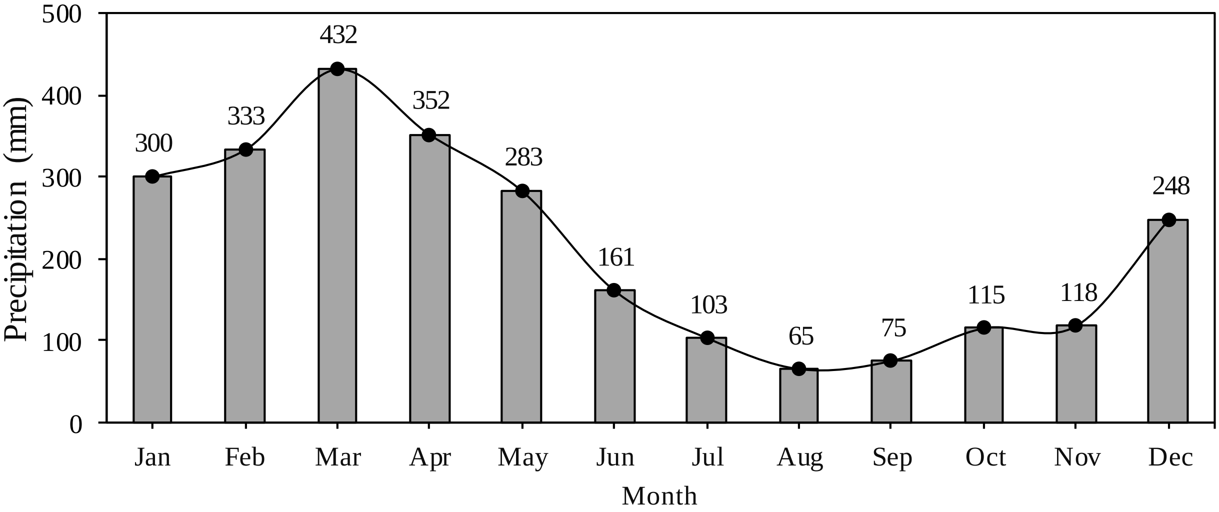


Fig. 1. Monthly average of precipitation between 1998 and 2019 in Itacoatiara-AM. (Courtesy of National Institute of Meteorology - INMET).

The *B. excelsa* plantations has about 939,000 trees planted in dense spacing (2.5 m x 1.5 m) for wood production (Ferreira et al., 2016), without fertilization and liming practices. The plantations were installed between 1998 and 2005 from seedlings with ages between 12 and 18 months and an average size of 40 cm, comprising an approximate area of 352.2 hectares. However, the present study was carried on 185.26 hectares where the age varied between 14 and 21 years, covering 27 plots with areas of 0.54 to 23.17 hectares, relatively well distributed on the property (Figure 2).

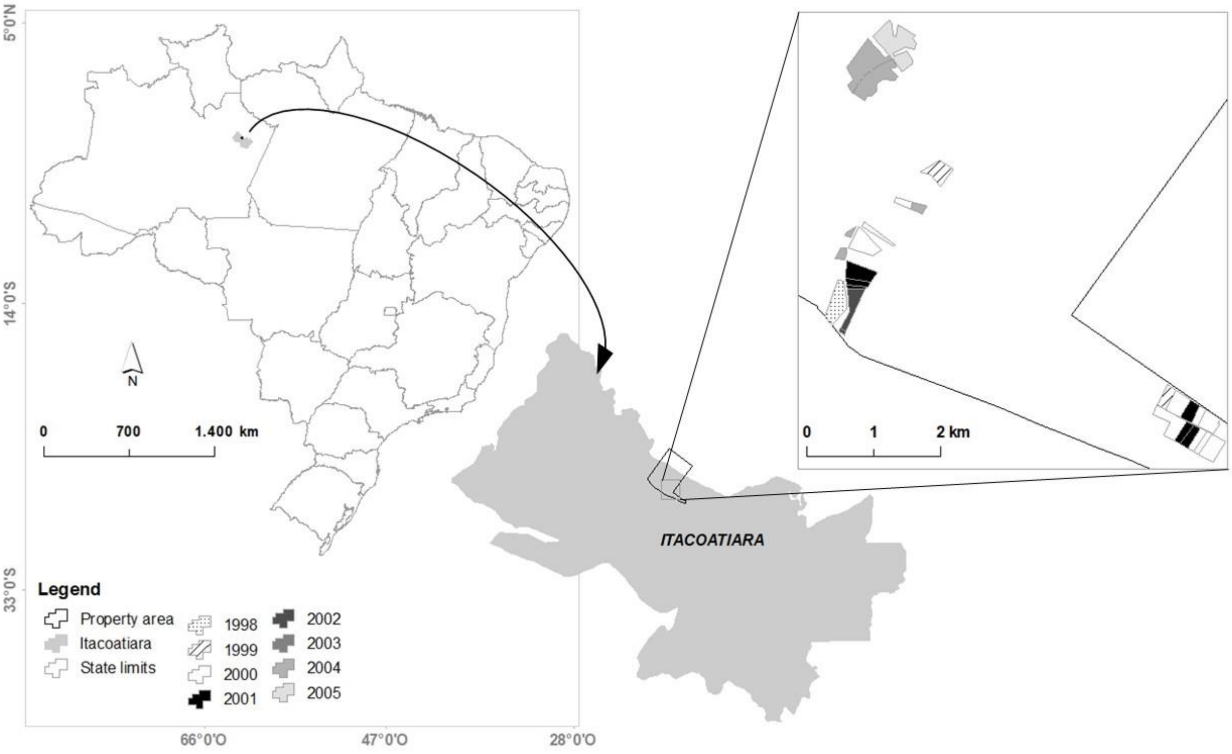


Fig. 2. Location map of the study area with the distribution of plots according to the year of planting.

2.2. Dendrometric measurements

Dendrometric measurements and sample collections were made in June 2019. The dominant height (H_d) was obtained according to Assmann concept, which is taken as the average height of the 100 trees with the largest diameter per hectare (Assmann, 1971). The sampling was systematic, where 75 plots of 300 m² (10 m x 30 m) were uniformly distributed in the study area, keeping a border of at least 20 m. Thus, in each plot the total height of three dominant trees was measured with the Haglöf hypsometer (Haglöf Sweden®, Model ECII, Sweden). The sample intensity was 1 plot per 2.47 hectares, maintaining a minimal distance of 150 m among plots. Complete stem analysis was made on 30 trees from 30 randomly selected plots to complement the database. For this, among the three dominant trees of each plot, one tree of average diameter closer to the value of plot was felled.

Discs of 4 cm thickness were collected for complete stem analysis at heights of 0.1 m, 0.7 m, 1.3 m and every 2 m until the first fork or every 1 m for trees smaller than 9 meters. After air drying, the surface of each sample was mechanically polished with grit sandpaper up to 600 grit, dust removed from the vessels with compressed air. Next, we moistened the cross-sectional surface of the samples to improve the visibility and contrast of the growth rings (Schöngart et al., 2015), that were characterized by alternating fiber and parenchyma bands. The growth ring boundaries were examined microscopically in 3 radii for counting and measuring the rings widths and to avoid anomalies such as discontinuous growth zones (Brienen and Zuidema, 2005) by a digital measuring device (LINTAB, Rinntech®, Germany) to the nearest 0.01 mm (Schöngart et al., 2015). To estimate the position at which annual height growth ceased within a stem section and obtain height at each age, the Tree Annual Radial Growth (TARG) method was used (Kariuki, 2002).

2.3 Adjustments and evaluation of models and site classification

The data obtained from temporary plots (75 pairs of H_d and Age) and complete stem analysis (423 pairs of H_d and Age) were aggregated for the adjustments of the nonlinear Schumacher, Chapman-Richards, Bailey-Clutter, Logistic, Gompertz and Hossfeld IV models (Table 1) by the Nonlinear Least Squares Method using the Gauss-Newton iterative process. However, data from the complete stem analysis (98 pairs of H_d and Age) of 5 trees selected at random were separated for further validation of the growth curves by the stability test.

Model evaluation was performed using different criteria as following: residual standard error (1) and percentage (2), Akaike Information Criteria (3) and Bayesian Information Criteria (4) based on Lindsey and Sheather (2010), graphical analysis of the residues and analysis of the consistency and stability of site index curves.

$$S_{xy} = \sqrt{\frac{\sum_{i=1}^{n}(y-\hat{y})^2}{n-p-1}} \tag{1}$$

$$S_{xy}\% = \frac{S_{xy}}{\bar{y}}100 \tag{2}$$

$$AIC = n + n\,log2\pi + nlog(SQ_{res}/n) + 2(p+1) \tag{3}$$

$$BIC = n + n\,log2\pi + nlog(SQ_{res}/n) + (logn)(p+1) \tag{4}$$

Where S_{xy} = residual standard error; $S_{xy}\%$ = relative standard error; y = observed dominant height; $\hat{y}$ = estimated dominant height; n = number of observations; p = number of parameters in the model; SQ_{res} = Sum of squares of residues; ln = neperian logarithm.

The site productive capacity classification was made by the algebraic difference method, with the construction of anamorphic and polymorphic site index curves for each adjusted model (Table 1), discriminating the data in site classes and considering a reference age of 19 years. Three site classes were defined and an amplitude of 7 meters was adopted in each class, considering the range of Hd values at the reference age. All statistical analyzes were performed using R and Microsoft Excel software.

After building the site curves, the test of stability for each set of curves was performed considering the number of times that the plots changed class and the number of plots fully contemplated by the curves over time based on the data of complete stem analysis of 30 trees. The stability test was performed for all models with the data used in the model adjustments and later for the model selected, with the independent database.

2.4 Polymorphism test

To verify any evidence of polymorphism, the comparison test between the slope parameters of the Schumacher model was used as proposed by Silva et al. (2018) for being an asymptotic and parsimonious model, which facilitates its interpretation. According to the interpretation of the parameters, $\emptyset_0$ represents the maximum asymptote that is equivalent to the value to be reached by H_d within each class, while the parameter $\emptyset_1$ represents the slope of the growth curves. Thus, adjustments were made by class of site based on the data set of complete stem analysis. For this, the trees were separated into classes considering the age of 14 years (age common to all trees).

Table 1. List of models tested to estimate dominant height and classify the site productive capacity in *B. excelsa* plantations.

Model	Statistical model	Anamorphic function Free parameter $\emptyset_0$	Polymorphic function Free parameter $\emptyset_1$	Polymorphic function Free parameter $\emptyset_2$
Schumacher	$\overline{H}_i = \emptyset_0\, e^{\left(\emptyset_1 \frac{1}{I_i}\right)} + \varepsilon_i$	$SI = \overline{H}_i\, e^{\left(\frac{\emptyset_1}{I_{ref}} - \frac{\emptyset_1}{I_i}\right)}$	$SI = \emptyset_0 \left(\frac{\overline{H}_i}{\emptyset_0}\right)^{\frac{I_{ref}}{I_i}}$	
Chapman-Richards	$\overline{H}_i = \emptyset_0 \left(1 - e^{\emptyset_1 I_i}\right)^{\emptyset_2} + \varepsilon_i$	$SI = \overline{H}_i \left(\frac{1}{1 - e^{\emptyset_1 I_{ref}}} - \frac{e^{\emptyset_1 I_i}}{1 - e^{\emptyset_1 I_{ref}}}\right)^{\emptyset_2}$	$SI = \emptyset_0 \left(1 - \left(1 - \left(\frac{\overline{H}_i}{\emptyset_0}\right)^{\frac{1}{\emptyset_2}}\right)^{\frac{I_i}{I_{ref}}}\right)^{\emptyset_2}$	$SI = \emptyset_0 \left(\frac{\overline{H}_i}{\emptyset_0}\right)^{\frac{\ln\left(1 - e^{\emptyset_1 I_{ref}}\right)}{\ln\left(1 - e^{\emptyset_1 I_i}\right)}}$
Bailey-Clutter	$\overline{H}_i = \emptyset_0 \left(1 - e^{\emptyset_1 {I_i}^{\emptyset_2}}\right) + \varepsilon_i$	$SI = \overline{H}_i\, \frac{e^{\emptyset_1 {I_i}^{\emptyset_2}} - 1}{e^{\emptyset_1 {I_{ref}}^{\emptyset_2}} - 1}$	$SI = \emptyset_0 - \emptyset_0 e^{\frac{I_i \ln\left(1 - \frac{\overline{H}_i}{\emptyset_0}\right)}{{I_{ref}}^{\emptyset_2}}}$	$SI = \emptyset_0 - \emptyset_0 \left(1 - \frac{\overline{H}_i}{\emptyset_0}\right)^{\frac{\ln(I_i)}{\ln(I_{ref})}}$
Logístico	$\overline{H}_i = \frac{\emptyset_0}{1 + e^{\left(\frac{\emptyset_1 - I_i}{\emptyset_2}\right)}} + \varepsilon_i$	$SI = \overline{H}_i\, \frac{e^{\emptyset_1 - I_{ref}\emptyset_2} + 1}{e^{\emptyset_1 - I_i \emptyset_2} + 1}$	$SI = -\frac{\overline{H}_i \emptyset_0}{(\overline{H}_i - \emptyset_0)\, e^{I_i \emptyset_2 - I_{ref}\emptyset_2} - \overline{H}_i}$	$SI = \frac{\emptyset_0}{1 + e^{\frac{I_i \ln\left(\frac{\emptyset_1}{\overline{H}_i} - 1\right)}{I_{ref}} - \frac{I_i \emptyset_1}{I_{ref}} + \emptyset_1}}$
Gompertz	$\overline{H}_i = \emptyset_0 e^{-e^{\emptyset_1 - \emptyset_2 I_i}} + \varepsilon_i$	$SI = \overline{H}_i e^{e^{\left(\emptyset_1 - \emptyset_2 I_{ref}\right)} - e^{\left(\emptyset_1 - \emptyset_2 I_i\right)}}$	$SI = \emptyset_0 e^{\ln\left(\frac{\overline{H}_i}{\emptyset_0}\right) e^{\emptyset_2 I_{ref} - \emptyset_2 I_i}}$	$SI = \emptyset_0 e^{-e^{\frac{I_i \ln\left(-\ln\left(\frac{\overline{H}_i}{\emptyset_0}\right)\right)}{I_{ref}} - \frac{I_i \emptyset_0}{I_{ref}} + \emptyset_1}}$
Hossfeld IV	$\overline{H}_i = \emptyset_0 \frac{{I_i}^{\emptyset_1}}{\emptyset_0\, \emptyset_2 + {I_i}^{\emptyset_1}} + \varepsilon_i$	$SI = \frac{\overline{H}_i {I_i}^{\emptyset_1} {I_{ref}}^{\emptyset_1}}{\left(\overline{H}_i\, \emptyset_2 + {I_i}^{\emptyset_1}\right) {I_{ref}}^{\emptyset_1} - \overline{H}_i\, \emptyset_2 {I_i}^{\emptyset_1}}$	$SI = \frac{\emptyset_0 e^{\frac{\ln(\emptyset_i) ln\left(\frac{\overline{H}_i \emptyset_0\, \emptyset_2}{\emptyset_0 - \overline{H}_i}\right)}{\ln(I_{ref})}}}{e^{\frac{\ln(\emptyset_i) ln\left(\frac{\overline{H}_i \emptyset_0\, \emptyset_2}{\emptyset_0 - \overline{H}_i}\right)}{\ln(I_{ref})}} + \emptyset_0 \emptyset_2}$	$SI = \frac{\overline{H}_i {I_i}^{\emptyset_1} \emptyset_0}{(\emptyset_0 - \overline{H}_i) {I_{ref}}^{\emptyset_1} + \overline{H}_i {I_i}^{\emptyset_1}}$

Where: $\emptyset_0$, $\emptyset_1$ e $\emptyset_2$= parameters; SI = site index, $\overline{H}_i$ = dominant height; I_i = age; I_{ref} = reference age.

2.3. Spatialization of sites in the stands

After the estimative of SI from model selected for each plot, the site classes were spatialized in the study area through the ordinary point kriging method. The interpolation technique enables the spatial distribution of sample data, estimating the data occurring between the samples, through mathematical function adjustments (Yamamoto and Landim, 2013). Kriging is an optimal interpolation procedure (Isaaks and Srivastava, 1989), being the most widely used in studies of precision silviculture.

Semi-variances (5) were obtained for the construction of the theoretical variogram, adjustment of theoretical variogram models (Kravchenko, 2003), Spherical, Exponential, Gaussian, Cubic and Cauchy, using the weighted least squares (WLS) method (Webster and Oliver, 2007) and interpolation by means of punctual ordinary kriging (6). The models were evaluated based on the sum of squares of the weighted deviations ($SSWD$), determination coefficient (R^2), determination coefficient of cross-validation R^2vc and relative standard error (Syx%).

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} \{Z(x_i) - Z(x_i + h)\}^2 \qquad (5)$$

$$Z_{KO}^{*}(x_0) = \sum_{i=1}^{n} \lambda_i [Z(x_i)] \qquad (6)$$

Where: $\gamma(h)$ = semi-variance; h = distance; $n(h)$ = number of measured point separated by a distance h; $Z_{KO}^{*}(x_0)$ = estimated value in an unsampled location; $Z(x_i)$ = value of sample variable; λ_i = weight associated with the value obtained in the position x_i, using the Lagrange multiplier technique; n = data number.

2.4. Topoedaphic characteristics

Soil measurements and samples collections were made in June 2019. The deformed soil samples were collected at two depths (0-20 and 20-40 cm), with the aid of the Dutch auger (SONDATERRA®, Model TF-10, Brazil). Three samples were collected by depth in each plot. After homogenization, one sample was formed for each soil depth. Undisturbed soil samples were extracted with steel cylinders (5 cm diameter and 5 cm tall) from 0-10, 10-20, 20-30 and 30-40 cm depths from each plot, where one undisturbed soil sample was collected by depth in each plot.

The deformed soil samples were air dried and passed through a 2 mm sieve. The analytical procedures were: pH in water (25 ml) and pH in KCl solution (1 mol L^{-1}) were determined electronically by a combined electrode immersed in solution (soil: solution ratio 1: 2.5) (Embrapa, 1997); Al^{3+}, Ca^{2+} and Mg^{2+} contents were extraction in KCl (1 mol L^{-1}), where Al^{3+} was determined by titration with NaOH solution and bromothymol blue as an indicator (McLean, 1965), while Ca^{2+} and Mg^{2+} were determined by atomic absorption spectrophotometry; P, K^{+}, Fe^{2+}, Mn^{2+}, Zn^{2+} and Na^{+} were extracted in Mehlich-1 solution (HCl 0,05 mol L^{-1} + H_2SO_4 0,125 mol L^{-1}), where P was determined by colorimetry on the molecular absorption spectrophotometer ($\lambda = 660$ nm) (Murphy and Riley, 1962), while K^{+}, Fe^{2+}, Mn^{2+}, Zn^{2+}, Na^{+} were determined by atomic absorption spectrophotometry (Embrapa, 1997); organic carbon (OC) was determined by the Walkley-Black method and organic matter (O. M.) was determined by multiplying the C content by 1.72 (100/58) - “Van Bemmelen” factor (Walkley and Black, 1934). From undisturbed soil samples, soil density was determined by the volumetric cylinder method, volumetric water content by the gravimetric method and texture by the pipette method (Embrapa, 1997). The volumetric water content was used only to correct the values of soil resistance to penetration, as discussed later.

The topographic variables, in turn, were obtained by GPS (GARMIN®, Model GPSMAP 64s, USA) and the processing of Digital Elevation Model (DEM) images from the Shuttle Radar Topography Mission (SRTM) that were obtained on the United States Geological Survey (USGS) website. For each plot, a central coordinate and its respective altitude was obtained with Global Positioning System (GPS) equipment. From the reference coordinates, slope values were obtained in the DEM image through digital processing using the Quantum GIS software. Altitude values were also obtained by the DEM after a correction to attenuate the effect of deforestation on SRTM data using the methodology proposed by Brochado (2015). The corrected altitude values were used together with the slope values to perform classification in other areas on the property and to identify potential areas for planting the species.

2.4.1. Penetration resistance of soils

Penetration resistance (PR) was obtained using the impact penetrometer (SONDATERRA®, Model PI-60, Brazil) (Guimarães et al., 2017), up to 40 cm deep, and the values of PR were calculated in a spreadsheet supplied by the manufacturer of instrument. To obtain real values of PR, the measurements should be collected when soil moisture is close to field capacity (Busscher et al., 1997; Smith et al., 1997). However, due to soil moisture variation (21.5% to 66.8%), it was necessary to perform the modeling and correction of penetration resistance values for water content corresponding to field capacity. For this, the Jakobsen and Dexter (1987) function proposed by Vaz et al. (2011) was used to model the penetration resistance at each depth (Table S1). However, in the original function, soil density was replaced by sand content, due to a higher correlation (7).

$$PR = e(a + \mathrm{b}\theta_s + c\theta_v) \tag{7}$$

Where: PR = penetration resistance, θ_s = sand content; θ_v = volumetric water content; a, b, c = parameters.

After modeling, the PR values were parameterized based on average field moisture values by soil texture class, obtained by Andrade and Stone (2011).

2.5.Analysis and selection of topoedaphic variables

The relationships between topoedaphic variables and SI were evaluated by correlation matrix to identify characteristics limiting the height growth of *B. excelsa* and interpreted by principal component analysis (PCA). For the selection of edaphic variables by PCA, were retained in the analysis the components with eigenvalues greater than 1 (Kaiser, 1960) and representing at least 70% of the total data variability (Johnson and Wichern, 1998). In each retained component, one variable with higher eigenvector was selected and submitted to regression analysis.

In *stepwise backward* method also used variables significantly correlated with SI. This method aims to obtain a more parsimonious model based on the significance of each variable (Montgomery and Runger, 2009). The models were compared using adjusted determination coefficient (7), relative standard error and graphical analysis of the residues. The variance inflation factor (VIF) was also used to diagnose collinearity between the independent variables, considering that VIF < 10 indicates that there are no collinearity problems (Field, 2009).

$$R_{aj.}^2 = 1 - \frac{n-1}{n-(k+1)}(1 - 1 - \frac{\sum_{i=1}^{n}(y-\hat{y})^2}{\sum_{i=1}^{n}(y-\bar{y})^2}) \qquad (7)$$

Where: $R_{aj.}^2$ = adjusted coefficient of determination; y = observed value of dependent variable; $\hat{y}$ = estimated value of the dependent variable; $\bar{y}$ = mean of dependent variable; $k+1$ = number of parameters; n = data number.

3. Results

3.1. Model evaluation and curves stability

Despite of the small difference in the values of statistical criteria among the adjusted models, the Logistic model showed the best result, followed by the Chapman-Richards and Hossfeld IV models, which had the lowest values of relative standard error, Akaike (AIC) and Bayesian information criteria (BIC) (Table 2). All models showed an asymptotic behavior, because the values of intercept ($\emptyset_0$) were close to the maximum value of H_d.

Table 2. Estimated parameters from fitted models and accuracy statistics.

Model	Parameters			AIC	BIC	S_{yx} (%)
	$\emptyset_0$	$\emptyset_1$	$\emptyset_2$			
Schumacher	25.48^{**}	-9.65^{**}		1333.5	1341.9	44.2
Chapman-Richards	28.71^{**}	-0.05^{ns}	1.29^{**}	1303.0	1315.6	42.8
Bailey-Clutter	26.80^{*}	-0.04^{**}	1.01^{**}	1315.0	1327.6	43.4
Gompertz	25.78^{**}	2.32^{**}	0.16^{**}	1306.0	1318.6	43.0
Logistic	35.46^{**}	1.10^{**}	0.07^{**}	1299.6	1312.2	42.7
Hossfeld IV	30.02^{**}	1.42^{**}	1.98^{*}	1308.1	1320.6	43.0

** $P < 0.01$. * $P < 0.05$. ^{ns} $P \geq 0.05$.

Regarding to the distribution of residues criteria, although all models had a slight overestimation for the highest values of H_d from 12 m, the Chapman-Richards and Hossfeld IV models showed a more homogeneous distribution of residues along of the regression line. The Schumacher model overestimated the values at early ages while the Logistic and Gompertz models underestimated at early ages (Figure 3).

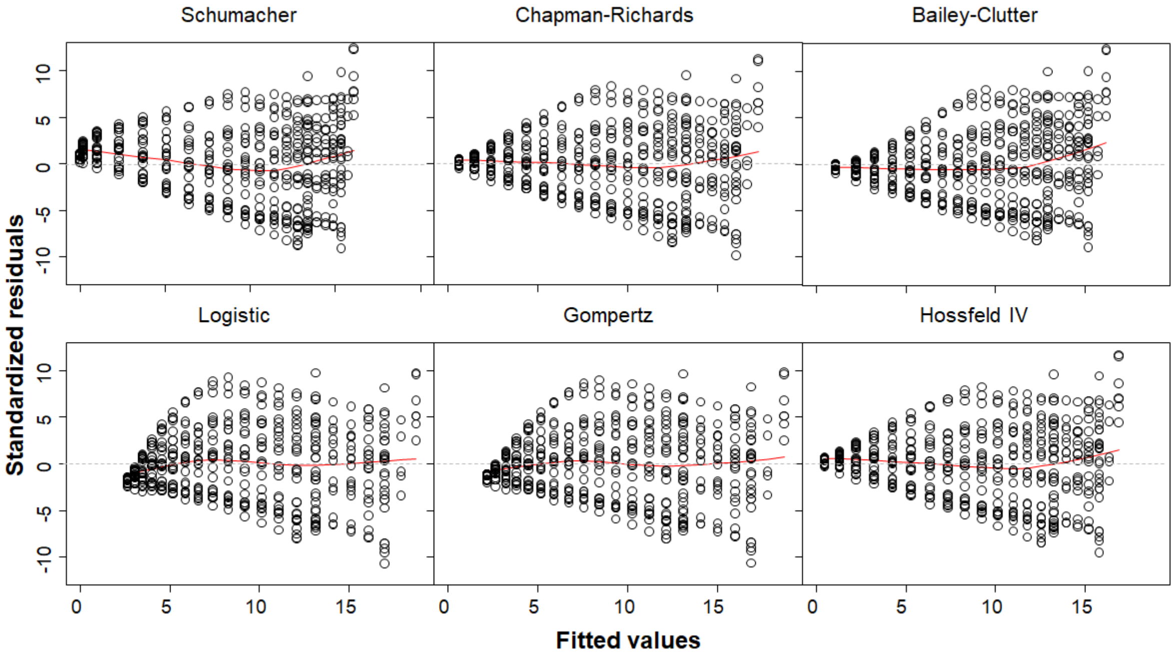


Fig. 3. Dispersion of the values of relative related percentage errors over time for the models adjusted for *B. excelsa* stands.

The consistency of the polymorphic and anamorphic curves of the models was evaluated for data dispersion along the curves (Figure 4). Three site classes were delimited with a 7 m interval at the reference age (19 years), considering the total amplitude of 21 m (5 - 26 m).

Anamorphic curves showed larger deficiency in data conformation over time with data not being fully included along the curves, with better performance for the Bailey-Clutter model (Figure 4). The polymorphic curves, when the parameter $\emptyset_1$ was free, showed very accented and displaced upper curve except for the curves generated by the Chapman-Richards and Hossfeld IV models, which showed more adequate curves (Figure 4). For the same curves, when the parameter $\emptyset_2$ was free, the Hossfeld IV model was more adequate (Figure 4).

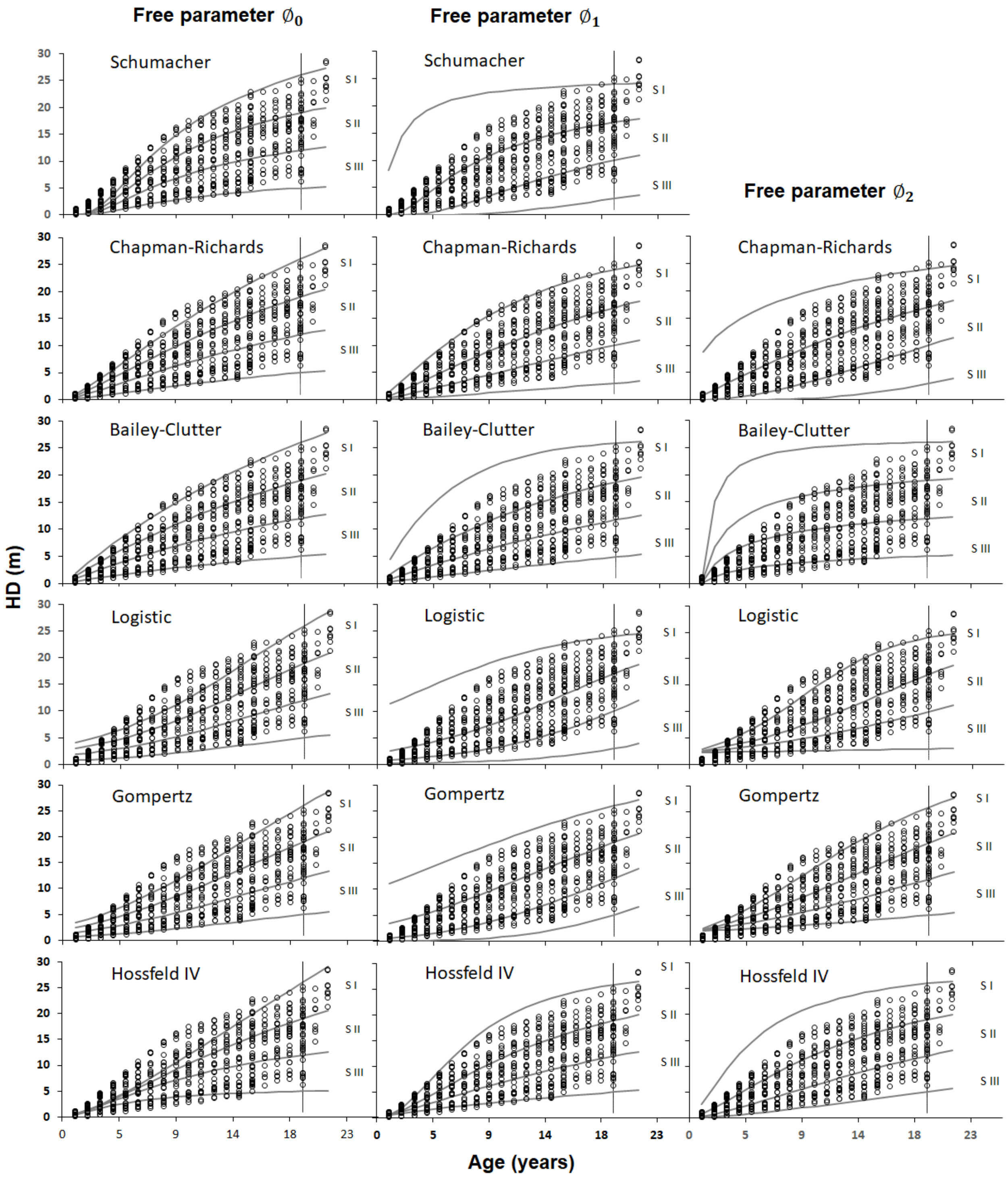


Fig. 4. Dispersion of dominant heights values (HD) for the anamorphic and polymorphic site index curves of models adjusted for *B. excelsa* stands.

There were differences in the asymptotic behavior of the curves generated by the adjusted models. Anamorphic curves tended to stabilize later in relation to polymorphic curves. This behavior it appeared inadequate to the dispersion of H_d values over the ages.

The Logistic and Gompertz models had the highest deficiencies in the data conformation in both anamorphic curves and polymorphic curves when the parameter $\emptyset_2$ was free. For the polymorphic curves, when the parameter $\emptyset_1$ was free, the same models showed very displaced curves (Figure 4). In turn, the anamorphic curves generated by the Bailey-Clutter model and the polymorphic generated by the Chapman-Richards model, when the parameter $\emptyset_1$ was free, showed more consistency between the pairs of values of height dominant and age.

Regarding the stability of the curves, the Bailey-Clutter and Chapman-Richards models with the free parameters $\emptyset_1$ and $\emptyset_2$ (polymorphic curves), respectively, showed the highest percentage of plots included by the curves over time with 40% and 33%, respectively, followed by the Bailey-Clutter, Chapman-Richards and Hossfeld IV models with the free parameters $\emptyset_0$, $\emptyset_1$ and $\emptyset_2$, respectively, which had each one 30% of the plots included over time. Despite of the low values of curves stability, Chapman-Richards and Hossfeld IV models showed a more homogeneous distribution among site classes (Table 3).

Although not a common procedure, with the objective to improve the model's stability, we removed the early ages until to reach at least 70% of plots included over time in the classes. Thus, when the ages between 1 and 3 years were removed, Chapman-Richards model, with the free parameter $\emptyset_1$, and Hossfeld IV, with the free parameter $\emptyset_2$, had the highest percentages of plots included by the curves over time, with 73.3% and 70%, respectively, as well as homogeneous distribution among site classes (Table 3). Then, the Chapman-Richards model, with the free parameter $\emptyset_1$, was finally selected to estimate the site indices for *B. excelsa* stands, since that it showed the best fit and consistency of the curves for H_d. Besides that, the model Chapman-Richards model, with the free parameter $\emptyset_1$, presented a lower percentage of stability with only 9.9% of class changes by the H_d and Age value pairs and when we use an independent database and considering in the classification of site from 4 years-old, the Chapman-Richards model showed only 6% of class changes and 60% of the trees were completely included in the curves (Figure 5).

Table 3. Number of plots included by the curves over time (absolute and relative), relative stability and relative number of plots per site class for each model adjusted for *B. excelsa* stands.

Models	Free Parameter	Ages (1-20 years)						Ages (4-20 years)					
		N° plot	Plot (%)	Stability (%)	S I (%)	S II (%)	S III (%)	N° plot	Plot (%)	Stability (%)	S I (%)	S II (%)	S III (%)
Schumacher	$\varnothing_0$	1	3.3	34.0	-	-	-	3	10.0	23.1	-	-	10.0
	$\varnothing_1$	1	3.3	24.0	3.3	-	-	10	33.3	15.5	-	33.3	-
Chapman-Richards	$\varnothing_0$	5	16.7	24.4	-	-	16.7	13	43.3	20.4	-	13.3	30.0
	$\varnothing_1$	9	30.0	15.4	16.7	3.3	10.0	22	73.3	9.9	23.3	23.3	26.7
	$\varnothing_2$	10	33.3	22.6	-	33.3	-	11	36.7	16.8	3.3	30.0	3.3
Bailey-Clutter	$\varnothing_0$	9	30.0	16.7	-	13.3	16.7	17	56.7	13.5	3.3	20.0	33.3
	$\varnothing_1$	12	40.0	13.1	-	23.3	16.7	17	56.7	10.3	3.3	23.3	30.0
	$\varnothing_2$	7	23.3	31.9	-	-	23.3	11	36.7	27.1	-	-	36.7
Logistic	$\varnothing_0$	6	20.0	30.7	-	-	20.0	11	36.7	27.1	3.3	3.3	30.0
	$\varnothing_1$	2	6.7	32.2	-	-	6.7	7	23.3	22.9	-	3.3	6.7
	$\varnothing_2$	6	20.0	20.7	-	-	20.0	18	60.0	15.2	23.3	6.7	30.0
Gompertz	$\varnothing_0$	6	20.0	30.5	-	-	20.0	12	40.0	27.8	3.3	6.7	30.0
	$\varnothing_1$	7	23.3	23.8	-	16.7	6.7	11	36.7	18.6	13.3	20.0	3.3
	$\varnothing_2$	6	20.0	31.1	-	-	20.0	12	40.0	27.1	3.3	6.7	30.0
Hossfeld IV	$\varnothing_0$	5	16.7	38.2	-	-	16.7	10	33.3	32.3	-	-	33.3
	$\varnothing_1$	5	16.7	18.6	-	-	16.7	16	53.3	12.3	13.3	10.0	30.0
	$\varnothing_2$	9	30.0	17.5	20.0	3.3	6.7	21	70.0	10.5	20.0	23.3	26.7

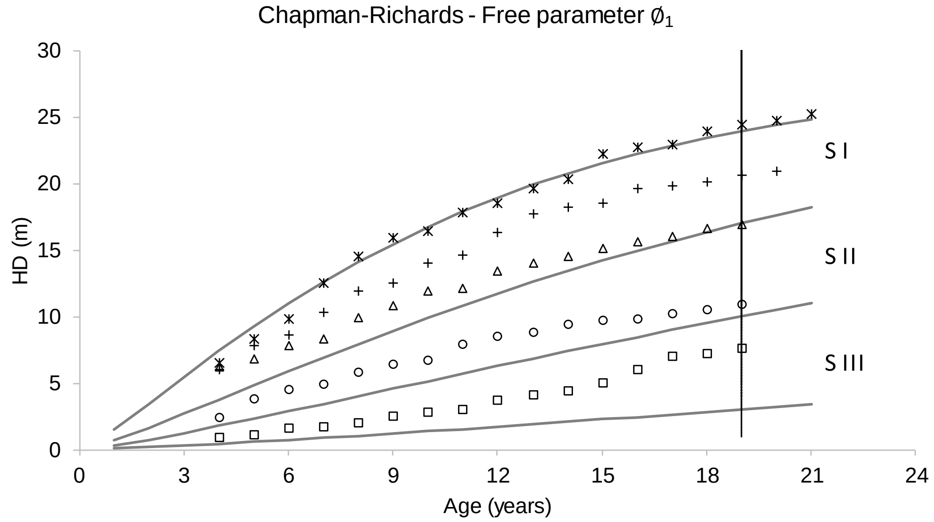


Fig. 5. Stability analysis of dominant height (HD) growth curves over time for *B. excelsa* stands.

3.2. Polymorphism testing

The data obtained from the complete stem analysis were separated by site class based on the selected model. The site class I was constituted of 14 trees while the other two classes were constituted of eight trees each. The Schumacher model was used for the adjustment of the three data sets.

The comparison test between the parameters $\emptyset_1$ indicated the presence of polymorphism, since that there was a significant difference among classes, except between classes I and II (Table 4), corroborating the better consistency and stability of the polymorphic curves. The differences observed between the values of $\emptyset_0$, were expected, since that the more productive sites can reach higher values of H_d.

Table 4. Values of Z statistic comparing the parameters $\emptyset_0$ and $\emptyset_1$ among the site classes and estimatives of the parameters by Schumacher model adjustment.

Classes	S I	S II	Coefficients
$\emptyset_0$			
S I	-		27.88
S II	8.49*	-	17.47
S III	12.31*	3.55*	13.23
$\emptyset_1$			
S I	-		-7.10
S II	0.20^{ns}	-	-7.27
S III	4.16*	3.63*	-11.00

Note: The critical Z value considering an interval of 90%, significance of 0.1(*), is equal to 1.65.
* Significance is 0.1 (10%). $\emptyset_0$ e $\emptyset_1$ = parameters

3.3. Spatialization of sites in the B. excelsa stands

According to Grubbs test no discrepant values were found in the database (0.94; p-value = 1.0). In addition, the Kolmogorov-Smirnov test (0.09; p-value = 0.46) confirmed the normal distribution of the variable.

The spatial dependence of the site index (SI) was confirmed by the possibility of adjusting models of theoretical variograms, despite of the low values of determination coefficient (R^2), probably due to the spatial discontinuity of the sampling, considering the location of the stands. The low values of the nugget effect (C_0) in all adjusted models compared to the a priori variance (C), confirmed that the sampling intensity was enough to capture the spatial continuity (Table 5).

The spherical model showed the highest values of determination coefficient (R^2), determination coefficient of cross validation (R_v^2), least sum of squares of the weighted deviations ($SSWD$) and least the relative standard error of cross validation (Syx_v%). Therefore, this model was selected for the spatialization of the SI by punctual ordinary kriging and the construction of the thematic map (Figure 6). Thus, we found that the intermediate site class (Site II) had the largest coverage in *B. excelsa* stands with 83.3 hectares (45%), followed by classes III and I with 57.5 (31%) and 44.4 (24%) hectares, respectively.

Table 5. Parameters of the adjusted variograms and criteria for selecting the models.

Model	C_0	$C_0 + C$	a (m)	R^2	$SSWD$	R_v^2	Syx$_v$%
Spherical	4.33	34.74	1223.40	0.62	963.15	0.64	23.04
Exponential	0.00	39.65	482.39	0.55	1153.42	0.63	23.18
Gaussian	9.89	29.30	612.40	0.61	992.49	0.63	23.29
Cubic	9.68	29.50	1463.58	0.62	963.40	0.63	23.28
Cauchy	6.39	38.23	291.13	0.53	1205.34	0.64	22.92

C_0 = nugget effect; C = priori variance; a = range; R^2 = determination coefficient; $SSWD$ = sum of squares of the weighted deviations; R_v^2 = determination coefficient of cross validation; Syx$_v$% = relative standard error of cross validation.

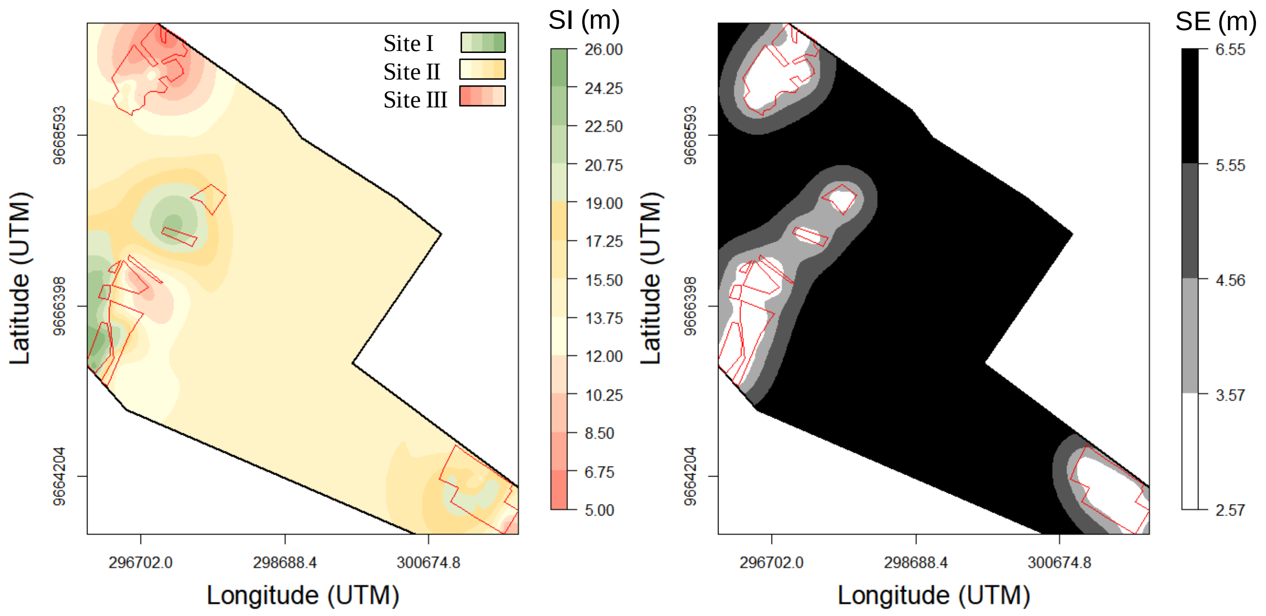


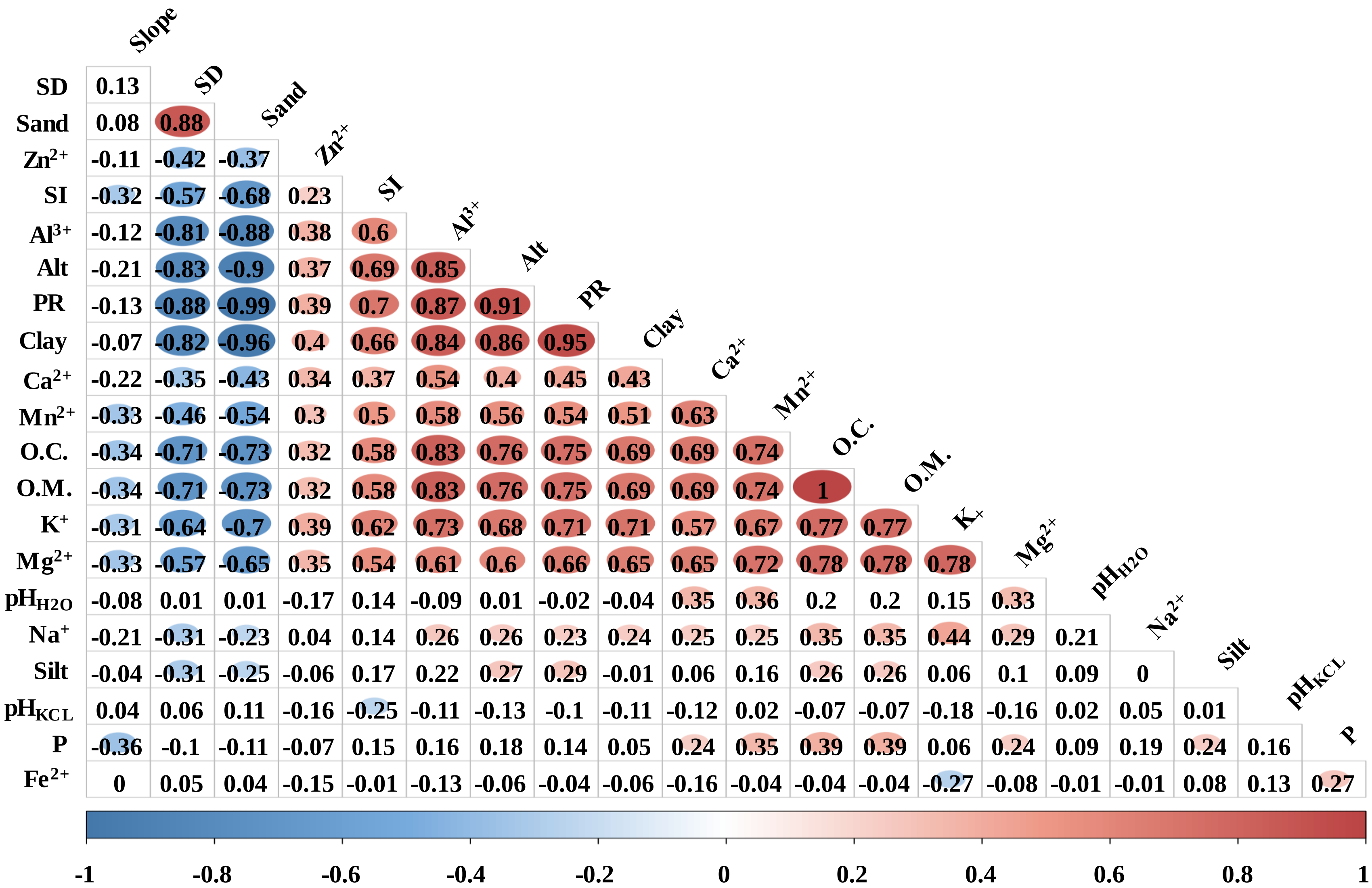
Fig. 6. Thematic map and standard error (SE) map of the spatial distribution of the site index (SI) for *B. excelsa* stands.

3.4. *Topoedaphic characteristics and site index relationships*

The most of the topoedaphic characteristics were significantly related to the site index (SI), exception for pH$_{H2O}$, P, Fe^{2+}, Na^{+} and silt at depth of 0 - 20 cm and pH$_{H2O}$, P, Fe^{2+}, Zn^{2+} and Na^{+} at depth of 20 - 40 cm (Figure 7 and 8). The altitude and physical characteristics, exception for silt content, were strongly related to the SI. Soil clay content and penetration resistance (PR) showed close and positive relationships, while soil sand content and density showed a close and negative relationship with site index (SI) (Figure 7 and 8). The altitude showed a close and positive relationship with the SI, where the most productive site presented higher altitude value (Table 7), and was correlated with the most edaphic characteristics, except for P at both depths (Figure 7 and 8). Specifically, for the chemical characteristics, at depth 0-20 cm, K^+, Al^{3+}, organic carbon (O. C.) and organic matter (O. M.), were strongly correlated with SI, with the highest correlation for K^+, where the most productive site presented higher contents of this nutrient (Table 6). At depth 20-40 cm, Mn^{2+}, Al^{3+} and pH_{KCl}, were strongly correlated with SI, with the highest correlation for Mn^{2+} (Figure 7 and 8), evidenced by the coincidence of the vectors Mn^{2+} and SI (Figure 9), beyond the higher levels of this nutrient in the most productive sites (Table 6). Despite the weak but significant correlation, the slope was negatively correlated with the SI and was not much correlated with other variables (Figure 7 and 8).

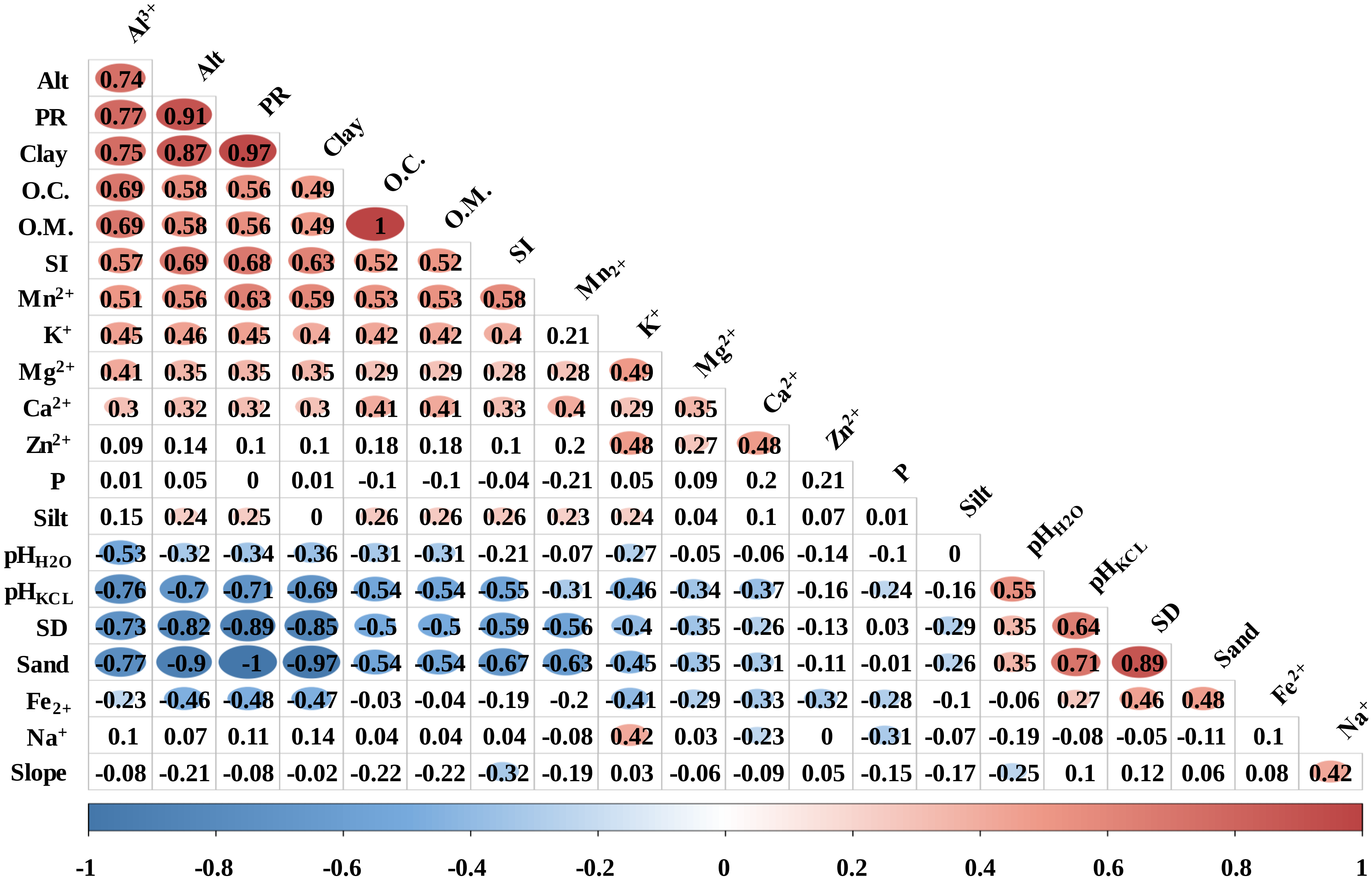
There was a close and positive relationship between the soil sand content and density (SD) at both depths, evidenced by the coincidence of the SD and Sand vectors (Figure 9). There was also a close and positive relationship between PR and clay content at both depths (Figure 9). There was a close and positive relationship between altitude and clay content, Al^{3+} and PR, while the slope was negatively related to Ca^{2+}, Mn^{2+}, Mg^{2+}, OM, O. C. and K^+ (Figure 9). The nutrients Ca^{2+}, Mg^{2+}, Mn^{2+} and K^+ were correlated with the content of the O. M. (Figure 9).

The soils are acidic (pH_{KCl} less than 5.0) and have high levels of Al^{3+} (Table 6). At the second depth, the vector Al^{3+} was directly opposite to the pH_{KCl} vector (Figure 9). The intermediate and higher site indices were associated with lower pH_{KCl} and higher levels of Al^{3+} (Figure 9 and Table 6).



	Slope	SD	Sand	Zn^{2+}	SI	Al^{3+}	Alt	PR	Clay	Ca^{2+}	Mn^{2+}	O.C.	O.M.	K^{+}	Mg^{2+}	pH$_{H2O}$	Na^{2+}	Silt	pH$_{KCL}$	P
SD	0.13																			
Sand	0.08	0.88																		
Zn^{2+}	-0.11	-0.42	-0.37																	
SI	-0.32	-0.57	-0.68	0.23																
Al^{3+}	-0.12	-0.81	-0.88	0.38	0.6															
Alt	-0.21	-0.83	-0.9	0.37	0.69	0.85														
PR	-0.13	-0.88	-0.99	0.39	0.7	0.87	0.91													
Clay	-0.07	-0.82	-0.96	0.4	0.66	0.84	0.86	0.95												
Ca^{2+}	-0.22	-0.35	-0.43	0.34	0.37	0.54	0.4	0.45	0.43											
Mn^{2+}	-0.33	-0.46	-0.54	0.3	0.5	0.58	0.56	0.54	0.51	0.63										
O.C.	-0.34	-0.71	-0.73	0.32	0.58	0.83	0.76	0.75	0.69	0.69	0.74									
O.M.	-0.34	-0.71	-0.73	0.32	0.58	0.83	0.76	0.75	0.69	0.69	0.74	1								
K^{+}	-0.31	-0.64	-0.7	0.39	0.62	0.73	0.68	0.71	0.71	0.57	0.67	0.77	0.77							
Mg^{2+}	-0.33	-0.57	-0.65	0.35	0.54	0.61	0.6	0.66	0.65	0.65	0.72	0.78	0.78	0.78						
pH$_{H2O}$	-0.08	0.01	0.01	-0.17	0.14	-0.09	0.01	-0.02	-0.04	0.35	0.36	0.2	0.2	0.15	0.33					
Na^{+}	-0.21	-0.31	-0.23	0.04	0.14	0.26	0.26	0.23	0.24	0.25	0.25	0.35	0.35	0.44	0.29	0.21				
Silt	-0.04	-0.31	-0.25	-0.06	0.17	0.22	0.27	0.29	-0.01	0.06	0.16	0.26	0.26	0.06	0.1	0.09	0			
pH$_{KCL}$	0.04	0.06	0.11	-0.16	-0.25	-0.11	-0.13	-0.1	-0.11	-0.12	0.02	-0.07	-0.07	-0.18	-0.16	0.02	0.05	0.01		
P	-0.36	-0.1	-0.11	-0.07	0.15	0.16	0.18	0.14	0.05	0.24	0.35	0.39	0.39	0.06	0.24	0.09	0.19	0.24	0.16	
Fe^{2+}	0	0.05	0.04	-0.15	-0.01	-0.13	-0.06	-0.04	-0.06	-0.16	-0.04	-0.04	-0.04	-0.27	-0.08	-0.01	-0.01	0.08	0.13	0.27

Fig. 7. Correlation matrix between topoedaphic characteristics and site index at depth 0-20 cm. **Notes:** O. C. = organic carbon; O. M. = organic matter; SD = soil density; PR = penetration resistance; Alt = Altitude. Significant correlations ($P < 0.05$) are given in color.



	Al^{3+}	Alt	PR	Clay	O.C.	O.M.	SI	Mn_{2+}	K^+	Mg^{2+}	Ca^{2+}	Zn^{2+}	P	Silt	pH_{H2O}	pH_{KCL}	SD	Sand	Fe^{2+}	Na^+
Alt	0.74																			
PR	0.77	0.91																		
Clay	0.75	0.87	0.97																	
O.C.	0.69	0.58	0.56	0.49																
O.M.	0.69	0.58	0.56	0.49	1															
SI	0.57	0.69	0.68	0.63	0.52	0.52														
Mn^{2+}	0.51	0.56	0.63	0.59	0.53	0.53	0.58													
K^+	0.45	0.46	0.45	0.4	0.42	0.42	0.4	0.21												
Mg^{2+}	0.41	0.35	0.35	0.35	0.29	0.29	0.28	0.28	0.49											
Ca^{2+}	0.3	0.32	0.32	0.3	0.41	0.41	0.33	0.4	0.29	0.35										
Zn^{2+}	0.09	0.14	0.1	0.1	0.18	0.18	0.1	0.2	0.48	0.27	0.48									
P	0.01	0.05	0	0.01	-0.1	-0.1	-0.04	-0.21	0.05	0.09	0.2	0.21								
Silt	0.15	0.24	0.25	0	0.26	0.26	0.26	0.23	0.24	0.04	0.1	0.07	0.01							
pH_{H2O}	-0.53	-0.32	-0.34	-0.36	-0.31	-0.31	-0.21	-0.07	-0.27	-0.05	-0.06	-0.14	-0.1	0						
pH_{KCL}	-0.76	-0.7	-0.71	-0.69	-0.54	-0.54	-0.55	-0.31	-0.46	-0.34	-0.37	-0.16	-0.24	-0.16	0.55					
SD	-0.73	-0.82	-0.89	-0.85	-0.5	-0.5	-0.59	-0.56	-0.4	-0.35	-0.26	-0.13	0.03	-0.29	0.35	0.64				
Sand	-0.77	-0.9	-1	-0.97	-0.54	-0.54	-0.67	-0.63	-0.45	-0.35	-0.31	-0.11	-0.01	-0.26	0.35	0.71	0.89			
Fe_{2+}	-0.23	-0.46	-0.48	-0.47	-0.03	-0.04	-0.19	-0.2	-0.41	-0.29	-0.33	-0.32	-0.28	-0.1	-0.06	0.27	0.46	0.48		
Na^+	0.1	0.07	0.11	0.14	0.04	0.04	0.04	-0.08	0.42	0.03	-0.23	0	-0.31	-0.07	-0.19	-0.08	-0.05	-0.11	0.1	
Slope	-0.08	-0.21	-0.08	-0.02	-0.22	-0.22	-0.32	-0.19	0.03	-0.06	-0.09	0.05	-0.15	-0.17	-0.25	0.1	0.12	0.06	0.08	0.42

Fig. 8. Correlation matrix between topoedaphic characteristics and site index at depth 20-40 cm. **Notes:** O. C. = organic carbon; O. M. = organic matter; SD = soil density; PR = penetration resistance; Alt = Altitude. Significant correlations ($P < 0.05$) are given in color.

Table 6. Chemical and physical properties of soil at different sites for *B. excelsa* stands.

Depth	Classe	pH_{H2O}	pH_{KCl}	P	K^+	Fe^{2+}	Mn^{2+}	Zn^{2+}	Ca^{2+}	Mg^{2+}	Na^2	Al^{3+}	C	OM	SD	PR	Clay	Silt	Sand
(cm)				--------------------(mg kg^{-1})---------------------					---------------(cmol$_c$ kg^{-1})--------------				----(g kg^{-1})----		(g cm^{-3})	(Mpa)	------------(%)------------		
0-20	I	4.46	4.01	1.79	13.71	131.18	1.81	0.32	0.05	0.12	0.02	1.48	15.59	26.88	1.09	2.28	78.82	10.25	10.93
	II	4.46	4.01	1.47	12.27	142.20	1.42	0.35	0.04	0.11	0.02	1.46	15.05	25.94	1.10	2.22	77.82	8.78	13.40
	III	4.43	4.08	1.41	8.91	136.45	0.59	0.25	0.02	0.06	0.02	1.18	11.25	19.40	1.26	1.77	49.38	8.44	42.18
20-40	I	4.59	4.10	0.97	7.03	113.23	1.27	0.22	0.01	0.04	0.01	1.21	8.28	14.27	1.05	2.12	81.73	9.76	8.51
	II	4.57	4.10	1.10	6.32	107.07	0.98	0.19	0.01	0.05	0.01	1.20	7.71	13.30	1.05	2.09	82.39	7.37	10.25
	III	4.64	4.16	1.04	5.00	126.80	0.63	0.20	0.01	0.03	0.01	0.96	6.38	11.00	1.27	1.66	55.47	6.21	38.32
0-20	Min	4.27	3.93	0.50	5.10	54.70	0.11	0.13	0.00	0.03	0.00	0.84	8.37	14.43	0.95	1.34	20.32	4.12	8.03
	Max	4.66	4.95	3.27	18.70	296.20	5.08	0.97	0.23	0.21	0.05	1.87	23.96	41.31	1.48	2.45	85.05	38.92	72.03
20-40	Min	4.39	3.99	0.50	2.50	54.26	0.06	0.04	0.00	0.02	0.00	0.73	4.60	7.94	0.87	1.23	27.67	3.09	6.16
	Max	4.73	4.24	3.27	13.30	199.70	2.44	0.43	0.05	0.14	0.04	1.62	10.99	18.95	1.57	2.17	88.30	40.91	68.87

Notes: O. C. = organic carbon; O. M. = organic matter; SD = soil density; PR = penetration resistance.

Table 7. Topographic variables at different sites for *B. excelsa* stands.

Classe	Alt (m)	Slope (%)
I	71.18	3.04
II	70.74	4.27
III	57.36	3.84
Min	42.93	0.00
Max	79.84	9.66

Notes: Alt = Altitude.

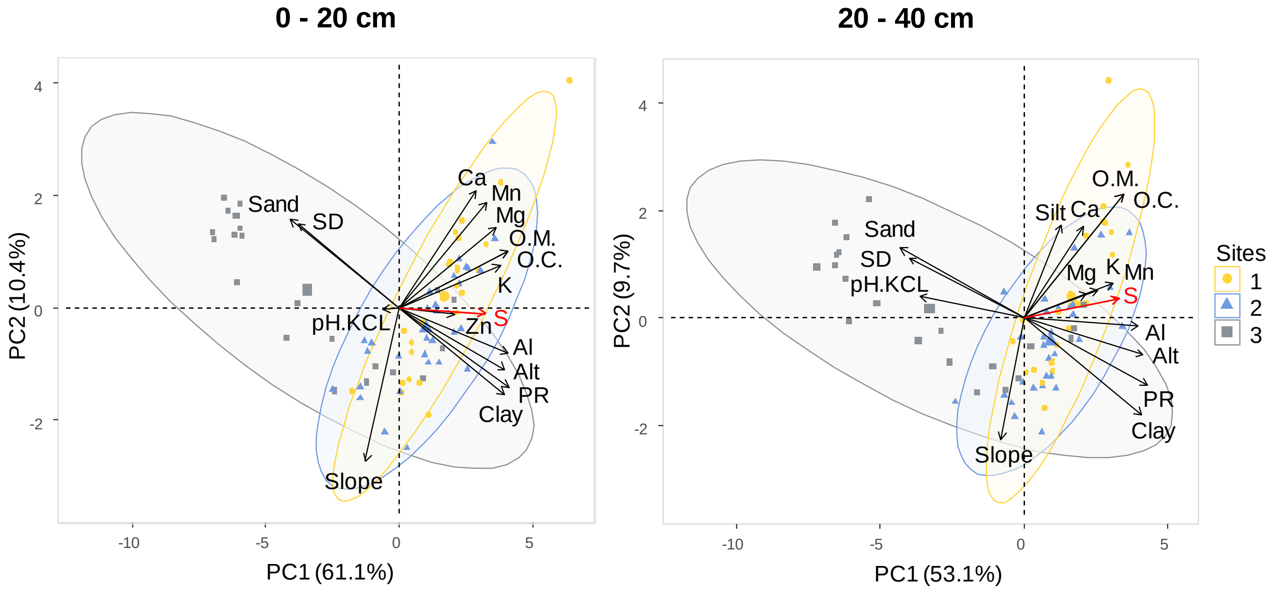


Fig. 9. Scores of the first two main components of the samples, considering the physical and chemical characteristics of the soil and topographic variables, at depths of 0 - 20 cm and 20 - 40 cm. **Notes:** O. C. = organic carbon; O. M. = organic matter; SD = soil density; PR = penetration resistance; Alt = Altitude.

3.5. Prediction models

Considering that the PR and O. M. were perfectly correlated to sand and O. C., respectively, these variables were excluded of the models as they would be redundant in the analysis. From the principal component analysis at depth 0-20 cm, the first three axes showed eigenvalues greater than 1 and, at the same time, they explained 76.8% of the total variation (Table 8). At depth 20-40 cm, the first three axes had eigenvalues greater than 1, but the fourth axis was used to obtain 76.2% of the total variation (Table 8). The 13 variables can be replaced by these variables with loss of only 23.2% and 31.1% of the information at depths 0-20 and 20-40 cm, respectively.

The variables that showed the highest absolute values in the three principal components were: Sand, Slope and pH_{KCl} at depth 0-20 cm and Sand, Slope, Mg^{2+} and Silt, at depth 20-40 cm (Table 9). Then, these variables were selected for the prediction models (Table 10).

Table 8. Eigenvalues and principal component extracted for each soil depth (0-20 and 20-40 cm).

PC	Soil depth 0 - 20 cm			Soil depth 20 - 40 cm		
	Eigenvalues	Relative Variation	Accumulated variation	Eigenvalues	Relative Variation	Accumulated variation
1	7.50	57.67	57.67	6.54	50.29	50.29
2	1.41	10.86	68.53	1.25	9.60	59.89
3	1.06	8.17	76.70	1.17	9.03	68.92
4	0.80	6.17	82.86	0.96	7.35	76.28
5	0.76	5.82	88.69	0.79	6.10	82.37
6	0.38	2.94	91.62	0.67	5.19	87.56
7	0.30	2.31	93.93	0.55	4.20	91.76
8	0.24	1.84	95.78	0.43	3.31	95.07
9	0.21	1.62	97.39	0.24	1.88	96.95
10	0.15	1.12	98.51	0.18	1.35	98.30
11	0.11	0.84	99.35	0.14	1.07	99.37
12	0.06	0.48	99.83	0.08	0.63	100.00
13	0.02	0.17	100.00	0.00	0.00	100.00

Table 9. Eigenvectors extracted from the principal components with eigenvalues above 1 for each depth (0-20 and 20-40 cm).

Variables	Soil depth 0 - 20 cm			Variables	Soil depth 20 - 40 cm			
	PC 1	PC 2	PC 3		PC 1	PC 2	PC 3	PC 4
pH_{KCl}	-0.15	-0.02	0.92	pH_{KCl}	-0.80	0.13	-0.03	-0.05
K^{+}	0.86	0.16	-0.06	K^{+}	0.58	-0.08	0.52	0.38
Ca^{+2}	0.66	0.44	-0.07	Ca^{+2}	0.47	0.20	0.50	-0.37
Mg^{+2}	0.83	0.31	-0.04	Mg^{+2}	0.50	-0.09	0.62	-0.09
Mn^{+2}	0.75	0.41	0.18	Mn^{+2}	0.67	0.26	-0.12	-0.27
Zn^{+2}	0.48	-0.02	-0.38	Al^{+3}	0.87	-0.12	-0.03	0.00
Al^{+3}	0.91	-0.21	0.05	O. C.	0.72	0.28	0.12	-0.07
O. C.	0.90	0.18	0.12	SD	-0.88	0.06	0.25	-0.10
SD	-0.84	0.35	-0.06	Clay	0.89	-0.30	-0.23	-0.11
Clay	0.89	-0.34	0.02	Silt	0.28	0.62	-0.02	0.67
Sand	-0.91	0.35	-0.05	Sand	-0.94	0.13	0.23	-0.07
Alt	0.89	-0.26	0.04	Alt	0.91	-0.02	-0.19	0.01
Slope	-0.29	-0.65	-0.05	Slope	-0.17	-0.73	0.16	0.33

Notes: O. C. = organic carbon; O. M. = organic matter; SD = soil density; PR = penetration resistance; Alt = Altitude.

The multiple regression analysis for soil depths 0 - 20 cm and 20 - 40 cm were statistically significant and explained 55% and 50%, respectively, of the site productivity variation (Table 10). By the stepwise backward method, the variables Sand, Slope and pH_{KCl} were selected at a depth of 0 - 20 cm (same as the PCA method) and pH_{KCl}, Mn^{2+} Alt and Slope, at a depth of 20 - 40 cm, which both explained 55%, of the site productivity variation (Table 10). By the same method considering only the chemical variables, pH_{KCl}, K^+ and Al^{3+} were selected at a depth of 0 - 20 cm and pH_{KCl}, K^+ and Mn^{2+}, at a depth of 20 - 40 cm, which explained 48% and 46%, respectively, of the site productivity variation (Table 10).

Considering that the topographic variables showed a good correlation with the SI and because they are easily obtainable and applicable to extensive areas, models also were generated with the two topographic variables. One model using the slope and altitude obtained with GPS and another using the corrected SRTM altitude and the slope, which explained 50% and 46%, respectively, of the variation of the SI (Table 10). Despite explaining less of the variation in site productivity, the second model allows classification of the site based only processing of DEM images, without the need to go to the field (Figure S1).

The graphs of residues distribution for the model obtained from the *stepwise backward* method in the soil depth 20-40 cm showed more adequate estimative along the regression line (Figure S2). This model also showed a higher coefficient of determination and a lower relative standard error, however, the pH_{KCl} variable was not significant in the regression.

The model obtained from the *stepwise backward* and PCA method in the soil depth 0-20 cm showed an adequate estimative along the regression line and stood out for the higher value of the coefficient of determination, lower relative standard error and less variables in the model. The chemical variable models showed non-significant variables, however between these models for the second depth there was a greater explanation for the variation in the quality of the site and less error in estimation, in addition to a better distribution of the residues (Figure S2). In turn, the model including only topographic variables also showed a good distribution of the residues (Figure S2). In addition, the independent variables in all models met the assumption of non-multicollinearity, since the VIF statistic was less than 10 for each of the variables.

Table 10. Multiple linear regression equations predicting the site index for *B. excelsa* stands from topoedaphic characteristics.

Method	Equation per soil depth	$R^2_{aj.}$	Syx	P
PCA	0-20 cm			
	$SI = 56.310^{***} - 0.197^{***}Sand - 0.656^{**}Slope - 8.401^{*}pH_{KCl}$	0.55	4.09	< 0.001
	20-40 cm			
	$SI = 20.785^{***} - 0.196^{***}Sand - 0.680^{**}Slope + 14.453^{ns}Mg^{2+} + 0.067^{ns}Silt$	0.50	4.26	< 0.001
Stepwise	0-20 cm			
Backward	$SI = 56.314^{***} - 0.197^{***}Sand - 0.656^{**}Slope - 8.401^{*}pH_{KCl}$	0.55	4.09	< 0.001
	$SI = 25.907^{ns} - 7.433^{ns}pH_{KCl} + 0.655^{**}K^{+} + 8.811^{*}Al^{3+}$	0.43	4.41	< 0.001
	20-40 cm			
	$SI = -6.836^{ns} - 22.767^{ns}pH_{KCl}^{+} + 3.542^{**}Mn^{2+} + 0.220^{**}Alt - 0.418^{*}Slope$	0.55	3.90	< 0.001
	$SI = 174.338^{***} - 40.393^{***}pH_{KCl} + 0.418^{ns}K^{+} + 5.494^{***}Mn^{2+}$	0.48	4.16	< 0.001
Topographic Variables				
	$SI = -9.181^{*} + 0.399^{***}Alt – 0.450^{*}Slope$	0.50	4.12	< 0.001
	$SI = -13.379^{**} + 0.384^{***}Alt(SRTM) – 0.500^{*}Slope$	0.46	4.27	< 0.001

Sand (%); pH_{KCl} = pH in KCl; Mg^{2+} ($cmol_c\ kg^{-1}$); K^{+} ($mg\ kg^{-1}$); Mn^{2+} ($mg\ kg^{-1}$); Al^{3+} ($cmol_c\ kg^{-1}$); Alt = Altitude (m); Alt(SRTM) = Altitude based on SRTM digital elevation model; Slope (%). *** $P < 0.001$. ** $P < 0.01$. * $P < 0.05$. ^{ns} $P \geq 0.05$.

4. Discussion

4.1. Classification of productive capacity of B. excelsa stands

The Chapman-Richards model was more efficient and flexible among the tested models, resulting in polymorphic curves (free parameter $\emptyset_1$) that best represented the behavior of the H_d variable, with the highest percentages of plots included by the curves over time (73% to data used in the adjustment and 60% to independent data), as well as homogeneous distribution among site classes. Sigmoid models like Chapman-Richards have been widely used in silviculture, as they have interpretable parameters such as asymptote, inflection point and scale, in addition to estimating consistently outside the adjusted data range (Bravo and Montero, 2001; Machado et al., 2011).

Moreover, this model has better represented the asymptotic behavior of the H_d variable at older ages (Retslaff et al., 2015).

In several studies using the guide curve method or the algebraic difference approach in native (*Mimosa scabrella* Benth.) or exotic (*Eucaliptus* sp. or *Pinus* sp.) plantations, the Chapman-Richards model also was selected for presenting better adjustments criteria and stability of the curves (Cunha Neto et al., 1996; Machado et al., 2011; Bila et al., 2012; Retslaff et al., 2015; Silva et al., 2018). These results demonstrate as found here the efficiency and flexibility of the Chapman-Richards model for classifying productive capacity of forest stands (Silva et al., 2018).

In turn, the Logistic model, despite showing good statistical criteria, generated curves with less consistency in the distribution of H_d values among ages. Therefore, although the evaluation of statistical parameters is essential to analyze the estimation accuracy of the models, it is necessary to observe the behavior of site index curves in relation to the dispersion of H_d observed over time (Silva et al., 2018), since that appropriate models should generate consistent curves for the distribution of H_d values among ages (Campos and Leite, 2013). Similar this study, Silva et al. (2018) found that the Logistical and Gompertz models presented larger deficiencies in data conformation than the other models, due to their more marked sigmoid configurations that resulted in deficient classification at younger ages. On the other hand, the models Bailey-Clutter, Chapman-Richards and Hossfeld IV showed more consistency between the pairs of values of H_d and age.

Despite the evaluation of the dispersion of the values makes it possible to verify the consistency of the curves, it is also essential to verify the stability of these curves. According to Clutter et al. (1983), when the height of the dominant trees of each sample unit remains constant in the same site class, there is thus a strong basis for growth and yield studies. Thus, different authors consider the stability of growth curves as an important criterion for classification of the productive capacity (Machado et al., 2011; Silva et al., 2018). For some of them, the classes delimited by the curves must comprise all plots over time, while other authors consider that plots outside the curves can be considered as belonging to the more or less productive classes (Silva et al., 2018). In addition, there is no defined limit in the literature on the percentage of trees that should be included in the curves over time and generally the works only evaluate graphically, as in the example of Machado et al. (2011). However, Silva et al. (2018) obtained about 75% of the plots fully included in the curves over time (2-10 years) for *Eucalyptus* stands. Thus, in our study the curves stability test was performed considering the number of times that the plots changed class and the number of plots fully contemplated by the curves over time based on the data of complete stem analysis (Silva et al., 2018). Then, the curves generated by the models showed better stability and consistency to data over of 4 (four) years-old. The low consistency of the curves is usually the result of inconsistencies in the classification of the site at younger ages (Silva et al., 2018). Other authors such as Machado et al. (2011), Cruz et al. (2008), Scolforo and Machado (1988) and Selle et al. (1994) found inconsistencies at younger ages with class changes at initial ages, that suggest to avoid the classification of sites in plantations with younger ages (Machado et al., 2011; Liziniewicz et al., 2016).

After the classification and spatialization of the sites, we verified that the intermediate class (Sitio II) had the largest coverage in *B. excelsa* stands with 45%, followed by classes III and I with 31% and 24%, respectively. Thus, the prospecting of production through growth models such as volume, as well as the management of plantations should consider the stratification of the stands to improve the production estimates and supports the application of more specific silvicultural treatments in the stands.

4.2. *Topoedaphic characteristics predicting the site productivity in B. excelsa stands*

The most of the topoedaphic characteristics were significantly related to the site index (SI). Particularly, the soil texture and altitude influenced strongly the productive capacity of *B. excelsa* stands. According with this finding, in an experimental plantation, the same species at two years-old exhibited the best growth in soil with a clayey to very clayey texture, while the worse performance was shown in sandy soils (Lima et al., 2004). In degraded areas by bauxite mining, the soil fertility was not the main cause of differences in the growth of *B. excelsa* trees at six years-old, but the physical degradation of the soil represented by the increase in the soil density, greater Fe–laterite mass on the soil surface and beginning of the Fe–laterite layer in soil profiles (Melo et al., 2018). In the present study, the site III with the lowest values of site index (SI) was the main responsible for the greater influence of soil texture on the productive capacity, evidenced by the greater number of points close to the Sand vector and greater separation of this site in relation to the others (Figure 9). In addition, topographic variables are locally important determinants of site quality and although these factors do not have direct effects on the growth of trees, they are more directly correlated with causal factors, such as the amount of solar radiation, microclimate conditions, soil and humidity (Carmean, 1971; Johnson et al., 2019; Rachid-Casnati et al., 2019).

In eastern beech forests in Turkey, the altitude was positively correlated with the SI, mainly due to the increase in horizons A and B and the physiological soil (*i. e.*, the potential depth for root growth without physical limitation) depth, as well as an increase in the clay content and a reduction in the content of sand, while the positive correlation of the slope with the SI was probably due to better soil drainage (Yilmaz, 2019). In *Pinus Taeda* plantations in Uruguay, the positive correlation between altitude and SI is probably related with low drainage in lower areas, that are drenched for short periods (Rachid-Casnati et al., 2019). In turn, in stands of *Eucalyptus grandis* in the municipality of Paraibuna in the state of São Paulo - Brazil, the productive potential of this species occurred in areas less elevated in the relief due to greater fertility and better soil drainage associated with lower clay contents and greater soil porosity (Ortiz et al., 2006). In the present study, the differences in altitude and slope are relatively small and probably have little influence on the specific temperature and humidity of the place, but certainly influence the texture of the soil, which in turn reflects on the soil fertility. Thus, sloping sites and low areas with a lower SI are associated with a sandier texture. Marques et al. (2016) observed changes in soil and soil texture along a topographic gradient Oxisol (plateau), Ultisol (slope) and Spodosol (valley) that varied according to altitude (50-120 m), in an area of forest in the Central Amazon. In addition, a study realized by Botschek et al. (1996) on the same property in our study, found a decrease in agricultural potential along a toposequence Yellow Latossol Allic (Oxisol) in plateau, Yellow Latossol Epiallic Dystrophic (Oxisol) in slope and Quartzose Sand Hydromorphic Dystrophic (Entisol / Quartzipsamments) in lower slope mainly due to the variation of soil texture and slope that influence fertility and susceptibility to soil erosion.

Chemical variables of the soil, whereas in a minor magnitude, also influenced the capacity productive of sites, mainly in the second depth, due to the lower content of organic matter (Table 6). Once the soil texture is directly or indirectly related to the cation exchange capacity (CTC), where more clayey soils have a higher CTC (Meurer, 2007). The soil chemical characteristics are not always considered useful to derive equations for predicting the quality of the site, probably due to the large number of correlations among variables (Post et al., 1969). Even, some chemical variables contributed significantly to explain the variation of the productive capacity as K^+, Mn^{2+} and pH_{KCl}. Specifically, Mg^{2+} and organic carbon, although not significantly contributing to the prediction models, showed a strong relationship with SI. Several experiments of forest nutrition have shown positive responses of *B. excelsa* to nutrients supply. The organic fertilization of *B. excelsa* young plants, for example, contributed to increase mainly on C and N levels in the soil and also in the contents of K^+, Ca^{2+}, Mg^{2+} and Mn^{2+}, which favored the increasing on phosphorus use-efficiency, consequently, improving the annual growth rate (Ferreira et al., 2012; Ferreira et al., 2015). In agroforestry systems in Central Amazonia, the species also responded positively to the application of limestone and fertilization, where the greatest availability of Mg^{2+} and Ca^{2+} in the soil provided significant increases in the concentrations of these nutrients in the leaves, which may have been responsible for the significant increase on tree growth (Schroth et al., 2015).

The increase in acidity and Al^{3+} content of soils was strongly related to the SI. The soils are acidic, with the clay fraction consisting mainly by kaolinite and iron and aluminum oxides (Ker, 1997), which can result in the occurrence of Al^{3+} toxic to plants (Vitorello et al., 2005; Singh et al., 2017; Rahman et al., 2018), since that a pH reduction below 5, aluminum is solubilized in the soil solution (Kochian et al., 2005). Melo et al. (2018) found a positive relationship of content of Al^{3+} and a negative relationship of pH with the growth of trees of Brazil nut and suggested that the greater growth of the trees may have favored the soil acidification. This can be explained by the greater exudation of low molecular weight organic acids in the rhizosphere, due to the greater volume of roots (Jones et al., 2009) and by the biological decomposition of a greater amount of organic matter accumulated on the soil, releasing organic acids that infiltrate the soil (Tani et al., 2001). In addition, the acidification of soils is associated with the loss of exchangeable bases and the formation of low-quality organic matter (Boruvka et al., 2005). Consequently, in native stands, the highest fruit production of *B. excelsa* was associated with a higher content of Al^{3+} in the topsoil (0 - 20 cm), probably due to the removal of exchangeable bases, favoring soil acidification (Costa et al., 2017).

Considering the effects of topographic, physical and, in minor magnitude, of chemical soil characteristics on productive capacity of sites, a model based on sand, slope and pH_{KCl} variables, proved to be promising for estimating the site quality, explaining 55% of the variation of site quality in *B. excelsa* stands (Table 10). According to Blyth and MacLeod (1981), for models of productivity of tree species to have some practical use in forest management, they must be able to explain at least 50% of the variation of the SI and must be based on easily measurable variables. Edaphic characteristics such as pH, clay content, coarse fragments and depth to root-restricting layer and topographic variables such as slope were closely related to the SI in populations dominated by jack pine (*Pinus banksiana* Lamb.) in the northwest of Ontario, resulting in equations with R^2 values ranging from 0.65 to 0.83 (Schmidt and Carmean, 1988). In a Douglas-fir forests in north central Idaho, a model composed of topographic variables and volcanic ash depth explained 50% of the variation in the SI (Kimsey et al., 2008). In the same way, for *Pinus taeda* (L.) and *Eucalyptus grandis* (L.) plantations in Uruguay, the use of edaphic and topographic variables, such as water holding capacity, elevation, slope and aspect, improved the predictions of the H_d variable (Rachid-Casnati et al., 2019).

4.3. Implications for management of planted forest in Amazonia

Reforestation programs using native tree species are considered urgent issues for tropical silviculture in Amazonia. In this context, the site zoning from topographic, edaphic and climatic factors constitutes one of the main research gaps and priorities for the establishing of plantings (Rolim et al., 2019). Particularly, among the 45 pre-selected native tree species for plantations, only two (*Schizolobium parahyba* var. *amazonicum* and *Tachigali vulgaris*) had filled this research gap.

The results found here may support the adequate planning of operational activities related to the installation and management of *B. excelsa* stands in Amazonas. Bearing in mind that one of the challenges to intensify forest management practices is the identification of more productive forest areas for tree growth (Carmean 1996; Rolim et al., 2019), in *B. excelsa* stands, for example, we show that the species presents a better development under certain topoedaphic conditions (higher clay content and higher topographic positions) that can be used as factors for the diagnosis of potential areas to the species establishment, contributing to the expansion of commercial plantations in the Amazonia region.

Still the possibility of applying the curves generated by the Chapman-Richards model in view of the consistency and stability of the curves to the data of H_d over the ages, makes it possible to stratify the stands of *B. excelsa* for purposes of specific production management. In addition, it may make it possible to prospect for production when associated with volumetric production models. However, it is important to continuously monitor the growth of dominant trees to confirm the site index (SI) estimates at the reference age, as well as performing modeling with the addition of new measurements at ages closer to the age of rotation.

In addition, it is important to collect data in other stands of *B. excelsa* in the region to obtain greater variation in the quality of site the species in different topoedaphic conditions to contribute to the zoning of sites more appropriate to the species. For example, in our study area on soils with low fertility, without correction of soil acidity and application of fertilizers, we obtained values of mean annual increment in height and diameter that varied from 0.52 to 1.17 m and 0.70 to 1.37 cm respectively (Table S2), however in others sites in the Amazon region in homogeneous plantations with ages between 6 to 27 years implanted in dense spacing, higher mean annual increment values in height and diameter were obtained that varied from 0.50 to 1.54 m and 0.39 to 1.85 cm, respectively, in different types of soil and climate (Yared et al., 1998; Fernandes and Alencar, 1993; Tonini et al., 2008; Machado et al., 2017). Thus, considering higher values at other sites and that we calculated the values of mean annual increment in height and diameter based only on the dominant trees, our study did not cover the entire range of variation in site quality for this species in the Amazon region.

Finally, we made some recommendations to support the adequate planning of operational activities related to the stages of implantation and management of the *B. excelsa* stands in Amazonas: i) the use of the Chapman-Richards model for classifying the productive capacity in *B. excelsa* plantations in the region; ii) planting the species in soils with a clayey to very clayey texture and in higher topographic positions in the area with less slope; iii) more in-depth studies on the species response to K^+, Mn^{2+}, Ca^{2+}, Mg^{2+} and incorporation of organic matter in plantations of different ages for wood production; iv) practices to correct the soil acidity; v) use of topographic variables in prediction models for identification and rapid diagnosis of areas with productive potential for planting the species and use of edaphic variables for better diagnosis.

5. Conclusions

In summary, our main findings were as follows: first, the Chapman-Richards model is more accurate to estimate the site productive capacity in *B. excelsa* stands; second, the existence of polymorphism indicate a divergent growth pattern of *B. excelsa* trees over time as affected by site class and, third, the site quality in *B. excelsa* stands can be mainly related to the soil sand content and altitude and, in a minor order of magnitude, by soil chemical characteristics K^+, Mn^{2+} and pH_{KCl}. These results can support the best planning of operational activities related to installation and management of *B. excelsa* stands in the Amazon, besides to identification of potential areas to expand the plantations of this important commercial tree species.

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6. References

Andrade, R.S., Stone, L.F. 2011. Estimativa da umidade na capacidade de campo em solos sob Cerrado. Revista Brasileira de Engenharia Agrícola e Ambiental, 15(2), 111-116. https://dx.doi.org/10.1590/S1415-43662011000200001

Assmann, E. 1971. The Principles of Forest Yield Study, first ed. Pergamon press.

Bila, J.M., Sanquetta, C.R., Machado, S.A. 2012. Classificação de sítios com base em fatores edáficos para *Pinus caribaea* var. *hondurensis* na região de Prata, Minas Gerais. Floresta, 42(3), 465-474. http://dx.doi.org/10.5380/rf.v42i3.19014

Blyth, J.F., MacLeod, D.A. 1981. Sitka Spruce *Picea sitchensis* in North-East Scotland II. Yield Prediction by Regression Analysis. Forestry, 54(1), 63-73. https://doi.org/10.1093/forestry/54.1.63

Borém, A., Lopes, M.T.G., Clement, C.R. 2009. Domesticação e melhoramento: espécies amazônicas. Viçosa.

Boruvka, L., Mladkova, L., Drabek, O. 2005. Factors controlling spatial distribution of soil acidification and Al forms in Forest soils. Journal of Inorganic Biochemistry, 99(9), 1796-1806. http://dx.doi.org/10.1016/j.jinorgbio.2005.06.028

Botschek, J., Ferraz, J., Jahnel, M., Skowronek, A. 1996. Soil chemical properties of a toposequence under primary rain forest in the Itacoatiara vicinity (Amazonas, Brazil). Geoderma, 72(1-2), 119-132. http://dx.doi.org/10.1016/0016-7061(96)00026-2

Bravo, F., Montero, G. 2001. Site index estimation in Scots pine (*Pinus sylvestris* L.) stands in the High Ebro Basin (northern Spain) using soil attributes. Forestry, 74(4), 395-406. https://dx.doi.org/10.1093/forestry/74.4.395

Bravo-Oviedo, A., Río, M.D., Montero, G. 2004. Site index curves and growth model for Mediterranean maritime pine *Pinus pinaster* Ait.in Spain. Forest Ecology and Management, 201(2-3), 187-197. https://doi.org/10.1016/j.foreco.2004.06.031

Brienen, R.J.W., Zuidema, P.A. 2005. Relating tree growth to rainfall in Bolivian rain forests: a test for six species using tree ring analysis. Oecologia, 146(1), 1-12. https://doi.org/10.1007/s00442-005-0160-y

Brochado, G.T. 2015. Atenuação do efeito de desflorestamento em dados SRTM por meio de diferentes técnicas de interpolação. Dissertação (Mestrado). Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil. 113 p.

Burkhart, H.E., Tomé, M. 2012. Modeling Forest Trees and Stands, first ed. New York.

Busscher, W.J., Bauer, P.J., Camp, C.R., Sojka, R.E. 1997. Correction of cone index for soil water content differences in a coastal plain soil. Soil and Tillage Research, 43(3-4), 205-217. https://doi.org/10.1016/s0167-1987(97)00015-9

Campos, J.C.C., Leite, H.G. 2013. Mensuração florestal: perguntas e respostas. fifth ed. Viçosa.

Carmean, W.H. 1971. Soil-site relationships of the upland oaks. Oak Symp. Proc. USDA Forest Service Research Paper. Northeast. Forest Exp. Sta., Upper Darby, PA. 23-29.

Carmean, W.H. 1975. Forest Site Quality Evaluation in The United States. Advances in Agronomy, 27(0), 209-269. https://doi.org/10.1016/s0065-2113(08)70011-7

Carmean, W.H. 1996. Forest site-quality estimation using Forest Ecosystem Classification in Northwestern Ontario. Environmental Monitoring and Assessment, 39(1-3), 493-508. https://doi.org/10.1007/BF00396164

Carvalho, J.P., Parresol, B.R. 2005. A site model for Pyrenean oak *Quercus pyrenaica* stands using a dynamic algebraic difference equation. Canadian Journal of Forest Research, 35(1), 93-99. https://doi.org/10.1139/x04-155

Clutter, J.L., Forston, J.C., Piennar, L.V., Brister, G.H., Bailey, R.L. 1983. Timber management: a quantitative approach. New York.

Corona, P., Scotti, R., Tarchiani, N. 1998. Relationship between environmental factors and site index in *Douglas-fir* plantations in central Italy. Forest Ecology and Management, 110(1-3), 195-207. https://doi.org/10.1016/s0378-1127(98)00281-3

Costa, J.R., Castro, A.B.C., Wandelli, E.V., Coral, S.C.T., Souza, S.A.G. 2009. Aspectos silviculturais da castanha-do-Brasil *Bertholletia excelsa* em sistemas agroflorestais na Amazônia Central. Acta Amazônica, 39(4), 843-850. http://dx.doi.org/10.1590/S0044-59672009000400013

Costa, M.G., Tonini, H., Mendes Filho, P. 2017. Atributos do Solo Relacionados com a Produção da Castanheira-do-Brasil *Bertholletia excelsa* Floresta e Ambiente, 24(0), 2-10. http://dx.doi.org/10.1590/2179-8087.004215

Cronkleton, P., Guariguata, M.R, Albornoz, M.A. 2012. Multiple use forestry planning: timber and Brazil nut management in the community forests of Northern Bolivia. Forest Ecology and Management, 268(1), 49-56. https://doi.org/10.1016/j.foreco.2011.04.035

Cruz, J.P., Leite, H.G., Soares, C.P.B., Campos, J.C.C., Smit, L., Nogueira, G.S. 2008. Curvas de crescimento e de índice de local para povoamentos de *Tectona grandis* em Tangará da Serra, Mato Grosso. Revista Árvore, 32(4), 679-685. https://dx.doi.org/10.1590/S0100-67622008000400009

Cunha Neto, F.R., Scolforo, J.R., Calegario, N., Kanegae Júnior, H. 1996. Uso da diferença algébrica para construção de curvas de índice de sítio para *Eucalyptus grandis* e *Eucalyptus urophylla* na região de Luiz Antônio, SP. Revista Cerne, 22(0), 119-141.

Curt, T., Bouchaud, M., Agrech, G. 2001. Predicting site index of *Douglas-Fir* plantations from ecological variables in the Massif Central área of France. Forest Ecology and Management, 149(1-3), 61-74. https://doi.org/10.1016/S0378-1127(00)00545-4

Embrapa. 1997. Manual de métodos de análise de solo. second ed. Rio de Janeiro.

Farrelly, N., Ní Dhubháin, Á., Nieuwenhuis, M. 2011. Site index of Sitka spruce *Picea sitchensis*in relation to different measures of site quality in Ireland. Can. J. For. Res. 41(2), 265-278. https://doi.org/10.1139/X10-203

Fernandes, N.P., Alencar, J.C. 1993. Desenvolvimento de árvores nativas em ensaios de espécies. 4. Castanha-do-brasil *Bertholletia excelsa* H. B. K., dez anos após o plantio. Acta Amazonica, 23(2-3), 191-198. http://dx.doi.org/10.1590/1809-43921993233198

Ferreira, L.M.M., Tonini, H. 2009. Comportamento da castanha-do-brasil *Bertholletia excelsa* e da cupiúba *Goupia glabra*em sistema agrosilvicultural na região da Confiança, Cantá – Roraima. Acta Amazônia, 39(4), 83-842. http://dx.doi.org/10.1590/S0044-59672009000400012

Ferreira, M.J., Gonçalves, J.F.C., Ferraz, J.B.S. 2012. Crescimento e eficiência do uso da água de plantas jovens de castanheira-da-amazônia em área degradada e submetidas à adubação. Ciência Florestal, 22(2), 393-401. http://dx.doi.org/10.5902/198050985747

Ferreira, M.J., Gonçalves, J.F.C., Ferraz, J.B.S., Corrêa, V.M. 2015. Características nutricionais de plantas jovens de *Bertholletia excelsa* Bonpl. sob tratamentos de fertilização em área degradada na Amazônia. Scientia Forestalis, 43(108), 863-872. http://dx.doi.org/10.18671/scifor.v43n108.11

Ferreira, M.J., Gonçalves, J.F.D.C., Ferraz, J.B.S., Santos Junior, U.M., Rennenberg, H. 2016. Clonal variation in photosynthesis, foliar nutrient concentrations, and photosynthetic nutrient use efficiency in a Brazil nut *Bertholletia excelsa* plantation. Forest Science, 62(3), 323-332. https://doi.org/10.5849/forsci.15-068

Field, A 2009. Discovering statistics using SPSS. third ed. London.

Guimarães, R.M.L., Neves Júnior, A.F., Silva, W.G., Rogers, C.D., Bola, B.C., Montes, C., Pereira, B.F.F. 2017. The merits of the Visual Evaluation of Soil Structure method VESS for assessing soil physical quality in the remote, undeveloped regions of the Amazon basin. Soil and Tillage Research, 173(0), 75-82. https://doi.org/10.1016/j.still.2016.10.014

Hoch, L., Pokorny, B., Jong, W. 2009. How successful is tree growing for smallholders in the Amazon?. International Forestry Review, 11(3), 299-310. https://doi.org/10.1505/ifor.11.3.299

Isaaks, E.H., Srivastava, M. 1989. An introduction to applied geostatistics. New York: Oxford University Press.

Jakobsen, B.F., Dexter, A.R., 1987. Effect of soil structure on wheat root growth, water uptake and grain yield. A computer simulation model. Soil Till. Res. 10(4), 331-345. https://doi.org/10.1016/0167-1987(87)90022-5

Johnson, P.S., Shifley, S.R., Rogers, R., Dey, D.C., Kabrick, J.M. 2019. The Ecology and Silviculture of Oaks. third ed. Boston, MA : CABI.

Johnson, R.A., Wichern, D.W. 1998. Applied multivariate statistical analysis. fourth ed. New Jersey, USA: Prentice Hall.

Jones, D.L., Nguyen, C., Finlay, R.D. 2009. Carbon flow in the rhizosphere: carbon trading at the soil–root interface. Plant and Soil, 321(1-2), 5–33. https://doi.org/10.1007/s11104-009-9925-0

Kaiser, H.F. 1960. The Application of Electronic Computers to Factor Analysis. Educational and Psychological Measurement, 20(1), 141-151. https://doi.org/10.1177/001316446002000116

Kariuki, M. 2002. Height estimation in complete stem analysis using annual radial growth measurements. Forestry, 75(1), 63-74. https://doi.org/10.1093/forestry/75.1.63

Kato, A.K. 1995. Dinâmica da entrada de nutrientes via liteira em plantios de castanheira-do-Brasil *Bertholletia excelsa* H. B. K. em ecossistemas de pastagens degradadas e de floresta primária [Dynamic of nutrients by litter in Brazil nut *Bertholletia excelsa* H. B. K. plantations in ecosystems of degraded pastures and primary forests]. *PhD dissertation*, Instituto Nacional de Pesquisas da Amazônia, Manaus, AM, Brazil. 360 p.

Ker, J.C. 1997. Latossolos do Brasil: uma revisão. Geonomos, 5(1), 17-40. https://doi.org/10.18285/geonomos.v5i1.187

Kimsey, M.J., Moore Júnior, J., McDaniel, P. 2008. A Geographically Weighted Regression Analysis of Douglas-Fir Site Index in North Central Idaho. Forest Science, 54(3), 356-366. https://doi.org/10.1093/Forestscience/54.3.356

Kitikidou, K., Bountis, D., Milios, E. 2011. Site index models for calabrian pine *Pinus brutia* Ten.in Thasos Island, Greece. Ciênc. Florest., 21(1), 125-131. http://dx.doi.org/10.5902/198050982755

Kochian, L.V, Piñeros, M.A, Howkenga, O.A. 2005. The physiology, genetics and molecular biology of plant aluminum resistance and toxicity. Plant and Soil, 274(1-2), 175-195. http://dx.doi.org/10.1007/s11104-004-1158-7

Köppen, W. Climatologia: com un estudio de los climas de la tierra. México: Fondo de Cultura Economica, 1948. 478 p.

Kravchenko, A.N. 2003. Influence of Spatial Structure on Accuracy of Interpolation Methods. Soil Science Society of America Journal, 67(5), 1564. http://dx.doi.org/10.2136/sssaj2003.1564

Lima, R.M.B., Higa, A.R., Souza, C.R. 2004. Influência dos fatores edáficos no crescimento da *Bertholletia excelsa* H. B. K. na Amazônia. In: Congresso Brasileiro de Sistemas Agroflorestais, Curitiba. Anais. Colombo: Embrapa Florestas, p. 319-321.

Lindsey, C., Sheather, S. 2010. Variable selection in linear regression. The Stata Journal, 10(4), 650-669. https://doi.org/10.1177/1536867X1101000407

Liziniewicz, M., Nilsson, U., Agestam, E., Ekö, P.M., Elfving, B. 2016. A site index model for lodgepole pine *Pinus contorta* Dougl. var. latifolia in northern Sweden. Scandinavian Journal of Forest Research, 31(6), 583-591. https://doi.org/10.1080/02827581.2016.1167238

Locatelli, M., Marcante, P.H., Cipriani, H.N. Martins, E.P., Vieira, A.H. 2015. Avaliação do crescimento da Castanha-do-Brasil *Bertholletia excelsa* BONPL. em um plantio no munícipio de Machadinho do Oeste - Rondônia. Enciclopédia Biosfera, 11(22), 457-470.

Louw, J.H., Scholes, M.C. 2006. Site index functions using site descriptors for *Pinus patula* plantations in South Africa. Forest Ecology and Management, 225(1-3), 94-103. https://doi.org/10.1016/j.foreco.2005.12.048

Machado, M.R., Souza, R.C., Sampaio, P.T.B., Ferraz, J.B.S. 2017. Aspectos silviculturais da Castanha-do-Brasil (*Bertholletia excelsa* Humb. e Bonpl.). Biota Amazônia, 7(3), 41-44. http://dx.doi.org/10.18561/2179-5746/biotaamazonia.v7n3p41-44

Machado, S.A., Oliveira, E.B., Carpanezzi, A.A., Bartoszeck, A.C.P.S. 1997. Classificação de sítio para bracatingais na região metropolitana de Curitiba. Boletim de Pesquisa Florestal, Colombo, 35(0), 21-37.

Machado, S.A., Souza, R.F., Jaskiu, E., Cavalheiro, R. 2011. Construction of site curves for native *Mimosa scabrella* stands in the metropolitan region of Curitiba. Cerne, Lavras, 17(4), 489-497. http://dx.doi.org/10.1590/S0104-77602011000400007

Marques, J.D.O., Luizão, F.J., Teixeira, W.G., Vitel, C.M., Marques, E.M.A. 2016. Soil organic carbon, carbon stock and their relationships to physical attributes under forest soils in Central Amazonia. Revista Árvore, 40(2), 197-208. https://doi.org/10.1590/0100-67622016000200002

Mckenney, D.W., Pedlar, J.H. 2003. Spatial models of site index based on climate and soil properties for two boreal tree species in Ontario, Canadá. Forest Ecology and Management, 175(1-3), 497-507. https://doi.org/10.1016/S0378-1127(02)00186-X

McLean, E.O. 1965. Aluminum. In: BLACK, C. A. Ed., Methods of soil analysis: Part 2, Chemical methods. Madison: ASA.

Melo, V.F., Batista, A.H., Barbosa, J.Z., Barbeiro, L., Gomes, R., Dultra, M.T.M. 2018. Soil quality and reforestation of the Brazil nut tree *Bertholletia excelsa* Bonpl. after laterite-type bauxite mining in the Brazilian Amazon forest. Ecological Engineering, 125(0), 111-118. https://doi.org/10.1016/j.ecoleng.2018.10.016

Meurer, E.J. 2007. Fatores que influenciam o crescimento e o desenvolvimento das plantas. In: Novais, R.F., Venegas, V.H.A., Barros, N.F., Fontes, R.L.F., Cantarutti, R.B., Neves, J.C.L. 2007. Fertilidade do solo. First ed. Viçosa.

Montgomery, D.C., Runger, G.C. 2009. Estatística aplicada e probabilidade para engenheiros. fourth ed. Rio de Janeiro.

Murphy, J., Riley, J.P. 1962. A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta, 27(0), 31-36. https://doi.org/10.1016/s0003-2670(00)88444-5

Ortega, A., Montero, G. 1988. Evaluación de la calidad de las estaciones forestales. Revisión bibliográfica. Ecología, 2(0), 155-184.

Ortiz, J.L., Vettorazzi, C.A., Couto, H.T.Z., Goncalves, J.L.M. 2006. Relações espaciais entre o potencial produtivo de um povoamento de eucalipto e atributos do solo e do relevo. IPEF. Instituto de Pesquisas e Estudos Florestais, 72(0), 67-79.

Palahí, M., Tomé, M., Pukkala, T., Trasobares, A., Montero, G. 2004. Site index model for *Pinus sylvestris* in north-east Spain. Forest Ecology and Management, 187(1), 35-47. https://doi.org/10.1016/s0378-1127(03)00312-8

Post, B.W., Carmean, W.H., Curtis, R.O. 1969. Birch soil-site requirements. In: Proceedings, Birch Symposium. pp. 95– 101. USDA Forest Service, Northeastern Forest Experiment Station, Upper Darby, PA.

Rachid-Casnati, C., Mason E.G., Woollons, R.C. 2019. Using soil-based and physiographic variables to improve stand growth equations in Uruguayan forest plantations. iForest 12(3), 237-245. https://doi.org/10.3832/ifor2926-012

Rahman, M., Lee, S.H., Ji, H., Kabir, A., Jones, C., Lee, K.W. 2018. Importance of Mineral Nutrition for Mitigating Aluminum Toxicity in Plants on Acidic Soils: Current Status and Opportunities. International Journal of Molecular Sciences, 19(10), 3073. https://doi.org/10.3390/ijms19103073

Retslaff, F.A.S., Figueiredo Filho, A., Dias, A.N., Bernett, L.G., Figura, M.A. 2015. Curvas de sítio e relações hipsométricas para *Eucalyptus grandis* na região dos Campos Gerais, Paraná. Cerne, 21(2), 219-225. https://dx.doi.org/10.1590/01047760201521021349

Rigatto, P.A., Dedecek, R.A., Mattos, J.L.M. 2005. Influência dos atributos do solo sobre a produtividade de *Pinus taeda*. Revista Árvore, 29(5), 701-709. http://dx.doi.org/10.1590/S0100-67622005000500005

Rolim, S.G., Piña-Rodrigues, F.C.M., Piotto, D., Batista, A., Freitas, M.L.M., Brienza Junior, S., Zakia, M.J.B., Calmon, M. 2019. Research Gaps and Priorities in Silviculture of Native Species In Brazil. Working Paper. São Paulo, Brasil: WRI Brasil. Available online at https://wribrasil.org.br/pt/publicacoes

Salomão, R.P. 2014. A castanheira: história natural e importância socioeconômica. Boletim do Museu Paraense Emílio Goeldi: Ciências Naturais, 9(2), 259-266.

Schmidt, M.G., Carmean, W.H. 1988. Jack pine site quality in relation to soil and topography in north central Ontario. Canadian Journal of Forest Research, 18(3), 297-305. https://doi.org/10.1139/x88-046

Schöngart, J., Gribel, R., Ferreira da Fonseca-Junior, S., Haugaasen, T. 2015. Age and Growth Patterns of Brazil Nut Trees *Bertholletia excelsa* Bonpl.in Amazonia, Brazil. Biotropica, 47(5), 550-558. https://doi.org/10.1111/btp.12243

Schroth, G., Mota, M.S.S., Assis Elias, M.E. 2015. Growth and nutrient accumulation of Brazil nut trees *Bertholletia excelsa* in agroforestry at different fertilizer levels. Journal of Forestry Research, 26(2), 347-353. http://dx.doi.org/10.1007/s11676-015-0037-9

Scoles, R., Gribel, R., Klein, G.N. 2011. Crescimento e sobrevivência de castanheira *Bertholletia excelsa* Bonpl. em diferentes condições ambientais na região do rio Trombetas, Oriximiná, Pará. Boletim do Museu Paraense Emílio Goeldi: Ciências Naturais, 6(3), 273-293.

Scolforo, J.R.S. 1992. Curvas de índice de sítio para *Pinus caribaea* var. *hondurensis*. IPEF, 45(0), 40-47.

Scolforo, J.R.S. 1997. Biometria florestal: métodos para classificação de sítios florestais. Lavras.

Scolforo, J.R.S. 2006. Biometria florestal: modelos de crescimento e produção florestal. Lavras.

Scolforo, J.R.S., Machado, S.A. 1988. Curvas de índice de sítio para plantações de *Pinus elliotti* nos estados do Paraná e Santa Catarina. Revista Floresta, 18(1-2), 1982-4688. http://dx.doi.org/10.5380/rf.v18i12.6392

Selle, G.L., Schneider, P.R., Guimarães Finger, C.A. 1994. Classificação de sítio para *Pinus taeda* L., através da altura dominante, para a região de Cambará do Sul, RS, Brasil. Ciência Florestal, 41(1), 77-95. https://dx.doi.org/10.5902/19805098299

Silva, G.C.C., Calegario, N., Silva, A.A.L., Cruza, J.P., Leite, H.G. 2018. Site index curves in thinned and non-thinned *eucalyptus* stands. Forest Ecology and Management, 408(0), 36-44. https://doi.org/10.1016/j.foreco.2017.10.036

Silva, F.R., Silva, V., Miranda, S., Oliveira, B.R., Silva, J.C. 2016. Classificação da produtividade para um plantio de *Tectona grandis* em alta floresta, Mato Grosso. Ambiência, 12(4), 809-823.

Singh, S., Tripathi, D.K., Singh, S., Sharma, S., Dubey, N.K., Chauhan, D.K., Vaculík, M. 2017. Toxicity of aluminium on various levels of plant cells and organism: A review. Environmental and Experimental Botany, 137(0), 177-193. https://doi.org/10.1016/j.envexpbot.2017.01.005

Smith, C.W., Johnston, M.A., Lorentz, S. 1997. The effect of soil compaction and soil physical properties on the mechanical resistance of South African forestry soils. Geoderma, 78(1-2), 93-111. https://doi.org/10.1016/s0016-7061(97)00029-3

Tani, M., Shida, K.S., Tsutsuki, K., Kondo, R. 2001. Determination of water-soluble low-molecular-weight organic acids in soils by ion chromatography. Soil Science and Plant Nutrition, 47(2), 387-397. https://doi.org/10.1080/00380768.2001.10408401

Tonini, H., Oliveira Júnior, M.C.M., Schwengber, D. 2008. Crescimento de espécies nativas da Amazônia submetidas ao plantio no estado de Roraima. Ciência Florestal, 18(2), 151-158. https://doi.org/10.5902/19805098453

Vaz, C.M.P., Manieri, J.M., Maria, I.C., Tuller, M. 2011. Modeling and correction of soil penetration resistance for varying soil water content. Geoderma, 166(1), 92-101. https://doi.org/10.1016/j.geoderma.2011.07.016

Vitorello, V.A., Capaldi, F.R., Stefanuto, V.A. 2005. Recent advances in aluminum toxicity and resistance in higher plants. Brazilian Journal of Plant Physiology, 17(1), 129-143. https://doi.org/10.1590/s1677-04202005000100011

Walkley, A., Black, I.A. 1934. An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science, 37(1), 29–38. http://dx.doi.org/10.1097/00010694-193401000-00003

Webster, R., Oliver, M.A. 2007. Geostatistics for environmental scientists. second ed. West Sussex: John Wiley and Sons Ltd.

Yamamoto, J.K., Landim, P.M.B. 2013. Geoestatística: Conceitos e aplicações. São Paulo.

Yared, J.A.G., Kanashiro, M., Conceição, J.G.L. 1988. Espécies florestais nativas e exóticas: comportamento silvicultural no planalto do tapajós – Pará. EMBRAPA-CPATU.

Yared, J.A.G., Kanashiro, M., Viana, L.M., Castro, T.C.A., Pantoja, J.R.S. 1993. Comportamento silvicultural de castanheira *Bertholletia excelsa* H. B. K. em diversos locais da Amazônia. In: Congresso Florestal Panamericano, Curitiba-Pr. Anais. Sociedade Brasileira de Silvicultura/Sociedade Brasileira de Engenheiros Florestais, 2, 416-419.

Yilmaz, M. 2019. Effects of soil and environmental factors on the site productivity of pure Oriental beech forests in Akkuş Region of Turkey. Eurasian Journal of Forest Science, 7(2), 107-120. https://doi.org/10.31195/ejejfs.527905

7. Supplementary material

Table S1. Estimation parameters of the modified Jakobsen and Dexter (1987) adjusted model and adjustment and precision statistics.

Depth	Parameters			R^2	S_{yx}(%)
	a	*b*	*c*		
0-10	1.646^{**}	-0.013^{**}	-0.017^{**}	0.37	16.50
10-20	0.986^{**}	-0.006^{ns}	-0.002^{ns}	0.45	11.73
20-30	0.666^{**}	-0.007^{**}	0.005^{ns}	0.71	9.44
30-40	0.742^{**}	-0.010^{**}	0.001^{ns}	0.69	10.94

** $P < 0.01$. ^{ns} $P \geq 0.05$.

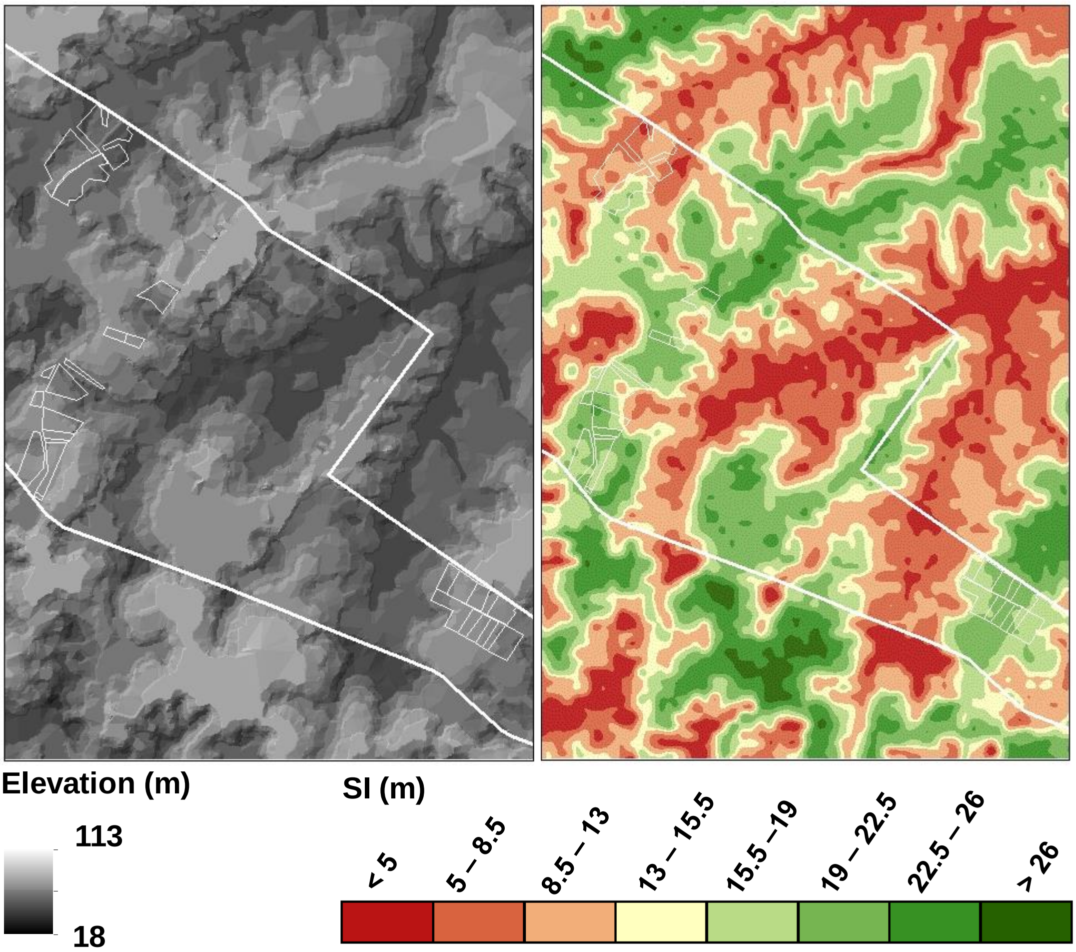

Fig. S1. Digital elevation model (DEM) to the left and site index (SI) thematic map generated based on the topographic model. The resolution of the map is 30 m.

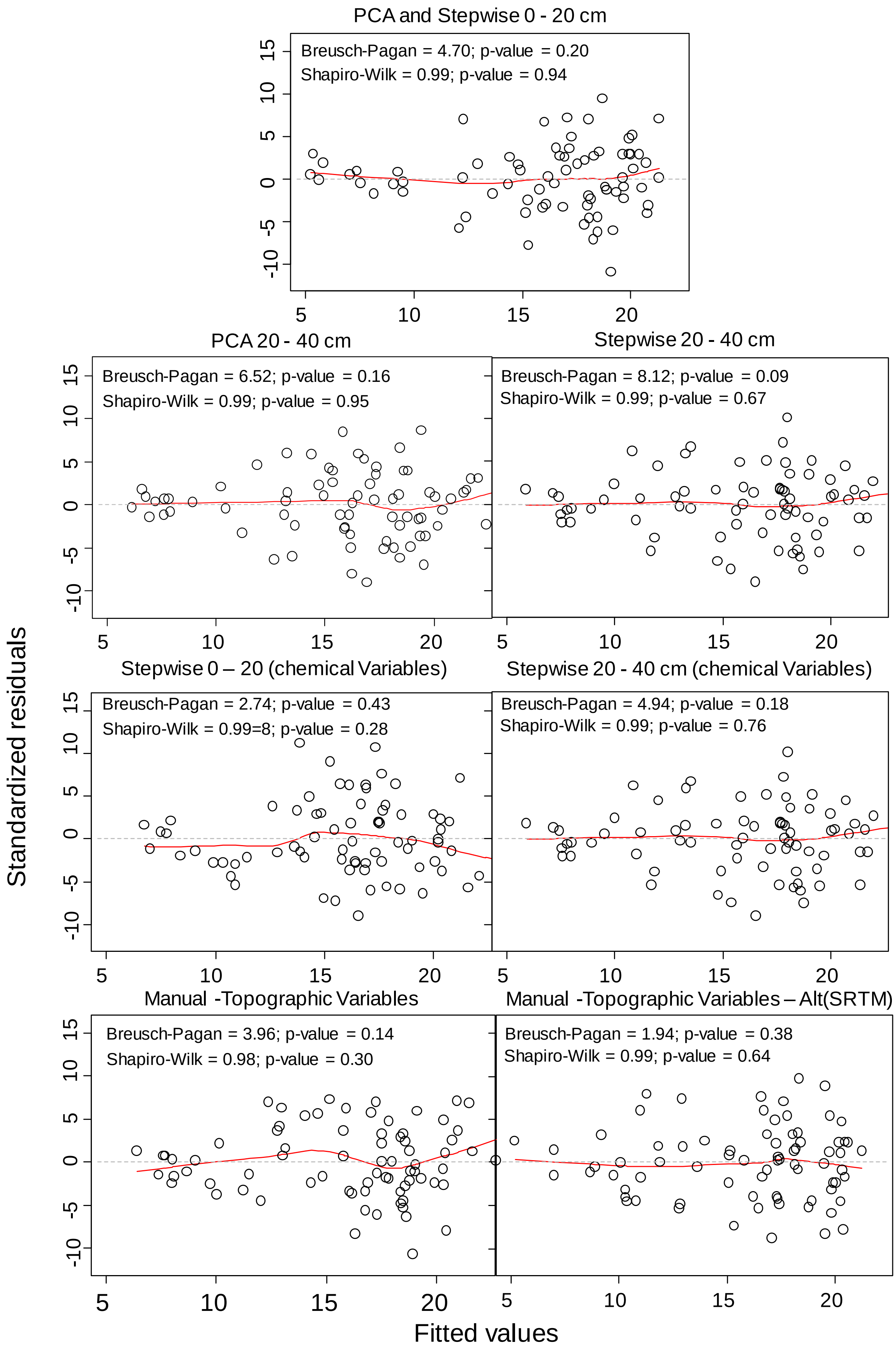

Fig. S2. Residual graphs for the site index predictions from the multiple regression equations.

Table S2. Growth of *B. excelsa* at different sites, using data from dominant trees of the temporary plots separated by productivity class.

Classes	**MAI-h (m)**	**SD (m)**	**IMA-d (cm)**	**SD (cm)**	**N° plots**
I	1,17	0,13	1,37	0,21	24
II	0,81	0,11	0,95	0,17	30
III	0,52	0,29	0,70	0,35	21

Notes: MAI-h = Mean annual increment in height; MAI-d = Mean annual increment in diameter; SD = standard deviation.

8. Conclusões

O modelo de Chapman-Richards apresentou bom desempenho estatístico entre os modelos testados e resultou em curvas polimórficas consistentes aos dados de altura dominante em função da idade dos plantios. A avaliação do polimorfismo indicou que o padrão de crescimento do sítio de qualidade inferior possui uma tendência diferente de crescimento em relação aos sítios de qualidade intermediária e superior. Assim, o uso da equação polimórfica derivada da função de Chapman-Richards é indicado para a classificação de sítios em plantios homogêneos de *B. excelsa*.

A textura do solo e a topografia, representados principalmente pelo teor de areia e altitude, foram os principais fatores que influenciaram a variação da capacidade produtiva entre os sítios. Características químicas, como K^+, Mn^{2+} e pH_{KCl}, tiveram importância secundária para a capacidade produtiva dos sítios.

O uso de variáveis edáficas e topográficas em modelos de predição da qualidade do sítio em plantios de *B. excelsa* é promissor e pode auxiliar na identificação e diagnóstico de áreas potenciais para a implantação da espécie. No entanto, futuras pesquisas, incluindo variáveis climáticas, por exemplo, em diferentes condições do solo e regimes silviculturais são necessárias para a confirmação das melhores condições de sítio relacionadas ao crescimento e produção desta espécie.

9. Referências Bibliográficas

Andrade, R.S., Stone, L.F. 2011. Estimativa da umidade na capacidade de campo em solos sob Cerrado. Revista Brasileira de Engenharia Agrícola e Ambiental, 15(2), 111-116. https://dx.doi.org/10.1590/S1415-43662011000200001

Assmann, E. 1971. The Principles of Forest Yield Study, first ed. Pergamon press.

Bila, J.M., Sanquetta, C.R., Machado, S.A. 2012. Classificação de sítios com base em fatores edáficos para *Pinus caribaea* var. *hondurensis* na região de Prata, Minas Gerais. Floresta, 42(3), 465-474. http://dx.doi.org/10.5380/rf.v42i3.19014

Blyth, J.F., MacLeod, D.A. 1981. Sitka Spruce *Picea sitchensis* in North-East Scotland II. Yield Prediction by Regression Analysis. Forestry, 54(1), 63-73. https://doi.org/10.1093/forestry/54.1.63

Borém, A., Lopes, M.T.G., Clement, C.R. 2009. Domesticação e melhoramento: espécies amazônicas. Viçosa.

Boruvka, L., Mladkova, L., Drabek, O. 2005. Factors controlling spatial distribution of soil acidification and Al forms in Forest soils. Journal of Inorganic Biochemistry, 99(9), 1796-1806. http://dx.doi.org/10.1016/j.jinorgbio.2005.06.028

Botschek, J., Ferraz, J., Jahnel, M., Skowronek, A. 1996. Soil chemical properties of a toposequence under primary rain forest in the Itacoatiara vicinity (Amazonas, Brazil). Geoderma, 72(1-2), 119-132. http://dx.doi.org/10.1016/0016-7061(96)00026-2

Bravo, F., Montero, G. 2001. Site index estimation in Scots pine (*Pinus sylvestris* L.) stands in the High Ebro Basin (northern Spain) using soil attributes. Forestry, 74(4), 395-406. https://dx.doi.org/10.1093/forestry/74.4.395

Bravo-Oviedo, A., Río, M.D., Montero, G. 2004. Site index curves and growth model for Mediterranean maritime pine *Pinus pinaster* Ait.in Spain. Forest Ecology and Management, 201(2-3), 187-197. https://doi.org/10.1016/j.foreco.2004.06.031

Brienen, R.J.W., Zuidema, P.A. 2005. Relating tree growth to rainfall in Bolivian rain forests: a test for six species using tree ring analysis. Oecologia, 146(1), 1-12. https://doi.org/10.1007/s00442-005-0160-y

Brochado, G.T. 2015. Atenuação do efeito de desflorestamento em dados SRTM por meio de diferentes técnicas de interpolação. Dissertação (Mestrado). Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil. 113 p.

Burkhart, H.E., Tomé, M. 2012. Modeling Forest Trees and Stands, first ed. New York.

Busscher, W.J., Bauer, P.J., Camp, C.R., Sojka, R.E. 1997. Correction of cone index for soil water content differences in a coastal plain soil. Soil and Tillage Research, 43(3-4), 205-217. https://doi.org/10.1016/s0167-1987(97)00015-9

Caldeira, M.V.W., Tonini, H.H., Hoppe, J.M., Watzlawick, L.F., Selle, G.L. 1996. Definição de sítios em povoamentos de *Pinus elliottii* Engelm. na região de Encruzilhada do Sul, RS. Ciência Florestal, 6(1), 1-13. http://dx.doi.org/10.5902/19805098320

Campos, J.C.C., Leite, H.G. 2013. Mensuração florestal: perguntas e respostas. fifth ed. Viçosa.

Carmean, W.H. 1971. Soil-site relationships of the upland oaks. Oak Symp. Proc. USDA Forest Service Research Paper. Northeast. Forest Exp. Sta., Upper Darby, PA. 23-29.

Carmean, W.H. 1975. Forest Site Quality Evaluation in The United States. Advances in Agronomy, 27(0), 209-269. https://doi.org/10.1016/s0065-2113(08)70011-7

Carmean, W.H. 1996. Forest site-quality estimation using Forest Ecosystem Classification in Northwestern Ontario. Environmental Monitoring and Assessment, 39(1-3), 493-508. https://doi.org/10.1007/BF00396164

Carvalho, A.P., Menegol, O., Oliveira, E.B., Machado, S.A., Oscar Potter, R.O., Fasolo, P.J. Ferreira, C.A., Bartoszeck, A. 1999. Efeitos de características do solo sobre a capacidade produtiva de *Pinus taeda*. Boletim de Pesquisa Florestal, 39(0), 51-66.

Carvalho, J.P., Parresol, B.R. 2005. A site model for Pyrenean oak *Quercus pyrenaica* stands using a dynamic algebraic difference equation. Canadian Journal of Forest Research, 35(1), 93-99. https://doi.org/10.1139/x04-155

Clutter, J.L., Forston, J.C., Piennar, L.V., Brister, G.H., Bailey, R.L. 1983. Timber management: a quantitative approach. New York.

Corona, P., Scotti, R., Tarchiani, N. 1998. Relationship between environmental factors and site index in *Douglas-fir* plantations in central Italy. Forest Ecology and Management, 110(1-3), 195-207. https://doi.org/10.1016/s0378-1127(98)00281-3

Costa, J.R., Castro, A.B.C., Wandelli, E.V., Coral, S.C.T., Souza, S.A.G. 2009. Aspectos silviculturais da castanha-do-Brasil *Bertholletia excelsa* em sistemas agroflorestais na Amazônia Central. Acta Amazônica, 39(4), 843-850. http://dx.doi.org/10.1590/S0044-59672009000400013

Costa, M.G., Tonini, H., Mendes Filho, P. 2017. Atributos do Solo Relacionados com a Produção da Castanheira-do-Brasil *Bertholletia excelsa* Floresta e Ambiente, 24(0), 2-10. http://dx.doi.org/10.1590/2179-8087.004215

Cronkleton, P., Guariguata, M.R, Albornoz, M.A. 2012. Multiple use forestry planning: timber and Brazil nut management in the community forests of Northern Bolivia. Forest Ecology and Management, 268(1), 49-56. https://doi.org/10.1016/j.foreco.2011.04.035

Cruz, J.P., Leite, H.G., Soares, C.P.B., Campos, J.C.C., Smit, L., Nogueira, G.S. 2008. Curvas de crescimento e de índice de local para povoamentos de *Tectona grandis* em Tangará da Serra, Mato Grosso. Revista Árvore, 32(4), 679-685. https://dx.doi.org/10.1590/S0100-67622008000400009

Cunha Neto, F.R., Scolforo, J.R., Calegario, N., Kanegae Júnior, H. 1996. Uso da diferença algébrica para construção de curvas de índice de sítio para *Eucalyptus grandis* e *Eucalyptus urophylla* na região de Luiz Antônio, SP. Revista Cerne, 22(0), 119-141.

Curt, T., Bouchaud, M., Agrech, G. 2001. Predicting site index of *Douglas-Fir* plantations from ecological variables in the Massif Central área of France. Forest Ecology and Management, 149(1-3), 61-74. https://doi.org/10.1016/S0378-1127(00)00545-4

Embrapa. 1997. Manual de métodos de análise de solo. second ed. Rio de Janeiro.

Farrelly, N., Ní Dhubháin, Á., Nieuwenhuis, M. 2011. Site index of Sitka spruce *Picea sitchensis*in relation to different measures of site quality in Ireland. Can. J. For. Res. 41(2), 265-278. https://doi.org/10.1139/X10-203

Fernandes, N.P., Alencar, J.C. 1993. Desenvolvimento de árvores nativas em ensaios de espécies. 4. Castanha-do-brasil *Bertholletia excelsa* H. B. K., dez anos após o plantio. Acta Amazonica, 23(2-3), 191-198. http://dx.doi.org/10.1590/1809-43921993233198

Ferreira, L.M.M., Tonini, H. 2009. Comportamento da castanha-do-brasil *Bertholletia excelsa* e da cupiúba *Goupia glabra*em sistema agrosilvicultural na região da Confiança, Cantá – Roraima. Acta Amazônia, 39(4), 83-842. http://dx.doi.org/10.1590/S0044-59672009000400012

Ferreira, M. 1990. Escolha de espécies arbóreas para a formação de maciços. Documentos florestais. Piracicaba: ESALQ.

Ferreira, M.J., Gonçalves, J.F.C., Ferraz, J.B.S. 2012. Crescimento e eficiência do uso da água de plantas jovens de castanheira-da-amazônia em área degradada e submetidas à adubação. Ciência Florestal, 22(2), 393-401. http://dx.doi.org/10.5902/198050985747

Ferreira, M.J., Gonçalves, J.F.C., Ferraz, J.B.S., Corrêa, V.M. 2015. Características nutricionais de plantas jovens de *Bertholletia excelsa* Bonpl. sob tratamentos de fertilização em área degradada na Amazônia. Scientia Forestalis, 43(108), 863-872. http://dx.doi.org/10.18671/scifor.v43n108.11

Ferreira, M.J., Gonçalves, J.F.D.C., Ferraz, J.B.S., Santos Junior, U.M., Rennenberg, H. 2016. Clonal variation in photosynthesis, foliar nutrient concentrations, and photosynthetic nutrient use efficiency in a Brazil nut *Bertholletia excelsa* plantation. Forest Science, 62(3), 323-332. https://doi.org/10.5849/forsci.15-068

Field, A 2009. Discovering statistics using SPSS. third ed. London.

Guimarães, R.M.L., Neves Júnior, A.F., Silva, W.G., Rogers, C.D., Bola, B.C., Montes, C., Pereira, B.F.F. 2017. The merits of the Visual Evaluation of Soil Structure method VESS for assessing soil physical quality in the remote, undeveloped regions of the Amazon basin. Soil and Tillage Research, 173(0), 75-82. https://doi.org/10.1016/j.still.2016.10.014

Hoch, L., Pokorny, B., Jong, W. 2009. How successful is tree growing for smallholders in the Amazon?. International Forestry Review, 11(3), 299-310. https://doi.org/10.1505/ifor.11.3.299

Isaaks, E.H., Srivastava, M. 1989. An introduction to applied geostatistics. New York: Oxford University Press.

Jakobsen, B.F., Dexter, A.R., 1987. Effect of soil structure on wheat root growth, water uptake and grain yield. A computer simulation model. Soil Till. Res. 10(4), 331-345. https://doi.org/10.1016/0167-1987(87)90022-5

Johnson, P.S., Shifley, S.R., Rogers, R., Dey, D.C., Kabrick, J.M. 2019. The Ecology and Silviculture of Oaks. third ed. Boston, MA : CABI.

Johnson, R.A., Wichern, D.W. 1998. Applied multivariate statistical analysis. fourth ed. New Jersey, USA: Prentice Hall.

Jones, D.L., Nguyen, C., Finlay, R.D. 2009. Carbon flow in the rhizosphere: carbon trading at the soil–root interface. Plant and Soil, 321(1-2), 5–33. https://doi.org/10.1007/s11104-009-9925-0

Kaiser, H.F. 1960. The Application of Electronic Computers to Factor Analysis. Educational and Psychological Measurement, 20(1), 141-151. https://doi.org/10.1177/001316446002000116

Kariuki, M. 2002. Height estimation in complete stem analysis using annual radial growth measurements. Forestry, 75(1), 63-74. https://doi.org/10.1093/forestry/75.1.63

Kato, A.K. 1995. Dinâmica da entrada de nutrientes via liteira em plantios de castanheira-do-Brasil *Bertholletia excelsa* H. B. K. em ecossistemas de pastagens degradadas e de floresta primária [Dynamic of nutrients by litter in Brazil nut *Bertholletia excelsa* H. B. K. plantations in ecosystems of degraded pastures and primary forests]. *PhD dissertation*, Instituto Nacional de Pesquisas da Amazônia, Manaus, AM, Brazil. 360 p.

Ker, J.C. 1997. Latossolos do Brasil: uma revisão. Geonomos, 5(1), 17-40. https://doi.org/10.18285/geonomos.v5i1.187

Kimsey, M.J., Moore Júnior, J., McDaniel, P. 2008. A Geographically Weighted Regression Analysis of Douglas-Fir Site Index in North Central Idaho. Forest Science, 54(3), 356-366. https://doi.org/10.1093/Forestscience/54.3.356

Kitikidou, K., Bountis, D., Milios, E. 2011. Site index models for calabrian pine *Pinus brutia* Ten.in Thasos Island, Greece. Ciênc. Florest., 21(1), 125-131. http://dx.doi.org/10.5902/198050982755

Kochian, L.V, Piñeros, M.A, Howkenga, O.A. 2005. The physiology, genetics and molecular biology of plant aluminum resistance and toxicity. Plant and Soil, 274(1-2), 175-195. http://dx.doi.org/10.1007/s11104-004-1158-7

Köppen, W. Climatologia: com un estudio de los climas de la tierra. México: Fondo de Cultura Economica, 1948. 478 p.

Kravchenko, A.N. 2003. Influence of Spatial Structure on Accuracy of Interpolation Methods. Soil Science Society of America Journal, 67(5), 1564. http://dx.doi.org/10.2136/sssaj2003.1564

Lima, R.M.B., Higa, A.R., Souza, C.R. 2004. Influência dos fatores edáficos no crescimento da *Bertholletia excelsa* H. B. K. na Amazônia. In: Congresso Brasileiro de Sistemas Agroflorestais, Curitiba. Anais. Colombo: Embrapa Florestas, p. 319-321.

Lindsey, C., Sheather, S. 2010. Variable selection in linear regression. The Stata Journal, 10(4), 650-669. https://doi.org/10.1177/1536867X1101000407

Liziniewicz, M., Nilsson, U., Agestam, E., Ekö, P.M., Elfving, B. 2016. A site index model for lodgepole pine *Pinus contorta* Dougl. var. latifolia in northern Sweden. Scandinavian Journal of Forest Research, 31(6), 583-591. https://doi.org/10.1080/02827581.2016.1167238

Locatelli, M., Marcante, P.H., Cipriani, H.N. Martins, E.P., Vieira, A.H. 2015. Avaliação do crescimento da Castanha-do-Brasil *Bertholletia excelsa* BONPL. em um plantio no munícipio de Machadinho do Oeste - Rondônia. Enciclopédia Biosfera, 11(22), 457-470.

Louw, J.H., Scholes, M.C. 2006. Site index functions using site descriptors for *Pinus patula* plantations in South Africa. Forest Ecology and Management, 225(1-3), 94-103. https://doi.org/10.1016/j.foreco.2005.12.048

Machado, M.R., Souza, R.C., Sampaio, P.T.B., Ferraz, J.B.S. 2017. Aspectos silviculturais da Castanha-do-Brasil (*Bertholletia excelsa* Humb. e Bonpl.). Biota Amazônia, 7(3), 41-44. http://dx.doi.org/10.18561/2179-5746/biotaamazonia.v7n3p41-44

Machado, S.A., Oliveira, E.B., Carpanezzi, A.A., Bartoszeck, A.C.P.S. 1997. Classificação de sítio para bracatingais na região metropolitana de Curitiba. Boletim de Pesquisa Florestal, Colombo, 35(0), 21-37.

Machado, S.A., Souza, R.F., Jaskiu, E., Cavalheiro, R. 2011. Construction of site curves for native *Mimosa scabrella* stands in the metropolitan region of Curitiba. Cerne, Lavras, 17(4), 489-497. http://dx.doi.org/10.1590/S0104-77602011000400007

Marques, J.D.O., Luizão, F.J., Teixeira, W.G., Vitel, C.M., Marques, E.M.A. 2016. Soil organic carbon, carbon stock and their relationships to physical attributes under forest soils in Central Amazonia. Revista Árvore, 40(2), 197-208. https://doi.org/10.1590/0100-67622016000200002

Mckenney, D.W., Pedlar, J.H. 2003. Spatial models of site index based on climate and soil properties for two boreal tree species in Ontario, Canadá. Forest Ecology and Management, 175(1-3), 497-507. https://doi.org/10.1016/S0378-1127(02)00186-X

McLean, E.O. 1965. Aluminum. In: BLACK, C.A. Ed., Methods of soil analysis: Part 2, Chemical methods. Madison: ASA.

Melo, V.F., Batista, A.H., Barbosa, J.Z., Barbeiro, L., Gomes, R., Dultra, M.T.M. 2018. Soil quality and reforestation of the Brazil nut tree *Bertholletia excelsa* Bonpl. after laterite-type bauxite mining in the Brazilian Amazon forest. Ecological Engineering, 125(0), 111-118. https://doi.org/10.1016/j.ecoleng.2018.10.016

Meurer, E.J. 2007. Fatores que influenciam o crescimento e o desenvolvimento das plantas. In: Novais, R.F., Venegas, V.H.A., Barros, N.F., Fontes, R.L.F., Cantarutti, R.B., Neves, J.C.L. 2007. Fertilidade do solo. First ed. Viçosa.

Montgomery, D.C., Runger, G.C. 2009. Estatística aplicada e probabilidade para engenheiros. fourth ed. Rio de Janeiro.

Murphy, J., Riley, J.P. 1962. A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta, 27(0), 31-36. https://doi.org/10.1016/s0003-2670(00)88444-5

Ortega, A., Montero, G. 1988. Evaluación de la calidad de las estaciones forestales. Revisión bibliográfica. Ecología, 2(0), 155-184.

Ortiz, J.L., Vettorazzi, C.A., Couto, H.T.Z., Goncalves, J.L.M. 2006. Relações espaciais entre o potencial produtivo de um povoamento de eucalipto e atributos do solo e do relevo. IPEF. Instituto de Pesquisas e Estudos Florestais, 72(0), 67-79.

Palahí, M., Tomé, M., Pukkala, T., Trasobares, A., Montero, G. 2004. Site index model for *Pinus sylvestris* in north-east Spain. Forest Ecology and Management, 187(1), 35-47. https://doi.org/10.1016/s0378-1127(03)00312-8

Pancel, L. 2015. Species Selection in Tropical Forestry. Tropical Forestry Handbook, 1-15. https://doi.org/10.1007/978-3-642-41554-8_114-2

Post, B.W., Carmean, W.H., Curtis, R.O. 1969. Birch soil-site requirements. In: Proceedings, Birch Symposium. pp. 95– 101. USDA Forest Service, Northeastern Forest Experiment Station, Upper Darby, PA.

Rachid-Casnati, C., Mason E.G., Woollons, R.C. 2019. Using soil-based and physiographic variables to improve stand growth equations in Uruguayan forest plantations. iForest 12(3), 237-245. https://doi.org/10.3832/ifor2926-012

Rahman, M., Lee, S.H., Ji, H., Kabir, A., Jones, C., Lee, K.W. 2018. Importance of Mineral Nutrition for Mitigating Aluminum Toxicity in Plants on Acidic Soils: Current Status and Opportunities. International Journal of Molecular Sciences, 19(10), 3073. https://doi.org/10.3390/ijms19103073

Retslaff, F.A.S., Figueiredo Filho, A., Dias, A.N., Bernett, L.G., Figura, M.A. 2015. Curvas de sítio e relações hipsométricas para *Eucalyptus grandis* na região dos Campos Gerais, Paraná. Cerne, 21(2), 219-225. https://dx.doi.org/10.1590/01047760201521021349

Rigatto, P.A., Dedecek, R.A., Mattos, J.L.M. 2005. Influência dos atributos do solo sobre a produtividade de *Pinus taeda*. Revista Árvore, 29(5), 701-709. http://dx.doi.org/10.1590/S0100-67622005000500005

Rolim, S.G., Piña-Rodrigues, F.C.M., Piotto, D., Batista, A., Freitas, M.L.M., Brienza Junior, S., Zakia, M.J.B., Calmon, M. 2019. Research Gaps and Priorities in Silviculture of Native Species In Brazil. Working Paper. São Paulo, Brasil: WRI Brasil. Available online at https://wribrasil.org.br/pt/publicacoes

Salomão, R.P. 2014. A castanheira: história natural e importância socioeconômica. Boletim do Museu Paraense Emílio Goeldi: Ciências Naturais, 9(2), 259-266.

Schmidt, M.G., Carmean, W.H. 1988. Jack pine site quality in relation to soil and topography in north central Ontario. Canadian Journal of Forest Research, 18(3), 297-305. https://doi.org/10.1139/x88-046

Schöngart, J., Gribel, R., Ferreira da Fonseca-Junior, S., Haugaasen, T. 2015. Age and Growth Patterns of Brazil Nut Trees *Bertholletia excelsa* Bonpl.in Amazonia, Brazil. Biotropica, 47(5), 550-558. https://doi.org/10.1111/btp.12243

Schroth, G., Mota, M.S.S., Assis Elias, M.E. 2015. Growth and nutrient accumulation of Brazil nut trees *Bertholletia excelsa* in agroforestry at different fertilizer levels. Journal of Forestry Research, 26(2), 347-353. http://dx.doi.org/10.1007/s11676-015-0037-9

Scoles, R., Gribel, R., Klein, G.N. 2011. Crescimento e sobrevivência de castanheira *Bertholletia excelsa* Bonpl. em diferentes condições ambientais na região do rio Trombetas, Oriximiná, Pará. Boletim do Museu Paraense Emílio Goeldi: Ciências Naturais, 6(3), 273-293.

Scolforo, J.R.S. 1992. Curvas de índice de sítio para *Pinus caribaea* var. *hondurensis*. IPEF, 45(0), 40-47.

Scolforo, J.R.S. 1997. Biometria florestal: métodos para classificação de sítios florestais. Lavras.

Scolforo, J.R.S. 2006. Biometria florestal: modelos de crescimento e produção florestal. Lavras.

Scolforo, J.R.S., Machado, S.A. 1988. Curvas de índice de sítio para plantações de *Pinus elliotti* nos estados do Paraná e Santa Catarina. Revista Floresta, 18(1-2), 1982-4688. http://dx.doi.org/10.5380/rf.v18i12.6392

Selle, G.L., Schneider, P.R., Guimarães Finger, C.A. 1994. Classificação de sítio para *Pinus taeda* L., através da altura dominante, para a região de Cambará do Sul, RS, Brasil. Ciência Florestal, 41(1), 77-95. https://dx.doi.org/10.5902/19805098299

Silva, G.C.C., Calegario, N., Silva, A.A.L., Cruza, J.P., Leite, H.G. 2018. Site index curves in thinned and non-thinned *eucalyptus* stands. Forest Ecology and Management, 408(0), 36-44. https://doi.org/10.1016/j.foreco.2017.10.036

Silva, F.R., Silva, V., Miranda, S., Oliveira, B.R., Silva, J.C. 2016. Classificação da produtividade para um plantio de *Tectona grandis* em alta floresta, Mato Grosso. Ambiência, 12(4), 809-823.

Singh, S., Tripathi, D.K., Singh, S., Sharma, S., Dubey, N.K., Chauhan, D.K., Vaculík, M. 2017. Toxicity of aluminium on various levels of plant cells and organism: A review. Environmental and Experimental Botany, 137(0), 177-193. https://doi.org/10.1016/j.envexpbot.2017.01.005

Smith, C.W., Johnston, M.A., Lorentz, S. 1997. The effect of soil compaction and soil physical properties on the mechanical resistance of South African forestry soils. Geoderma, 78(1-2), 93-111. https://doi.org/10.1016/s0016-7061(97)00029-3

Tani, M., Shida, K.S., Tsutsuki, K., Kondo, R. 2001. Determination of water-soluble low-molecular-weight organic acids in soils by ion chromatography. Soil Science and Plant Nutrition, 47(2), 387-397. https://doi.org/10.1080/00380768.2001.10408401

Tonini, H., Oliveira Júnior, M.C.M., Schwengber, D. 2008. Crescimento de espécies nativas da Amazônia submetidas ao plantio no estado de Roraima. Ciência Florestal, 18(2), 151-158. https://doi.org/10.5902/19805098453

Vaz, C.M.P., Manieri, J.M., Maria, I.C., Tuller, M. 2011. Modeling and correction of soil penetration resistance for varying soil water content. Geoderma, 166(1), 92-101. https://doi.org/10.1016/j.geoderma.2011.07.016

Vitorello, V.A., Capaldi, F.R., Stefanuto, V.A. 2005. Recent advances in aluminum toxicity and resistance in higher plants. Brazilian Journal of Plant Physiology, 17(1), 129-143. https://doi.org/10.1590/s1677-04202005000100011

Walkley, A., Black, I.A. 1934. An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science, 37(1), 29–38. http://dx.doi.org/10.1097/00010694-193401000-00003

Walters, B.B., Sabogal, C., Snook, L.K., Almeida, E. 2005. Constraints and opportunities for better silvicultural practice in tropical forestry: an interdisciplinary approach. Forest Ecology and Management, 209(1-2), 3-18. https://doi.org/10.1016/j.foreco.2005.01.003

Webster, R., Oliver, M.A. 2007. Geostatistics for environmental scientists. second ed. West Sussex: John Wiley and Sons Ltd.

Yamamoto, J.K., Landim, P.M.B. 2013. Geoestatística: Conceitos e aplicações. São Paulo.

Yared, J.A.G., Kanashiro, M., Conceição, J.G.L. 1988. Espécies florestais nativas e exóticas: comportamento silvicultural no planalto do tapajós – Pará. EMBRAPA-CPATU.

Yared, J.A.G., Kanashiro, M., Viana, L.M., Castro, T.C.A., Pantoja, J.R.S. 1993. Comportamento silvicultural de castanheira *Bertholletia excelsa* H. B. K. em diversos locais da Amazônia. In: Congresso Florestal Panamericano, Curitiba-Pr. Anais. Sociedade Brasileira de Silvicultura/Sociedade Brasileira de Engenheiros Florestais, 2, 416-419.

Yilmaz, M. 2019. Effects of soil and environmental factors on the site productivity of pure Oriental beech forests in Akkuş Region of Turkey. Eurasian Journal of Forest Science, 7(2), 107-120. https://doi.org/10.31195/ejejfs.527905