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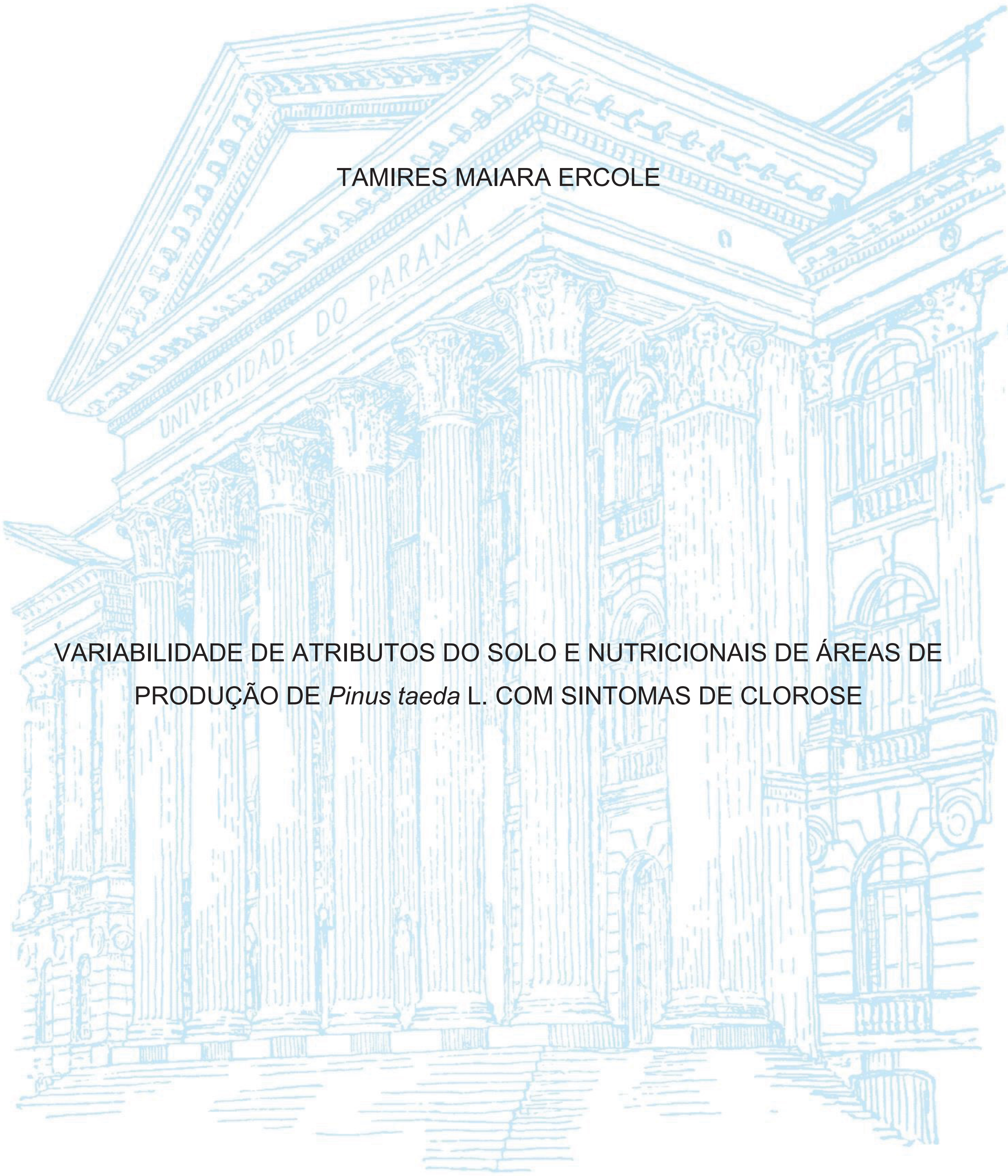

TAMIRES MAIARA ERCOLE

VARIABILIDADE DE ATRIBUTOS DO SOLO E NUTRICIONAIS DE ÁREAS DE PRODUÇÃO DE *Pinus taeda* L. COM SINTOMAS DE CLOROSE

CURITIBA

2023

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Dissertação apresentada ao curso de Pós-Graduação em Ciência do Solo, Setor de Ciências Agrárias, Universidade Federal do Paraná, como requisito parcial à obtenção do título de Mestre em Ciência do Solo.

Orientador: Prof. Dr. Antônio Carlos Vargas Motta

Coorientadores: Prof. Dr. Jairo Calderari de Oliveira Junior e Dr. João Bosco Vasconcellos Gomes

CURITIBA

2023

DADOS INTERNACIONAIS DE CATALOGAÇÃO NA PUBLICAÇÃO (CIP)
UNIVERSIDADE FEDERAL DO PARANÁ
SISTEMA DE BIBLIOTECAS – BIBLIOTECA DE CIÊNCIAS AGRÁRIAS

Ercole, Tamires Maiara
Variabilidade de atributos do solo e nutricionais de áreas de produção de *Pinus taeda* L. com sintomas de clorose / Tamires Maiara Ercole. – Curitiba, 2023.
1 recurso online: PDF.

Dissertação (Mestrado) – Universidade Federal do Paraná, Setor de Ciências Agrárias, Programa de Pós-Graduação em Ciência do Solo.
Orientador: Prof. Dr. Antônio Carlos Vargas Motta
Coorientador: Prof. Dr. Jairo Calderari de Oliveira Junior
Coorientador: Dr. João Bosco Vasconcellos Gomes

1. *Pinus taeda*. 2. Madeira - Densidade. 3. Solos. 4. Fitopatologia. I. Motta, Antônio Carlos Vargas. II. Oliveira Junior, Jairo Calderari de. III. Gomes, João Bosco Vasconcellos. IV. Universidade Federal do Paraná. Programa de Pós-Graduação em Ciência do Solo. V. Título.

Bibliotecária: Telma Terezinha Stresser de Assis CRB-9/944

MINISTÉRIO DA EDUCAÇÃO
SETOR DE CIÊNCIAS AGRÁRIAS
UNIVERSIDADE FEDERAL DO PARANÁ
PRÓ-REITORIA DE PESQUISA E PÓS-GRADUAÇÃO
PROGRAMA DE PÓS-GRADUAÇÃO CIÊNCIA DO SOLO -
40001016014P4

TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação CIÊNCIA DO SOLO da Universidade Federal do Paraná foram convocados para realizar a arguição da dissertação de Mestrado de **TAMIRES MAIARA ERCOLE** intitulada: **VARIABILIDADE DE ATRIBUTOS DO SOLO E NUTRICIONAIS DE ÁREAS DE PRODUÇÃO DE Pinus taeda L. COM SINTOMAS DE CLOROSE**, sob orientação do Prof. Dr. ANTONIO CARLOS VARGAS MOTTA, que após terem inquirido a aluna e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.
A outorga do título de mestra está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

CURITIBA, 23 de Janeiro de 2023.

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I dedicate this work to my parents and my
sister, for their support.

ACKNOWLEDGMENT

I am grateful to God, for blessing and protecting me throughout this journey, for his teachings and challenges.

I thank my family, my father - Altivir Antonio Ercole, my mother - Neide Luiza Benato Ercole and my little sister - Tairine Graziella Ercole, for all the support, understanding and love.

To my advisor, professor Antônio Carlos Vargas Motta, for his trust, dedication and professional and life teachings.

To my co-advisors, Dr. João Bosco Vasconcellos Gomes - who supported me, listened, advised and helped me during this journey, my immense gratitude, and to professor Jairo Calderari de Oliveira Junior - for the advice and teachings.

To my friend Camila de Oliveira, for so many years of friendship, for always being by my side, listening to me, supporting and watching over me. To the friends I made during my master's degree, Carla G. Albuquerque – thank you for the long conversations and advice, Valdécio S. Rodrigues and Nicolas S. Trentin – for all the help. I also thank Ana P. M. Mikoski, Fabiana Gavelaki, Ana E. L. Brumat and the undergraduate students (children) and so many other graduate colleagues.

The Federal University of Paraná, the Department of Soils and Agricultural Engineering and especially the graduate program in Soil Science and all the dear professors I had the opportunity to meet and learn from them, also Mrs. Denise and Mrs. Marla.

To professors Sérgio Henrique Godinho Silva and Nilton Curi for their help, advice and for providing the execution of analyses at the Federal University of Lavras and professor Mario Tommasiello Filho and Dr. Gabriel Assis-Pereira for the opportunity to perform analyses at the Superior School of Agriculture "Luiz de Queiroz".

The company Remasa, for the provision of the study area and the assistance in the field and for all the help of Dr. Amanda Pacheco Cardoso Moura.

This work was carried out with the support of the National Council for Scientific and Technological Development - CNPq.

My thanks to all the people who helped in this work in some way.

“Um guerreiro da luz compartilha com os outros o que sabe do caminho. Quem ajuda, sempre é ajudado, e precisa ensinar o que aprendeu. Por isso, ele senta-se ao redor da fogueira e conta como foi o seu dia de luta.
Um amigo sussurra: “Por que falar tão abertamente de sua estratégia? Não vê que, agindo assim, corre o risco de ter que dividir suas conquistas com os outros?”.
O guerreiro apenas sorri, e não responde. Sabe que, se chegar ao final da jornada num paraíso vazio, sua luta não terá valido a pena.”

Paulo Coelho

RESUMO

A heterogeneidade de crescimento e o aparecimento de clorose nas acículas de *Pinus taeda* em talhões comerciais de baixo crescimento tem se intensificado nos últimos anos. Logo, objetivou-se verificar se o Índice Resistente à Atmosfera na Região Visível (VARI) é capaz de representar a heterogeneidade de desenvolvimento do *Pinus taeda*, e se essa está associada a características pedológicas e químicas do solo, serapilheira e nutrição das árvores com clorose. O estudo foi conduzido em uma área de 18,42 hectares de reflorestamento de *Pinus taeda* (14 anos), em segundo desbaste, com solo formado sobre rocha eruptiva ácida (riodacito e riolito), sem utilização de corretivos e fertilizantes. O talhão foi escolhido por evidenciar elevada variação no crescimento das plantas e árvores com clorose. Utilizando imagens aéreas obtidas com drone foi realizada a confecção de um mapa para separar a área, quanto ao índice VARI, em quatro classes: muito baixo, baixo, médio e alto. Foram realizadas coletas de solo em três profundidade para análise química, serapilheira (< 2 mm >) e tecidos vegetais (acículas – terço superior da copa coletando primeiro e segundo lançamento e terço inferior da copa – coletando segundo lançamento, casca e lenho – ambos a seis alturas do tronco e raízes finas encontradas na serapilheira). A serapilheira e os tecidos vegetais coletados foram analisados quimicamente por digestão a seco (em mufla) e determinados por espectroscopia de emissão óptica de plasma indutivamente acoplado (ICP-OES). As árvores foram avaliadas quanto ao diâmetro a altura do peito (DAP), sendo uma selecionada para ser abatida, da qual foi medida a altura (comercial e total), volume e biomassa. Foi coletado um disco na altura do DAP e esse foi analisado por densitometria de raios-X, obtendo-se a largura dos anéis de crescimento e densidade da madeira. Também determinou-se a declividade das parcelas e a classificação dos solos. Não houve diferenças na classificação do solo e na fertilidade entre as classes, todas apresentaram solos de muito baixa fertilidade, extremamente ácidos. A classe alta quando comparada com as classes de menor VARI (baixa e muito baixa) apresentou volume de madeira (sem casca) superior em 0,20 m^3 $árvore^{-1}$. As classes de maior VARI apresentaram maiores concentrações de cálcio (Ca) e magnésio (Mg) nas acículas, cascas e raízes finas, principalmente para Mg. A classe alta e média também apresentaram maiores concentrações de Ca e Mg na serapilheira (> 2 mm), porém tiveram menor acúmulo dessa. O VARI se mostrou eficiente para representar a heterogeneidade de crescimento. A classe muito baixa apresentou clorose nas pontas das acículas e perda da copa das árvores, sintomas condizentes com os indicados para deficiência de Mg na literatura, entretanto, sugere-se um ajuste no limite crítico de Mg nas acículas para 0,30 g kg^{-1}. As acículas, raízes finas, casca e serapilheira (> 2 mm) mostraram-se como bons indicadores do estado nutricional da planta. A deficiência de Mg^{2+} é a causa mais provável do menor desenvolvimento das plantas, estando diretamente associada a baixa fertilidade natural do solo e o esgotamento desse pela não reposição de nutrientes.

Palavras-chave: Densidade da madeira. Desbalanço nutricional. VARI. Exaustão do solo. Raízes finas.

ABSTRACT

The heterogeneity of growth and the appearance of needle chlorosis in *Pinus taeda* needles in low growth commercial areas has intensified in recent years. Therefore, the goals of this study were to verify if Visible atmospherically Resistant Index (VARI) can represent the heterogeneity of *Pinus taeda* development and whether this is associated with pedological and chemical characteristics of the soil, litter, and tree nutrition with chlorosis symptoms. The study was conducted in an area of 18.42 hectares of *Pinus taeda* reforestation (14 years-old), in second thinning, with soil formed on acid eruptive rock (rhyodacite and rhyolite), without the use of correctives and fertilizers. The area was chosen because it shows high variation in the growth of plants and trees with chlorosis. Using aerial images obtained with a drone a map was created to separate the area, regarding the VARI index, into four classes: Very Low, Low, Medium, and High. Soil samples was collected at three depths for chemical analysis, litter (< 2 mm >) and plant tissues (needles – upper third of canopy collecting first and second flush and lower third of canopy – collecting second flush, bark and wood – both at six trunk heights, and fine roots found in the litter) were also collected. The litter and plant tissues were chemically analyzed by dry digestion (in muffle) and determined by inductively coupled plasma optical emission spectroscopy (ICP-OES). The trees were evaluated for diameter at breast height (DBH), one being selected to be felled, which was measured for height (commercial and total), volume and biomass. A disk was collected at the height of the DBH, and this was analyzed by X-ray densitometry, obtaining the width of the growth rings and wood density. The slope of the plots and the classification of the soils were also determined. There were no differences in soil classification and fertility between classes, all had very low fertility, extremely acidic soils. The High class, when compared to the lower VARI classes (Low and Very Low) presented a wood volume (without bark) superior by 0.20 m^3 $tree^{-1}$. The classes with the highest VARI showed higher concentrations of calcium (Ca) and magnesium (Mg) in the needles, bark, and fine roots, mainly for Mg. The High and Medium classes also presented higher concentrations of Ca and Mg in the litter (> 2 mm) but had a smaller accumulation of this. The VARI proved to be efficient to represent growth heterogeneity. The Very Low class showed chlorosis at the tips of the needles and loss of the tree canopy, symptoms consistent with indicated for Mg deficiency in the literature, however, an adjustment in the critical limit of Mg in the needles to 0.30 g kg^{-1} is suggested. The needles, fine roots, bark, and litter (> 2 mm) were good indicators of the nutritional status of the plant. Mg^{2+} deficiency is the most likely cause of reduced plant development, being directly associated with low natural soil fertility and soil depletion due to lack of nutrient replacement.

Keywords: Wood density. Nutritional imbalance. VARI. Soil exhaustion. Fine roots.

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LIST OF ABBREVIATIONS AND ACRONYMS

spp.	Species
L.	Lineu
VARI	Visible Atmospherically Resistant Index
Cfb	Temperate climate
UAV	Unmanned aerial vehicle
GPS	Global Positioning System
CBH	Circumference at breast height – 1.3 m
DBH	Diameter at breast height
ICP-OES	Inductively coupled plasma optical emission spectroscopy
pH	Hydrogen potential
SMP	Shoemaker, Mac Lean and Pratt
SB	Sum of bases
CEC eff.	Effective cation exchange capacity
CEC pH 7	Potential cation exchange capacity
m%	Aluminum saturation
V%	Base saturation
LR	Liming recommendation
P.	*Pinus*
NDVI	Normalized Difference Vegetation Index

LIST OF SYMBOLS

Mn	Manganese
Ca	Calcium
Mg	Magnesium
N	Nitrogen
%	Percentage
K	Potassium
P	Phosphororus
Al	Aluminum
ºC	Celsius degree
mm	Millimeter
S	South
W	West
m	Meter
ha	Hectares
C1	Very Low class
C2	Low class
C3	Medium class
C4	High class
m^2	Square meter
cm	Centimeter
™	Trademark
g	gram
HCl	Hydrochloric acid

L	Liter
mL	Milliliters
As	Arsenic
B	Boron
Ba	Barium
Cd	Cadmium
Co	Cobalt
Cr	Chrome
Cu	Copper
Fe	Iron
Mo	Molybdenum
Ni	Nickel
Pb	Lead
Sb	Antimony
Se	Selenium
V	Vanadium
Zn	Zinc
>	Greater than
<	Less than
$CaCl_2$	Calcium chloride
H	Hydrogen
Al^{3+}	Aluminum ion
KCl	Potassium chloride
Na	Sodium

NaOH	Sodium hydroxide
K^+	Potassium ion
Na^+	Sodium ion
Mg ha^{-1}	Megagram per hectare
≤	Less or equal than
m^3	Cubic meter
kg	Kilogram
g cm^{-3}	grams per cubic centimeter
mg kg^{-1}	Milligrams per kilogram
g kg^{-1}	Grams per kilogram
kg ha^{-1}	Kilogram per hectare
mg dm^{-3}	milligram per cubic decimeter
$cmol_c$ dm^{-3}	Charge centimol per cubic decimeter
Ca^{2+}	Calcium ion
Mg^{2+}	Magnesium ion

SUMMARY

1 INTRODUCTION

World wood demand is expected to increase significantly in coming decades due to expanding populations and economies (Food and Agriculture Organization of the United Nation [FAO], 2020). In relation to world production, Brazil occupies a prominent position in exportation of pulpwood, wood panels, and sawtimber (FAO, 2018; FAO, 2021). Thus, commercial forest operations play important roles in economic and social sectors, while contributing to ecosystem services such as carbon sequestration (Brazilian Tree Industry [IBÁ], 2021). *Pinus* spp. are the second most planted forest species in Brazil, especially in the southern region, where *Pinus taeda* L. is the main cultivated species due to regional climatic conditions that favor development (IBÁ, 2021). In addition, the relatively short harvest cycle (~15 to 20 yrs) of this species favors the supply of wood for pulp and paper industries (Dobner Jr. et al., 2018). Harvest cycles tend to be longer (close to 30 yrs) for the production of wood products (furniture and panels), with two to four thinning operations typically occurring during this period (Sampietro et al., 2022).

Due to the plasticity of *P. taeda* and the favorable subtropical climate of southern Brazil, most stands are commonly located on lands with low to medium agricultural potential, which improves the cost/opportunity ratio (Motta et al., 2014; Abrão et al., 2015; Batista et al., 2015; Sass et al., 2020) since these marginal and degraded areas have lower monetary value and do not suffer competition with primary agricultural commodities (Lu et al., 2009; Smethurst, 2010; Rodrigues-Corrêa et al., 2012; Consalter et al., 2021a). Lands with low agriculture potential commonly exhibit high heterogeneity of characteristics and productivity along short distances with variations according to relief, soil depth, stoniness, rockiness, nutrient supply, and water availability (Morales et al., 2010; Gomes et al., 2016; Horst et al., 2018; Horst-Heinen et al., 2021).

After several cultivations of *Pinus* spp., areas often exhibit growth heterogeneity and symptoms of needle chlorosis (or yellowing). In *Pinus caribeae* plantations cultivated on very low fertility soils (effective CEC between 1.01 and 1.41 $cmol_c\ dm^{-3}$) in the Cerrado region of Minas Gerais, Chaves and Corrêa (2003; 2005) observed that symptoms of needle chlorosis were associated with manganese (Mn), calcium (Ca), and magnesium (Mg) deficiencies in soil and plant tissue. While leaf tissue is typically used to diagnosis nutritional problems, bark (Wit et al., 2010; Pereira et al., 2022), woody tissue (Rodriguez & Tomazello-Filho, 2019), and roots (Adams et al., 1987) have also been used. In addition to nutrition, abiotic factors such as luminosity may also influence appearance of deficiency symptoms in leaf tissue, particularly for Mg (Cakmak & Marschner, 1992; Ende & Evers, 1997; Cakmak & Yazici, 2010). Therefore, canopy position and associated climatic conditions must also be considered.

In addition to low natural fertility, nutritional deficiency may be related to soil exhaustion since these production areas often do not replace exported nutrients (Federer et al., 1989; Richter et al., 1994; Ferreira et al., 2001; Moro et al., 2014; Batista et al., 2015; Gatiboni et al., 2017; 2020; Consalter et al., 2021b; Topanotti et al., 2021). In some regions, acid rain occurrence also results in decreased bases, which can intensify the occurrence of nutritional deficiencies (Meiwes, 1995; Hüttl & Schaaf, 1997; Huber et al., 2006). However, atmospheric contributions and slow release of nutrients can influence nutrient exhaustion in different ways. Over a 120 year period forests did not display losses in nitrogen (N), but losses of 2 to 10% for potassium (K), Mg and phosphorus (P), and 20 to 60% for Ca (Federer et al. 1989). A study by Horst et al. (2018) related heterogeneity in *P. taeda* plantations to soil depth, relief, and landscape location. Several studies have shown that cultivations on shallow soils limits root development, which consequently constrains adequate tree growth (Morales et al., 2010; Gomes et al., 2016; Horst-Heinen et al., 2021). Morales et al. (2010) also observed that compaction of surface soil layers can affect tree development. In restricted environments where root penetration is limited, large quantities of thinner roots are commonly found in litter (Zucon et al., 2020; Adam et al., 2021). On sites with natural poor fertility, *Pinus* spp. plantations commonly have greater litter accumulation of poor quality, which limits biological activity, decomposition, and nutrient supply (Cherobim et al., 2010).

Accurately identifying factors associated with chlorotic needle symptoms in *Pinus* spp. plantations is necessary to formulate production strategies. Factor identification is essential for production to remain competitive, by increasing productivity and soil quality in production areas (Horst-Heinen et al., 2021). The Visible Atmospherically Resistant Index (VARI) method can assist in evaluating these factors. VARI can provide information on plant nutrition since it is based on the variability of plant vigor and stress, and measures the amount of green reflected by plants (Gitelson et al., 2002). Studies conducted by Dell et al. (2019) and Larrinaga and Brotons (2019) show the potential of VARI use in forested areas.

Thus, the aims of our study were to verify if the VARI technique was able to confirm heterogeneity observed in a commercial *P. taeda* plantation, and if heterogeneity was associated with pedological and chemical characteristics of soil, litter, and nutrition of *Pinus taeda* trees exhibiting chlorotic symptoms. Our hypothesis is that low growth zones observed by aerial imaging are on shallow soils with low fertility and reflect insufficient volume of exploited soil required to maintain adequate nutritional status. This fact can be visualized by the low concentration of essential elements and accumulation of toxic elements [e.g., aluminum (Al)] in plant tissues (needles, wood, bark, and fine roots) and greater accumulation of litter.

2 MATERIAL AND METHODS

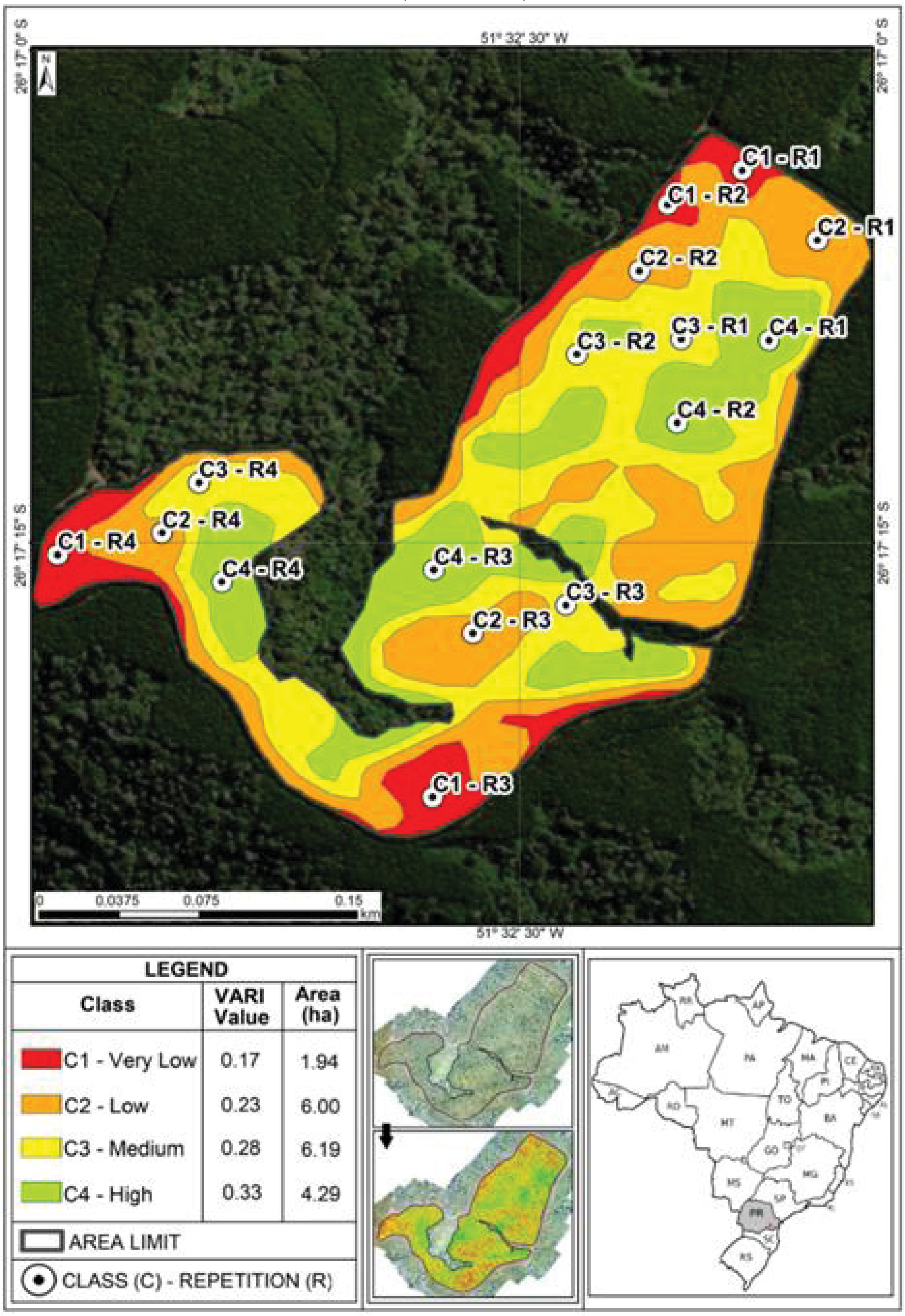
2.1 STUDY AREA

The study was conducted in a commercial *P. taeda* production area of Fazenda Lageado Grande I, (Remasa Company) located in the municipality of Bituruna in southern Brazil. The regional climate is Cfb - temperate, without dry season and with mild summer, with an annual average temperature of 17 ºC and rainfall of ~1550 mm (Alvares et al., 2013). Native site vegetation was subtropical Mixed Ombrophylous forest with abundance of Araucaria tree (*Araucaria angustifolia*). The selected area was located at the central coordinates 26°17'15" S and 51°32'30" W and consisted of 18.42 hectares exhibiting heterogeneity with many sites presenting low growth rates and trees with chlorosis. This area was in a second rotation of *P. taeda* cultivation, and at the time of sample collection trees were 14 years old and had already undergone two thinning operations. Tree spacing was 2.5 x 2.5 m (1600 plants ha^{-1}). The production system adopted for this site did not utilize fertilizers or soil correctives.

2.2 DELINEATING STUDY AREA INTO VARI CLASSES

Area selection was based on the presence of pine trees exhibiting a color gradient among needles ranging from a healthy color (no chlorosis) to symptomatic coloring (yellowing – chlorosis). For area delimitation, aerial images were obtained by an unmanned aerial vehicle drone (UAV; Phantom 4 Pro V2.0 – DJI). The camera had a wide-angle lens [field of vision (FOV) of 84º 8.8 mm/24 mm (35 mm equivalent format)] optimized at f/2.8 – f/11, integrated RGB and 1” CMOS sensors (20M effective pixels), and a mechanical shutter (DJI, 2023). Aerial images were continuously acquired every 5 cm. The original orthomosaic created was resampled to form 2 x 2 m pixels in order to partially break the exposed ground effect between lines. Afterwards, combined RGB images were processed through a program where the spatial distribution of the VARI index was smoothed. ArcGIS® (ESRI) sorted images into 4 classes using the Raster Calculator (Spacial Analyst) based on the standard VARI index algorithm (VARI = (Green – Red)/(Green + Red – Blue)) (Gitelson et al., 2002; ArcGis Pro, 2021a) and calculated Jenks natural breaks (ArcGis Pro, 2021b). Thus, generated the VARI map (Fig. 1) classified chlorotic plants entirely within the lowest VARI class; which was confirmed by aerial images and field observations.

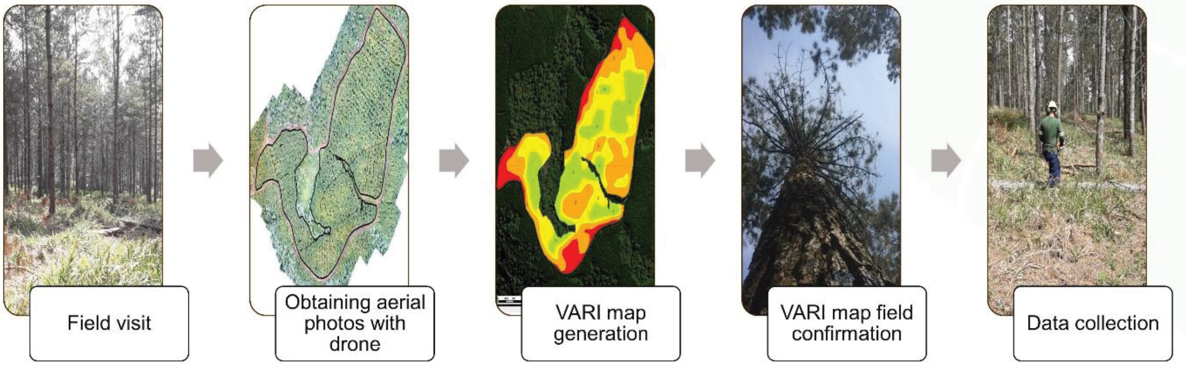
FIGURE 1 – VISIBLE ATMOSPHERICALLY RESISTAT INDEX (VARI) MAP SHOWING FOUR CLASSES OF REFLECTANCE INTENSITY (VERY LOW, LOW, MEDIUM, AND HIGH) AS INDICATORS OF GROWTH CONDITIONS IN A 14 YEAR-OLD *Pinus taeda* CULTIVATION (I.E., HIGHER VARI = BETTER TREE GROWTH) IN THE "LAGEADO GRANDE I" STUDY AREA IN BITURUNA, PARANÁ, BRAZIL.



SOURCE: The author (2023).
LEGEND: the map shows land polygon delimitations and respective evaluation points (being indicated as class (C) – repetition (R))

Therefore, as shown in Figure 2, the workflow consisted of a visit to the field, then obtaining aerial images by drone, making an VARI map, confirming the VARI map in the field and collecting data. Thus, as observed in the field, the lowest VARI value represented trees with yellow (chlorotic) needles, and the highest value was the healthiest trees with green needles.

FIGURE 2 – WORKFLOW SHOWING THE STEPS FOR CONDUCTION OF THE WORK ABOUT THE EVALUETION OF FOUR VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) IN A 14 YEAR-OLD *Pinus taeda* CULTIVATION IN THE "LAGEADO GRANDE I" STUDY AREA IN BITURUNA, PARANÁ, BRAZIL.



SOURCE: The author (2023).

Values of VARI obtained for the classes were 0.17, 0.23, 0.28 and 0.33, which were respectively called: C1 – Very low (red); C2 - Low (orange); C3 - Medium (yellow); and C4 - High (green) (Fig. 1). In polygons of each class (minimum size of 0.1 hectare), four plots were selected (each being ~160 m²) where spacing between trees did not follow an exact pattern due to two previous thinnings. This constituted four replications of each class (for a total of 16 plots evaluated); all plots were tagged via Global Positioning System (GPS) equipment (Fig. 1).

2.3 GROWTH DATA

Circumference at breast height (CBH) at 1.3 m (data not shown) was performed on 10 trees in each plot for a total of 40 trees per class (Figure S1a). Obtained values were used to calculate diameter at breast height (DBH = CBH/π) (Soares et al., 2011). Within each plot, the tree with a DBH closest to the average of the plot (10 trees) was harvested. To confirm if the harvested tree was representative of the plot, correlations between DBH of the harvested tree and the mean site DBH were very strong (r = 0.97) (Figure S2).

Each harvested tree was evaluated for total height and commercial height, where the latter considered length until the trunk diameter was 8 cm (Figure S1b). Trunk diameter was also measured at one meter spacings (using a brace) along the commercial height. Utilizing this information, sectional areas were calculated and commercial wood volume (with and without bark) was determined based on an adaptation of the Smalian formula (Soares et al. 2011).

2.4 TRUNK CROSS SECTION

After collecting height and diameter data of the harvested tree, the tree trunk was cut to obtain six cross sections (Figure S1c). Cross sections were obtained at the base of the tree, at breast height (1.3 m, corresponding to DBH), and at four different percentage values of commercial height (25%, 50%, 75%, and 100%). All cross sections were air dried and polished.

In the wood anatomy laboratory (located at the Superior School of Agriculture "Luiz de Queiroz" – University of São Paulo), analysis of density and width of cross sections growth rings at DBH were obtained. Following the methodology of Rodriguez (2018), a diametrical strip (1 cm wide) was demarcated with the medulla as the central reference (0.5 cm for each side) prior to cutting the strip. Cut strips were glued to a wooden support; after drying, strips mounted on supports were again cut crosswise (2 mm thickness) with a parallel double circular saw. Subsequently, 2 mm transverse samples of the cross sections were packed into a climatic chamber with 12% humidity (20 ºC, 60% relative humidity, 24 hours) and scanned using X-ray densitometry equipment (Faxitron® LX-60 Cabinet X-ray System). X-ray images were processed by the WinDENDRO^{TM} - Tree Rings and Wood Density program, and each sample was analyzed in the pith to bark direction to obtain the annual growth rate (growth ring width) and wood density. Furthermore, density and volume data were used to calculate wood biomass (with and without bark) as follows: wood biomass (kg) = wood volume (m^3) x wood density (kg m^{-3}) (Soares et al., 2011).

All collected the cross sections had their wood and bark chemically analyzed. The bark of each cross sections was completely ground in a Wiley mill before analysis. The wood of each cross sections was cut to obtain the last six growth rings, and this was passed through a cutting saw (resulting sawdust was used for analysis). Both materials were analyzed by dry digestion following the methodology of Martins and

Reissmann (2007). The digestion process of each sample consisted of the following initial steps: weighing 1 g of material in a porcelain crucible; incineration in a muffle furnace (500 ºC) for 3 hrs; cooling inside the open muffle furnace; addition of 3 drops of HCl (hydrochloric acid) 3 mol L^{-1}; and a new incineration period of 3 hrs in the muffle furnace. After cooling, 10 mL of HCl 3 mol L^{-1} per crucible was added and crucibles were arranged on a heating plate set at a temperature of ~80 ºC for 20 min. Cooled samples were filtered into a 100 mL balloon using deionized water and blue band filter paper. Levels of Al, arsenic (As), boron (B), barium (Ba), Ca, cadmium (Cd), cobalt (Co), chrome (Cr), copper (Cu), iron (Fe), K, Mg, Mn, molybdenum (Mo), nickel (Ni), P, lead (Pb), antimony (Sb), selenium (Se), vanadium (V), and zinc (Zn) were quantified in the obtained extract by inductively coupled plasma optical emission spectroscopy (ICP-OES).

2.5 NEEDLES

From each harvested tree, needles were collected from four branches in the lower and upper third of the canopy; those from the upper third were separated into first and second needle flushes (Rabel, 2019) (Figure S1d). Sampled needles were washed in deionized water and dried in a forced circulation oven at 65 °C until constant mass was obtained (~72 hours). Mass of 100 needles from each sampled section (i.e., lower third, upper third – first and second flush) was determined with a precision balance. As previously described for wood and bark, needles were then analyzed by dry digestion following the methodology of Martins and Reissmann (2007). Levels of Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Ni, P, Pb, Sb, Se, V, and Zn in extracts were quantified by ICP-OES.

2.6 LITTER AND FINE ROOTS

Litter was collected at three random points around harvested trees using a square template (0.2 x 0.2 m) and saw knife (Figure S1e). In the laboratory, litter was washed to remove adhered soil particles and dried in a forced circulation oven at 65 °C until constant mass was obtained. Mass of litter was determined with a precision balance. Pine fine roots were separated from the litter (Figure S1f) and shredded prior to chemical analysis (Martins & Reissmann, 2007). Litter was separated into two fractions [> 2 mm (freshly fallen needles - undecomposed material) and < 2 mm (fragmented and fermented material)] and both fractions were ground using an electric grinder. Fine roots and the two litter fractions were processed by dry digestion. Levels of Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Ni, P, Pb, Sb, Se, V, and Zn in extracts were determined by ICP-OES. Litter mass per hectare was then used to calculate nutrient content per hectare.

2.7 SOIL CHEMISTRY

Soil was collected at six points per plot with dutch auger at three depths (0–0.20, 0.20–0.40, and 0.40–0.60 m) (Figure S1g) and composited by depth. Prior to chemical analyses, samples were dried in an oven at 65 °C for 72 hours and manually ground to pass a 2 mm sieve. Soil chemical analyses consisted of evaluating pH in $CaCl_2$ (0.01 mol L^{-1}) – ratio 1:2.5, pH SMP - potential acidity (H + Al), organic carbon, exchangeable aluminum (Al^{3+}) extracted by KCl 1 mol L^{-1}, and P, K, Na, Ca, Mg, As, B, Ba, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Sb, Se, V, and Zn extracted by Mehlich-1. Al^{3+} was determined by titration with NaOH 0.2 mol L^{-1}, P by spectrophotometer, K^+ and Na^+ by flame photometry, and extracts of remaining elements were analyzed by ICP-OES (Brazilian Agricultural Research Corporation [Embrapa], 1997; 2017; Marques & Motta, 2003). From obtained results, the following parameters were calculated: sum of bases (SB = Ca + Mg + K + Na^+), effective cation exchange capacity (CEC eff. = SB + Al), potential cation exchange capacity ((CEC pH 7.0 = SB + (H + Al)), aluminum saturation (m% = Al/CEC eff. x 100), base saturation (V% = SB/CEC pH 7.0 x 100) (Embrapa, 1997; 2017; Marques & Motta, 2003), and lime recommendation (LR) by the Ca^{2+} and Mg^{2+} elevation method (LR (Mg ha^{-1}) = 2 – (Ca ($cmol_c$ dm^{-3}) + Mg ($cmol_c$ dm^{-3})) (Sousa & Lobato, 2004).

2.8 SOIL PEDOLOGY AND GRANULOMETRY

Observation of study plots in regards to relief and landscape (Figure S1h) indicated no significant variation in soil classes. Thus, a morphological description of the soil profile was performed to a depth of 1 m in the center of each evaluated plot (Figure S1i). In addition, samples were collected from each pedogenetic horizon for chemical and physical analyses. Chemical analysis consisted of the same sequence of analysis previously described for soil sample obtained at depths of 0–0.20, 0.20–0.40 and 0.40–0.60 m. Physical analysis (granulometry) was performed by the hydrometer method (Gee & Bauder, 1986). Using these field and laboratory data soil classification was performed according to the Brazilian Soil Classification System (SiBCS) (Embrapa, 2018) and the World Reference Base (WRB) (FAO, 2015). Slope of each plot was determined using a clinometer and plot position within the landscape was also evaluated.

2.9 STATISTICAL ANALYSES

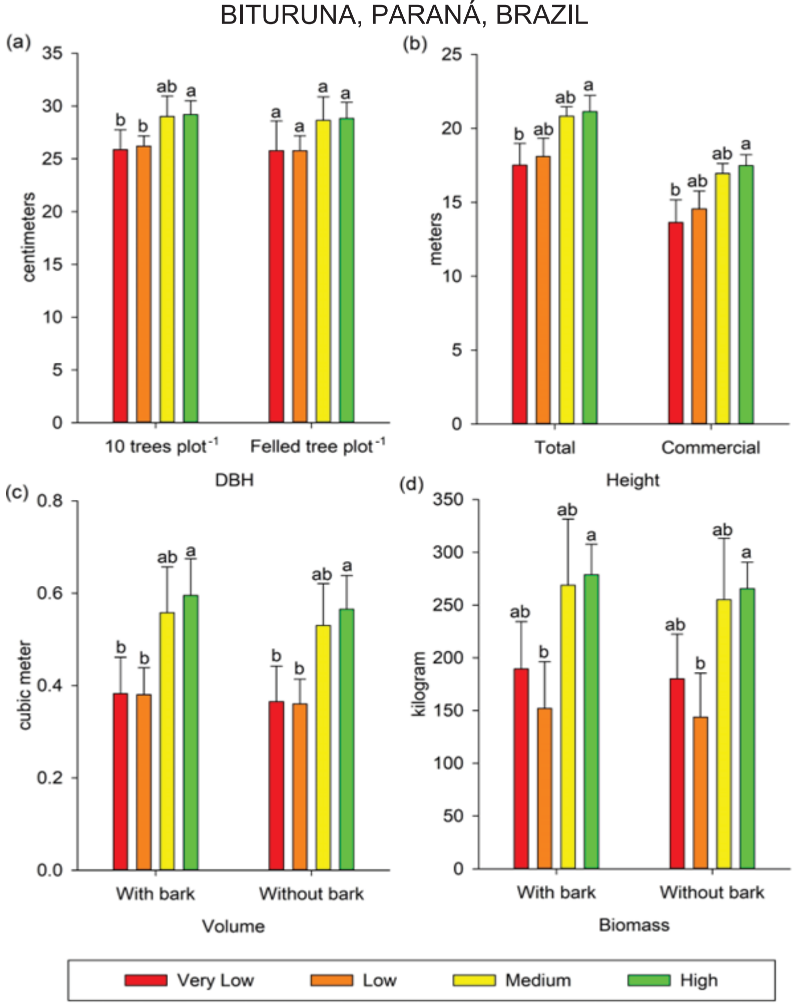
Collected data were analyzed by the Kruskal-Wallis test. Data were then submitted to the Nemenyi means test ($p \leq 0.01$, $p \leq 0.05$, and $0.05 < p \leq 0.10$) using the R program (v. 4.2.1).

3 RESULTS

3.1 VARI CLASSES AND TREE GROWTH

Use of the VARI method verified heterogeneity in commercial *P. taeda* plantings since differences in tree growth for most of the variables evaluated were efficiently identified by VARI maps and confirmed in the field (Figure 2). The greatest differences in tree growth usually observed between the High (0.33) and Very Low (0.17) VARI classes since the Low (0.23) and Medium (0.28) classes were often similar to each other or with the extreme classes (Very Low and High) (Figure 3).

FIGURE 3 – THE ASSOCIATION OF VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) WITH AVERAGE DIAMETER AT BREAST HEIGHT (DBH - 1.30 m) FOR PLOTS (10 TREES PLOT^{-1}) AND FELLED TREES (a), TOTAL AND COMMERCIAL HEIGHT (b), WOOD VOLUME PER TREE (WITH AND WITHOUT BARK) (c), AND TRUNK BIOMASS PER TREE AT 14 YEARS (WITH AND WITHOUT BARK) (d) IN A COMMERCIAL CULTIVATION OF *Pinus taeda* EVALUATED IN BITURUNA, PARANÁ, BRAZIL



SOURCE: The author (2023).

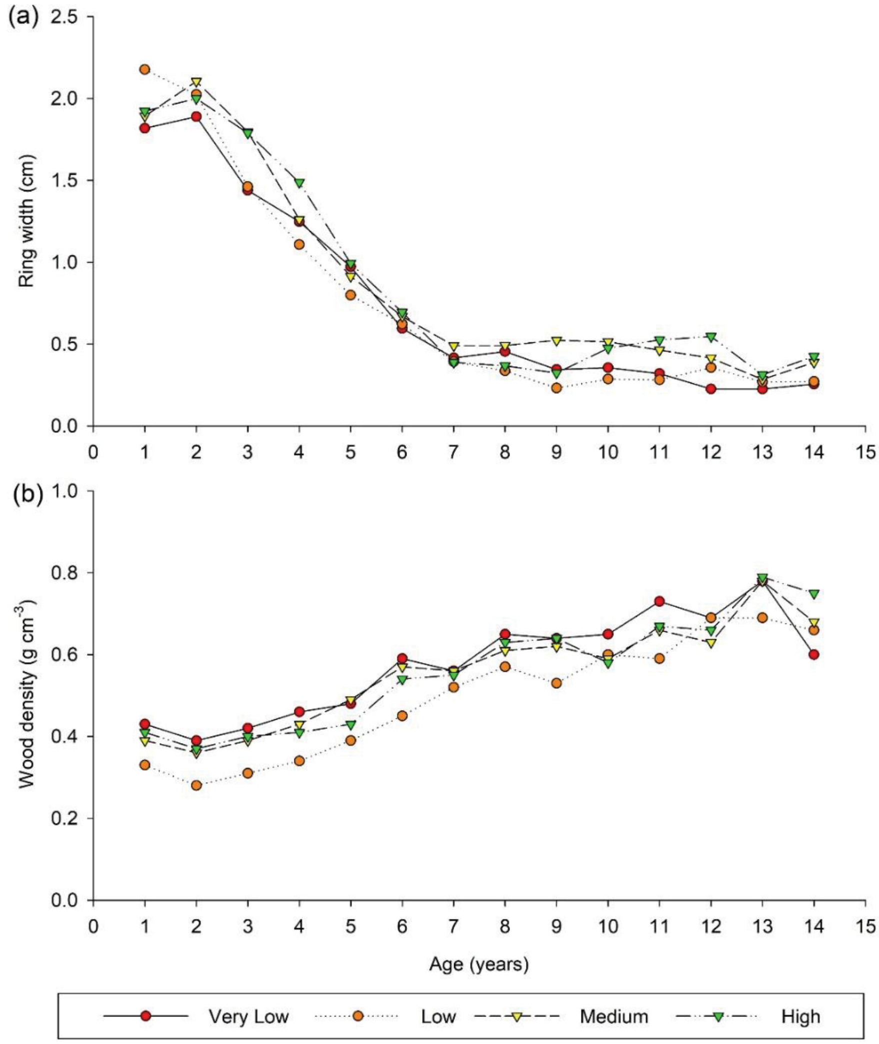
LEGEND: Colored bars represent means and vertical lines represent error bars (SD). The Y axes represent the respective measurement units of each variable. Each bar color represents a VARI class with the lowest VARI class on the left and the highest VARI class on the right. Means followed by different letters within each evaluated parameter between VARI classes differ statistically from each other by Kruskal-Wallis with the Nemenyi means test ($p \leq 0.05$).

The High VARI class represented the best performing trees with DBH for plot (29.18 cm) (Figure 3a), total height (21.13 m), and commercial height (17.49 m) (Figure 3b), which were higher than the Very Low class. In comparison, trees in the Very Low class exhibited the lowest growth indices in terms of total height (17.52 m) and commercial height (13.64 m) (Figure 3b). Similar responses were observed for wood volume (with and without bark). In regard to wood volume with bark, its increased by 0.21 m^3 from the Very Low class (0.38 m^3) to the High class (0.59 m^3); without considering bark, the volume increase was 0.20 m^3 between these classes (0.36 to 0.57 m^3) (Figure 3c). Trunk biomass was higher in the High VARI class (279 kg with bark and 266 kg without bark), compared to the Low class (152 kg with bark and 144 kg without bark). Although the Low class had the lowest values, they were numerically closer to the Very Low class (Figure 3d).

3.2 WOOD DENSITY AND GROWTH RING WIDTH

During the 14 years, X-ray profiles (Figure S3) showed no difference in wood density among classes, with averages from Very Low to High being 0.58, 0.50, 0.55, and 0.56 g cm^{-3}, respectively (Table S1). Regarding growth rings, all tree classes showed highest growth values in the first four years (on average, Very Low – 1.60 cm, Low - 1.69 cm, Medium - 1.76 cm, and High - 1.80 cm) that stabilized after the seventh (Figure 4a and Table S2). Thus, all classes displayed similar behavior for ring growth and density (Figure 4). Wood density generally increased over time in a non-linear fashion (Table S1 and Figure 4b). In the last four years (2018 to 2021), despite showing no differences, the classes exhibited linear behavior among themselves in relation to growth; respective average values from lowest to highest VARI classes were 0.26, 0.30, 0.39, and 0.45 cm (Table S2). Specifically, in the fourteenth year, the High class displayed numerically higher growth (0.43 cm) and density (0.75 g cm^{-3}), and the Very Low class displayed numerically lower growth (0.26 cm) and density (0.60 g cm^{-3}) (Figure 4 and Tables S1 and S2).

FIGURE 4 – ANNUAL WIDTH OF GROWTH RINGS (a) AND WOOD DENSITY (b) OF 14 YEAR-OLD *Pinus taeda* TREES IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) EVALUATED IN BITURUNA, PARANÁ, BRAZIL.



SOURCE: The author (2023).

LEGEND: The data showed no statistical difference according to the Kruskal-Wallis with the Nemenyi means test ($p \leq 0.05$).

3.3 SYMPTOMS AND ELEMENTS IN EVALUATED COMPONENTS

In the field, yellowing of needles (chlorosis) was only observed in trees belonging to the Very Low VARI class; yellowing beginning at needle tips migrated towards medial portions (Figures S4a and S4b). In needles with more advanced yellowing (closer to basal portions), needle tips began to present symptoms of necrosis (Figure S4a). In addition, trees in the Very Low and Low VARI classes presented thin cups, which may be indicative of early needle fall (Figure S4c).

In general, the evaluation of the different components (needles, wood, bark, fine roots, litter, and soil) among studied classes suggest that chlorosis was likely related to a Mg issue; observations indicated that Mg was significantly ($p \leq 0.01$ or $p \leq 0.05$) associated with symptoms or exhibited a trend ($0.5 < p \leq 0.10$) in seven of the nine components evaluated (Chart 1). Furthermore, Mg levels in first flush needles from the upper third of the canopy showed a strong correlation with total tree height (0.72) and a moderate correlation with volume of wood with bark (0.67) (Figure 5). Calcium was also shown to be associated with chlorotic symptoms with differences (significance of $p \leq 0.05$ and trend of $0.05 < p \leq 0.10$) noted in five of the components (Chart 1). Other elements showed responses such as Ba differing in wood and bark (trend also noted in needles), Cr differing in needles, B showing a trend in bark, and Mn showing a trend in fine roots (Chart 1). A commonality in differences and trends observed for Mg, Ca, Ba, Cr, B, and Mn in mentioned components was that they were all found to have smaller concentrations in the lowest VARI class (Very Low) where chlorostic symptoms were observed.

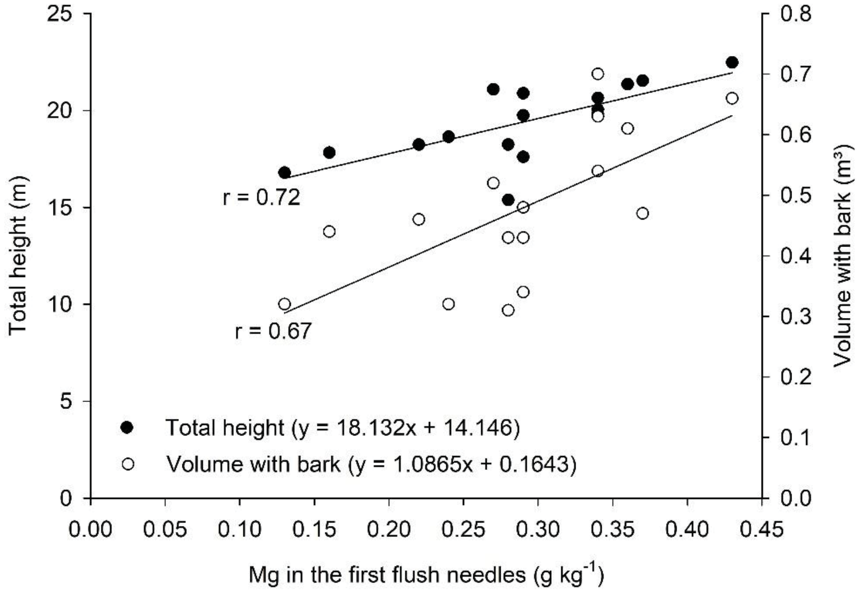
CHART 1 – RELATIONSHIP BETWEEN SYMPTOMS OF NUTRITIONAL DEFICIENCY (CHLOROSIS) AND ELEMENTS IN DIFFERENT COMPONENTS (NEEDLES, WOOD, BARK, FINE ROOTS, LITTER, AND SOIL) IN A 14 YEARS-OLD *Pinus taeda* CULITIVATION IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) EVALUATED IN BITURUNA, PARANÁ, BRAZIL.

Evaluated component	Observation[1]	Ca	Mg	P	K	Al	B	Ba	Cr	Cu	Fe	Mn	Zn
Needles	-	t	*	t	-	-	-	t	*	-	-	-	-
Wood	below < 50	*	-	t	t	*	* and **	*	-	*	*	-	* and **
	upper > 50	-	t	-	-	-	* and **	*	-	* and **	-	-	*
Bark	below < 50	*	t	-	-	-	t	* and **	-	-	t	-	-
	upper > 50	-	*	-	-	-	t	-	-	-	*	-	-
Fine roots	-	*	**	-	-	-	-	-	-	-	-	t	-
Litter	< 2 mm	t	t	-	-	-	t	-	-	-	-	-	-
	> 2 mm	*	*	-	-	-	-	-	-	-	-	-	-
Soil	-	-	-	-	-	-	-	-	-	-	-	-	-

[1] below < 50 = cross sections collected from the bottom of the tree (Base, DBH, and 25% of commercial height); upper > 50 = cross sections collected at the top of the tree (50, 75, and 100% of commercial height).
Symbols within the chart: t = trend between classes, significant difference between classes of $0.05 < p \leq 0.10$); * = Significant difference between classes of $p \leq 0.05$; ** = Significant difference between classes of $p \leq 0.01$; * and ** = Significant difference between classes of $p \leq 0.01$ and $p \leq 0.05$ for different height samplings.
Statistical differences based on analysis by Kruskal-Wallis with Nemenyi means test between classes.
Blue coloring indicate variables with a direct relationship to chlorotic symptoms (higher values in the High VARI class), and red coloring represents an inverse relationship to chlorotic symptoms (higher values in the Very Low VARI class).

SOURCE: The author (2023).

FIGURE 5 – CORRELATION GRAPH BETWEEN Mg IN NEEDLES FROM THE UPPER THIRD OF THE CANOPY OF THE FIRST FLUSH WITH TOTAL HEIGHT (y = 18.132x + 14.146, r = 72%) REPRESENTED BY BLACK DOTS AND TRUNK VOLUME WITH BARK (y = 1.0865x + 0.1643, r = 67%) REPRESENTEDED BY WHITE DOTS FOR 14 YEAR-OLD *Pinus taeda* IN BITURUNA, PARANÁ, BRAZIL



SOURCE: The author (2023).
LEGEND: Lines show equation trends.

On the other hand, levels of some elements seem to have an inverse relationship with chlorotic symptoms where their quantities were greater in lower VARI classes. Among elements, there were trends for P (needle and wood), K (wood), and Fe (bark) along with significant differences for Al, B, Cu, and Zn in wood (Chart 1). Other elements such as Ni and V showed no difference among classes. Thus, there were strong indications that P, K, Al, B, Ba, Cr, Cu, Fe, Mn, Ni, V, and Zn concentrations may be not related to observed symptoms, and the relationship with Ba, Cr, and Mn was not strong enough to explain field symptoms. In addition, other elements (i.e., As, Cd, Co, Mo, Pb, Sb, and Se) were below the quantifiable detections limits of the ICP-OES device in all classes.

3.4 TREE TISSUE - NEEDLE, WOOD, BARK AND FINE ROOTS IN LITTER

The mass of 100 needles did not vary among VARI classes. However, values of all classes were lower in the lower third (2.28 to 3.07 g) compared to the upper third of the canopy for the first (4.06 to 5.10 g) and second needle flushes (3.92 to 4.75 g) (Table 1).

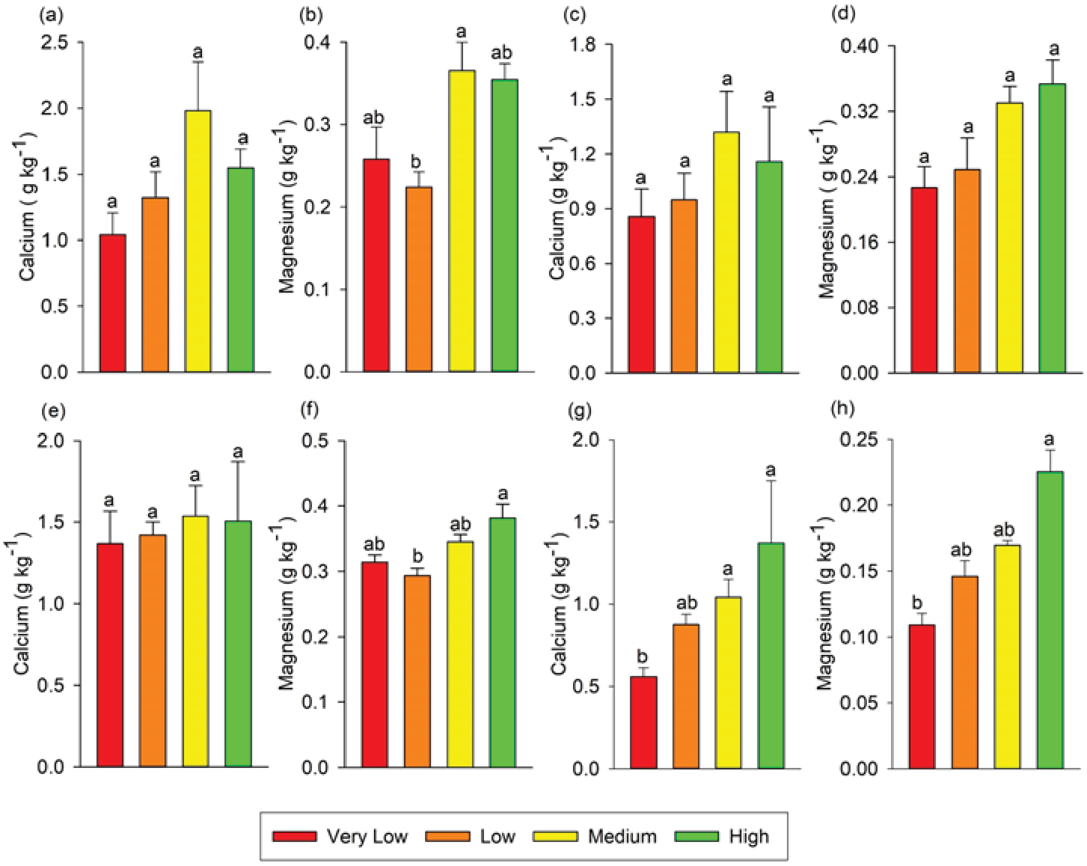
TABLE 1 – CONCENTRATIONS OF NUTRIENTS AND Al IN NEEDLES OF THE LOWER (SECOND FLUSH) AND UPPER THIRD (FIRST AND SECOND FLUSH) OF THE CANOPY OF A 14 YEAR-OLD *Pinus taeda* CULTIVATION IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) EVALUATED IN BITURUNA, PARANÁ, BRAZIL.

Classes	**Mass of 100 needles**	**P**	**K**	**Al**	**B**	**Ba**	**Cr**	**Cu**	**Fe**	**Mn**	**Ni**	**V**	**Zn**	**K/Mg**
-	g	----- $g\ kg^{-1}$ -----		---------- $mg\ kg^{-1}$ ----------										-
							Lower third of tree crown – Second flush							
Very Low	2.28 a	1.27 a	5.61 a	434 a	2.33 a	1.80 a	0.63 b	4.84 a	117 a	195 a	1.82 a	0.18 a	25.32 a	25 a
Low	3.07 a	1.10 a	4.64 a	361 a	2.37 a	1.63 a	0.64 b	4.44 a	99.31 a	200 a	0.83 a	0.12 a	20.54 a	21 a
Medium	2.53 a	1.04 a	4.78 a	333 a	2.89 a	2.80 a	0.76 ab	4.65 a	112 a	287 a	1.20 a	0.10 a	17.25 a	13 b
High	2.35 a	1.04 a	4.79 a	380 a	2.35 a	2.94 a	1.32 a	4.21 a	127 a	244 a	1.26 a	0.18 a	19.11 a	14 ab
							Upper third of tree crown – First flush							
Very Low	4.30 a	1.26 a	4.43 a	493 a	2.30 a	1.76 a	0.70 b	3.48 a	153 a	146 a	1.13 a	0.26 a	27.89 a	20 a
Low	5.10 a	1.10 a	4.05 a	390 a	2.44 a	1.61 a	0.81 ab	4.25 a	161 a	139 a	1.85 a	0.30 a	33.65 a	18 ab
Medium	4.28 a	1.07 a	4.44 a	427 a	3.01 a	1.76 a	0.87 ab	4.01 a	157 a	185 a	2.03 a	0.27 a	26.41 a	14 ab
High	4.06 a	1.04 a	4.57 a	483 a	2.17 a	2.33 a	1.14 a	4.82 a	150 a	160 a	1.40 a	0.30 a	21.91 a	13 b
							Upper third of tree crown – Second flush							
Very Low	4.47 a	1.37 a	5.02 a	513 a	3.80 a	1.67 a	0.75 b	4.61 a	157 a	255 a	2.07 a	0.24 a	39.99 a	16 a
Low	4.75 a	1.18 a	4.81 a	386 a	3.63 a	1.52 a	0.92 ab	4.84 a	133 a	199 a	3.74 a	0.20 a	46.16 a	16 a
Medium	4.69 a	1.12 a	4.54 a	414 a	4.94 a	1.63 a	0.75 b	4.19 a	142 a	247 a	3.24 a	0.21 a	30.00 a	13 a
High	3.92 a	1.08 a	4.66 a	471 a	3.18 a	2.33 a	1.10 a	4.40 a	134 a	231 a	2.79 a	0.22 a	28.31 a	12 a

Means followed by different letters in columns within each subdivision (lower third - second flush, upper third – first flush and upper third – second flush) differ statistically from each other by Kruskal-Wallis with Nemenyi mean test ($p \leq 0.05$).
SOURCE: The author (2023).

Needle Ca concentration showed a trend ($0.05 < p \leq 0.10$) for the lowest values being in the Very Low class in the three crown sampling positions (Figures 6a, 6c, and 6e). Mg concentration was higher ($p \leq 0.05$) or tended ($0.05 < p \leq 0.10$) to be higher in all needle portions evaluated for the higher VARI classes (Medium and High) (Figures 6b, 6d, and 6f). The highest VARI class had higher Cr levels in the three needle portions evaluated (Table 1). Thus, chlorotic symptoms observed in the field were probably associated with Mg and Ca deficiencies causing needle fall and thin canopies.

FIGURE 6 – RESPECTIVE CALCIUM AND MAGNESIUM LEVELS IN NEEDLES OF THE SECOND FLUSH OF THE LOWER CANOPY THIRD (a, b) AND OF THE FIRST (c, d) AND SECOND (e, f) FLUSHES OF THE UPPER CANOPY THIRD AND IN FINE ROOTS (g, h) OF 14 YEAR-OLD *Pinus taeda* IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) EVALUATED IN BITURUNA, PARANÁ, BRAZIL



SOURCE: The author (2023).

LEGEND: Colored bars represent means and vertical lines represent error bars (SD). The Y axes represent nutrients and respective measurement units. Each bar color represents a VARI class, with the lowest VARI class on the left and the highest VARI class on the right. Means followed by different letters within each evaluated parameter between VARI classes differ statistically from each other by Kruskal-Wallis with the Nemenyi means test ($p \leq 0.05$).

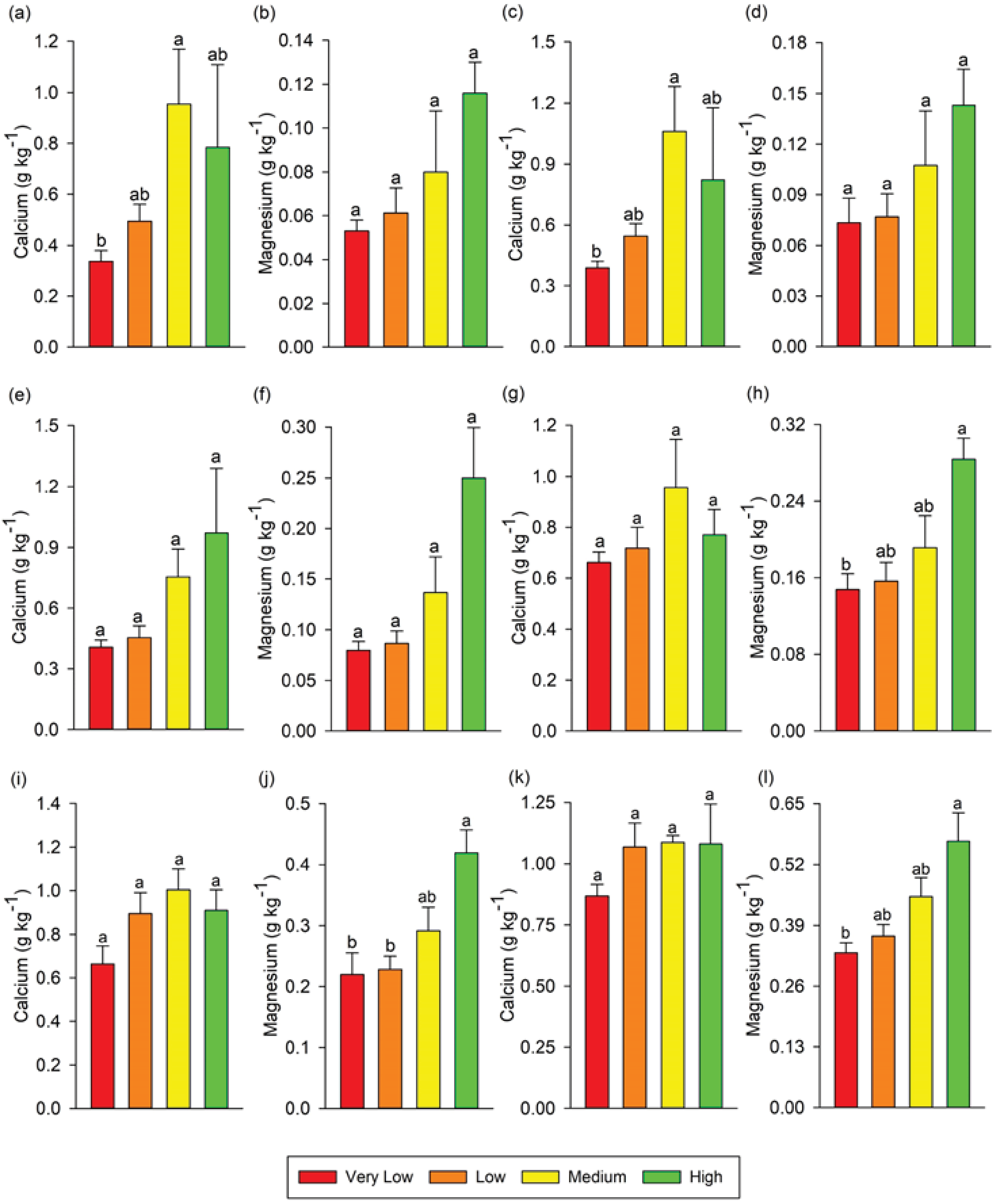
The most abundant elements in first flush needles (upper third of canopy) followed the order K > Ca > P > Mg. This same order was observed for needles of the second flush from the upper and lower thirds of the canopy (Table 1 and Figures 6a to

6f). Considering the superiority of K level over other nutrients (especially Mg), a high K/Mg ratio was noted in all classes (Table 1). In relation to other elements, the high levels of Al, Mn, and Fe in needles were notable and varied from 333 to 513, 139 to 287, and 99.31 to 161 mg kg^{-1}, respectively (Table 1).

Wood tissue from the Very Low class at most evaluated heights had the highest levels of B, Zn, and Al, while the opposite occurred for Ba, Ca, and Cu (Table S3). Boron concentrations were highest in the lowest VARI class (Very Low) at all heights evaluated, while Zn was highest along 50% of commercial height and Al was highest at the base. Conversely, the High class showed the highest levels of Ba up to 50%, while the Ca in wood at 25% of height was lower, as well as Cu at the same height and the last two heights (75 and 100% of commercial height) (Table S3). The most abundant element in wood in all classes was K, followed by Ca, P, and Mg, where the latter had very close values across classes and heights (Table S3). Among other elements, wide variation was observed between wood tissue along the commercial height for B (0.61 to 4.85 mg kg^{-1}), Zn (1.87 to 18.69 mg kg^{-1}), Fe (0.41 to 52.73 mg kg^{-1}), and Al (7.02 to 47.84 mg kg^{-1}).

Similar to wood, K was the most abundant element in bark followed by Ca, P, and Mg (Figure 7 and Table S4). However, elements in bark varied less as a function of sampling height. Calcium and Ba exhibited a direct relationship with VARI class in lower trunk portions (base, DBH, and 25% of commercial height); this was also true for Mg at all commercial height positions (Figure 7). In general, increased concentrations of Ca, Mg, K, B, Cu, Mn, and Zn were observed as a function of sampling height, with increases on the order of 1.6, 5.5, 5.2, 2.7, 1.8, 3.3, and 11 times, respectively. In both wood and bark, levels of As, Cd, Cr, Co, Mo, Ni, Pb, Sb, Se, and V were below ICP-OES detection limits.

FIGURE 7 – RESPECTIVE CALCIUM AND MAGNESIUM LEVELS IN BARK OF 14 YEAR-OLD *Pinus taeda* THE BASE (a, b), AT DIAMETER AT BREAST HEIGHT (1.3 m) (c, d), AND 25% (e, f), 50% (g, h), 75% (i, j), AND 100% (k, l) OF COMMERCIAL TREE HEIGHT FOR DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) EVALUATED IN BITURUNA, PARANÁ, BRAZIL



SOURCE: The author (2023).
LEGEND: Colored bars represent means and vertical lines represent error bars (SD). The Y axes represent the nutrient and its respective measurement units. Each bar color represents a class of VARI, with the lowest VARI class on the left and the highest VARI class on the right. Means followed by different letters within each evaluated parameter between VARI classes differ statistically from each other by Kruskal-Wallis with the Nemenyi means test ($p \leq 0.05$).

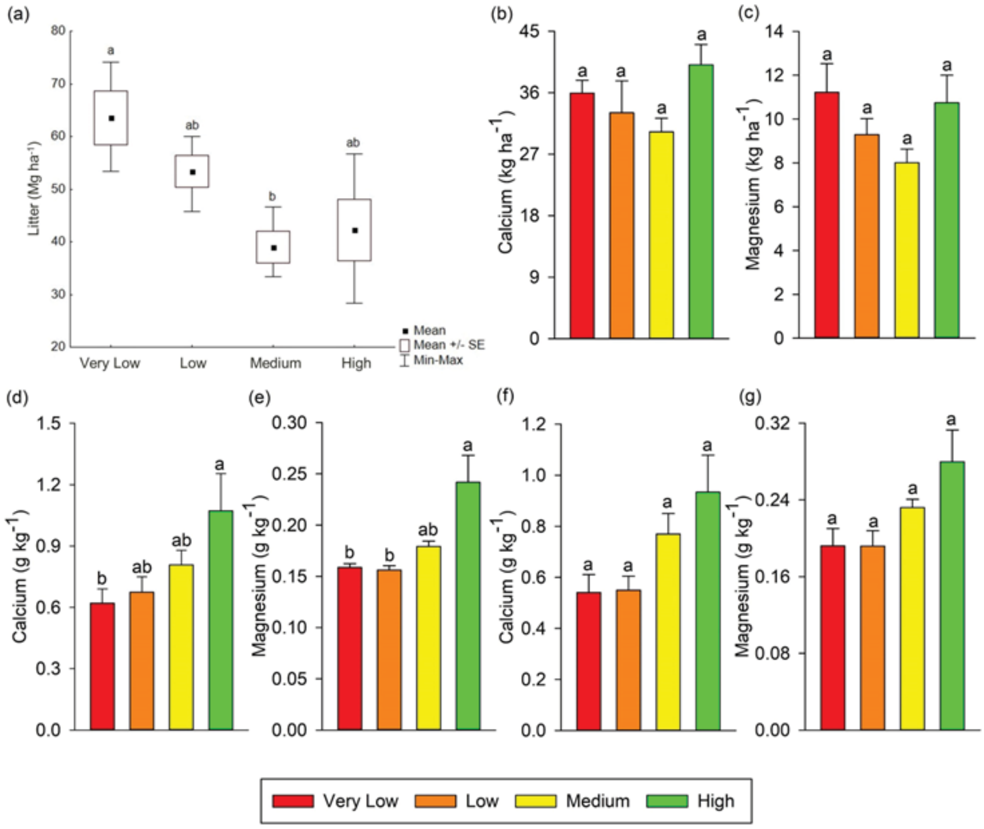
A direct relationship was observed between fine root Ca and Mg concentrations and VARI classes, with levels ranging from 0.11 to 0.23 $g\ kg^{-1}$ for Mg and 0.56 and 1.37 $g\ kg^{-1}$ for Ca from the Very Low to High classes, respectively

(Figures 6g and 6h). The Ca/Al ratio in fine roots had a lower numeric value in the Very Low class (0.77) and the highest in the High class (1.66). For the K/Mg ratio, behavior between classes varied with the lowest numeric value found in the High class (5.38) and the highest numeric value in the Low class (8.72) (Table S5).

3.5 LITTER

Litter accumulation followed the descending order of: Very Low > Low > High > Medium (Figure 8a). Although the High class (42 Mg ha^{-1}) did not differ from the Low and Very Low classes, the litter accumulation value was closer to the Medium class (39 Mg ha^{-1}). Thus, High and Medium classes showed greater differences in amounts versus the Very Low (64 Mg ha^{-1}) and Low (53 Mg ha^{-1}) classes. Despite the difference in litter accumulation, there were no differences in Ca and Mg contents in litter (Figures 8b and 8c). The only nutrient that had a difference content among classes in the litter was P, where it was higher in the Very Low class and lower in the Medium class (Table S6). In contrast, concentrations of Ca and Mg were higher ($p \leq 0.05$) in the litter fraction > 2 mm in the High class compared to the Very Low class. For the litter fraction < 2 mm, there was a tendency ($0.05 < p \leq 0.10$) for Ca and Mg concentrations to be lower in the Very Low class and higher in the High class (Figures 8d to 8g). The thin litter fraction (< 2 mm) showed no differences between classes for evaluated elements; this could be associated with soil contamination in this fraction given that high levels of Fe and Al were observed (Table S6).

FIGURE 8 – ACCUMULATED LITTER AMOUNT (a), CONTENT IN kg ha^{-1} OF CALCIUM (b) AND MAGNESIUM (c) IN THE ACCUMULATED LITTER AND RESPECTIVE CALCIUM AND MAGNESIUM LEVELS IN LITTER FRACTIONS GREATER THAN 2 mm (d, e) AND LESS THAN 2 mm (f, g) IN A 14 YEAR-OLD *Pinus taeda* CULTIVATION IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) EVALUATED IN BITURUNA, PARANÁ, BRAZIL



SOURCE: The author (2023).

LEGEND: Figure a: vertical lines represent standard errors; horizontal lines the minimum and maximum values; rectangles the mean ± the standard error; and the central black squares the mean. Figures b to g: bars represent the means and vertical lines represent the error bars (SD). The Y axes represent the nutrient and respective measurement units. Each bar color represents a VARI with the lowest VARI class on the left and the highest VARI class on the right. Means followed by different letters within each evaluated parameter between VARI classes differ statistically from each other by Kruskal-Wallis with the Nemenyi means test ($p \leq 0.05$).

3.6 SOIL CHEMISTRY

In general, soils associated with all classes were of very low fertility, extremely acidic, high in Al^{3+} and Al^{3+} saturation, low in bases and base saturation, and had high buffer power as a function of large organic matter amounts at all depths (Table S7 and S8). Unlike pine tissue, differences in soil for classes were very small, had lower P availability in the 0.20–0.40 m layer, and had lower lime recommendations in the 0–0.20 m layer for the High VARI class. At a depth of 0.40-0.60 m, the High class had the numeric lowest aluminum saturation (88%) and the highest numeric base saturation (1.78%) (Table S7).

Among micronutrients and other elements evaluated, there was only differences for Cr, Cu, and Mo. Smaller Cr quantities were observed for the Medium class at the 0-0.20 m and 0.20-0.40 m depths. Copper was higher in the Very Low class (5.61 mg dm^{-3} at 0.20-0.40 m and 6.06 mg dm^{-3} at 0.40-0.60 m) compared to the High class (4.14 mg dm^{-3} at 0.20-0.40 m and 4.55 mg dm^{-3} at 0.40-0.60 m). At the 0.20-0.40 m depth, Mo was at a higher level (5.20 mg dm^{-3}) in the High class, while the lowest value was found in the Medium class (1.47 mg dm^{-3}) (Table S8).

3.7 SOIL PEDOLOGY AND GRANULOMETRY

Evaluated areas showed several overlaps in soil classification (Table 2). However, separation by VARI showed that sites belonging to the High VARI class had a stronger water regime, which may have enhanced productivity at these sites (Table 2). All evaluated profiles identified soils of very low fertility (Tables S9 and S10), which could be associated with acidic eruptive rocks (rhyodacite/rhyolite) being poor parent material. Soil granulometry varied widely within the same class in the field but did not justify the separation of classes. Considering all VARI classes, the surficial horizon had soil clay content ranging from 288 to 750 g kg^{-1}, while differences in subsurface horizons ranged from 313 to 800 g kg^{-1}; in both cases, soils were classified as clay loam to very clayey in texture (Table S11). Therefore, there was no difference between VARI classes in terms of soil type, depth to impediment layer, surface horizon type, horizon thickness, and texture (Tables 2 and S11). However, attributes of landscape position and relief (when analyzed together) help explain behavior differences, especially for the Very Low and High VARI classes. Very Low VARI plots were positioned on slightly elevated sites in the upper third of the slope (1 and 3% slopes) and moderately steep to steep (12 and 22% slopes) sites in the middle third (Table 2). Plots of the High class were located in the middle and lower thirds, with three plots on landscapes that favored accumulation of water (Table 2) and the fourth plots on a slope with gentle relief (7% slopes). This information suggests favorable conditions for the High class in terms of water and nutrient conservation. In addition, two Very Low plots positioned in the upper third of the slope did not experience moisture benefits from subsurface runoff of upstream lands (Table 2). The other two VARI classes (Low and Medium) presented intermediate characteristics.

TABLE 2 – COORDINATES, POSITION IN THE LANDSCAPE, SLOPE, DRAINAGE, SOIL CLASSIFICATION, TYPE AND THICKNESS OF THE SURFICIAL HORIZON AND SOLUM DEPTH EVALUATED WITHIN EACH VARI CLASS (VERY LOW - VL, LOW - L, MEDIUM – M, AND HIGH - H) IN A 14 YEAR-OLD *Pinus taeda* CULTIVATION IN BITURUNA, PARANÁ, BRAZIL

Class - Repetition	Coordinates		Position in the landscape	Slope	Drainage	Soil classification		Surficial Horizon		Solum depth
	Latitude	Longitude				SiBCS[1]	WRB[2]	Type	Thickness	
-	-	-	-	%	-	-	-	-	cm	cm
VL - R1	-26.2844	-51.5398	Middle third	12	Well drained	CHd típico	dy Regosol (ce. ai. hu)	A Humic	35	100+
VL - R2	-26.2846	-51.5404	Middle third	22	Well drained	CHd típico	Endoleptic Regosol (ce. ai. dh)	A Humic	40	95+
VL - R3	-26.2897	-51.5424	Upper third	3	Well drained	CHd típico	dy Regosol (ce. ai. hu)	A Humic	35	100+
VL - R4	-26.2876	-51.5456	Upper third	1	Well drained	CHd típico	dy Regosol (ce. ai. hu)	A Humic	35	100+
L - R1	-26.2849	-51.5392	Middle third	8	Well drained	CHd típico	dy Regosol (ce. ai. hu)	A Humic	35	100+
L - R2	-26.2852	-51.5407	Middle third	16	Well drained	CHd leptofragmentário	Endoleptic Regosol (ce. ai. hu)	A Humic	30	85+
L - R3	-26.2883	-51.5421	Middle third	9	Well drained	RLh típico	Epileptic Regosols (ce. ai. hu)	A Humic	35	40+
L - R4	-26.2874	-51.5447	Middle third	15	Well drained	RRh léptico	Endoleptic Regosols (ce. ai. hu)	A Humic	20	80+
M - R1	-26.2858	-51.5403	Middle third	11	Well drained	CHd típico	gr Ferralsol (ce. ai. dy. hu)	A Humic	37	100+
M - R2	-26.2859	-51.5412	Middle third	14	Well drained	CHd típico	gr Ferralsol (lo. ai. dy. dh)	A Humic	30	91+
M - R3	-26.2880	-51.5413	Upper third	4	Well drained	CHd leptofragmentário	Endoleptic Regosol (ce. ai. dh)	A Humic	38	100+
M - R4	-26.2870	-51.5444	Middle third	11	Well drained	CHd leptofragmentário	Endoleptic Regosol (ce. ai. hu)	A Humic	35	98+
H - R1	-26.2858	-51.5396	Watered middle third	10	Imperfectly drained	CHd típico	Endoleptic Regosol (lo. ai. jh)	A Humic	47	79+
H - R2	-26.2865	-51.5403	Watered middle third	2	Imperfectly drained	RRd leptofragmentário	Endoleptic Regosols (ce. ai. hu)	A Humic	25	70+
H - R3	-26.2877	-51.5424	Watered bottom third	6	Imperfectly drained	CHd leptofragmentário	Endoleptic Regosol (ce. ai. jh)	A Humic	45	90+
H - R4	-26.2878	-51.5442	Middle third	7	Well drained	CHd típico	dy Regosol (ce. ai. jh)	A Humic	45	100+

(1) Following the classification criteria of the Brazilian Soil Classification System - SiBCS (Embrapa, 2018), where CHd = CAMBISSOLOS HÚMICOS Distróficos; RLh = NEOSSOLO LITÓLICO Húmico; RRh = NEOSSOLO REGOLÍTICO Húmico; RRd = NEOSSOLO REGOLÍTICO Distrófico.

(2) Based on the classification criteria of the World Reference Base for Soil Resources (WRB) (FAO, 2015) dy = Dystric, ce = Clayic, lo = Loamic, ai = Aric, hu = Humic, dh = profundihumic, and jh = hypergumic.

SOURCE: The author (2023).

4 DISCUSSION

4.1 SOIL DEPLETION BY SUCCESSIVE FOREST CROPS

Regardless of class, associated soils were of very low fertility, extremely acidic, and had high buffering power due to the impoverished acidic nature of parent igneous material such as rhyodacite and rhyolite (Bonfatti, 2012). Since the site had undergone two rotations without fertilization and liming, nutrient exhaustion could further help explain the low fertility status of soils (Ferreira et al., 2001; Gatiboni et al., 2017; 2020; Vidaurre et al., 2020; Consalter et al., 2021b). Since *Pinus* spp. are commonly planted on marginal poorly managed lands, impoverished soils in such areas are quite common (Smethurst, 2010; Cherobim et al., 2010; Moro et al., 2014; Abrão et al., 2015; Batista et al., 2015; Rabel et al., 2018; Sass et al., 2020; Consalter et al., 2021a). However, soils had high organic matter levels down to 40-60 cm, which provided high buffering capacity and a reservoir for N, S, and P.

According to the Manual of Fertilization and Liming for the State of Paraná (Paraná State Nucleus of the Brazilian Society of Soil Science [SBCS/NEPAR], 2019), soil pH was very low (< 4.0) with very high Al^{3+} (> 2.5 $cmol_c$ dm^{-3}). For all classes, manual guidelines indicated that K was low and Ca^{2+}, Mg^{2+}, and P were very low; there were very small variations among these limiting nutrients. The combination of very high Al and very low Mg has been reported to decrease needle Mg concentration in a spruce (*Picea abies*) forest (Wit et al., 2010) indicating that their interaction should not be overlooked.

4.2 GROWTH HETEROGENEITY VISUALIZATION BY VARI

The current study indicated that the VARI method was capable of capturing growth heterogeneity in a commercial *P. taeda* plantation. Studies of Larrinaga and Brotons (2019) and Pertille and Nicoletti (2022) showed good results for evaluating *Pinus* spp. cultivations using the VARI technique. Other remote sensing methods, such as the Normalized Difference Vegetation Index (NDVI) have also proven to be efficient for evaluation of *Pinus* spp. forest cultivations (Brito et al. 2021; Munhoz et al. 2022). The greatest differences observed in tree growth occurred between the High (0.33) and Very Low (0.17) VARI classes, where the High class had the largest trees and the

Very Low class had the smallest. This probably occurred since some parameters for the Low (0.23) and Medium (0.28) VARI classes were similar to each other or with extreme classes (Very Low and High).

Tree growth in our study could be considered normal since an evaluation of a 16 year-old forest in the same municipality by Carvalho et al. (2021) found a trunk biomass value of 286.5 kg, which was similar to the High VARI class (279 kg with bark and 266 kg without bark). Studying a 14 year-old forest in a nearby municipality, Watzlawick et al. (2013) also found mean values of DBH, total height, and volume (without bark) of 27.93 cm, 20.1 m, and 0.45 m^3, respectively. Their results were higher than those found in our study for the Very Low class (25.88 cm, 17.52 m, and 0.36 m^3), but lower than those of the High class (29.18 cm, 21.13 m, and 0.57 m^3). Thus, tree growth potential at our experimental site appeared to be limited in the lower VARI classes.

Despite signs of chlorosis, observed growth in our study area could be considered high. This high growth was probably related to favorable climatic conditions in southern of Brazil as well as soil properties such as a deep A horizon and high organic matter levels compared to other world regions (Motta et al., 2014). In a cultivation of *P. taeda* (14 year-old) under different conditions in North Carolina (USA), Drake et al. (2010) reported lower values of DBH (18 cm) and total height (15 m) compared to our study. Overall, even our Very Low class had greater tree growth compared to *P. taeda* growth in its region of origin.

4.3 DENSITY AND GROWTH RING WIDTH

Wood density was not affected by VARI class and supported observations of Pereira et al. (2022) who found growth enhancement with no compromise in density without residue application. However, 7 year-old trees had density variations of 0.39 to 0.42 g cm^{-3}, which was smaller than observed in our study. Similar to our findings, Rodriguez and Tomazello-Filho (2019) evaluated different residue application rates in a *P. taeda* system and observed that average growth of rings was 1.65 cm in the first three years; after 17 years, ring growth was 0.25 cm and density ranged from 0.47 to 0.82 g cm^{-3} over this period. Therefore, the behavior and values found in our study could be considered normal for pine, since such responses are often expected for fast-growing coniferous species (Panshin & Zeeuw, 1980; Tasissa & Burkhart, 1997;

Topanotti et al., 2021) and are in agreement with previous observations (Melo, 2015; Dobner Jr. et al., 2018; Topanotti et al., 2021). In addition, the proportion of late wood tends to be higher than early wood over time, which directly influences overall wood density since the late wood has higher density (Panshin & Zeeuw, 1980; Cown & Ball, 2001; Cato et al., 2006; Topanotti et al., 2021). In our study, we observed that the proportion of late wood became higher than early wood after 8 years of growth (Table S2).

4.4 RELATIONSHIP BETWEEN CHLOROTIC SYMPTOMS AND ELEMENTS IN TREE TISSUES AND LITTER

The mass of 100 needles did not differ between VARI classes and were generally similar or slightly below an average of 5 g for first and second flush needles from the upper crown as reported by Carlson et al. (2014) in North America. Second flush needles (lower third of canopy) in all VARI classes were very low and ranged from 2.28 to 3.07 g (Table 1), which indicates that the needle mass may be compromised.

Ours finding indicate that Mg was possibly the most limiting element, responsible for needle chlorosis and growth heterogeneity (Chart 1) as widely reported in other countries (Beets & Jokela, 1994; Meiwes, 1995; Ende & Evers; 1997; Sun & Payn, 1999; Mitchell et al., 2003; Cakmak & Yazici, 2010; Zhu et al., 2016; Chaudhry et al., 2021; Xie et al., 2021). Foliar Mg concentration ranged from 0.22 to 0.39 g kg^{-1} (Figures 6b, 6d and 6f), which was far below the 0.8 g kg^{-1} that many authors report as the critical limit (Table S12) (Reissmann, 1981; Sypert, 2006; Albaugh et al., 2010; Vogel et al., 2018). However, Sun and Payn (1999) defined 0.6 g kg^{-1} as the limit for *Pinus radiata*, while the range of 0.20 to 0.25 g kg^{-1} reported by Laing et al. (2000) was closer to that found in our study (Table S12).

In addition to concentration, observed field symptoms were consistent with those of deficiency previously reported in the literature for *P. taeda* Mg, where yellowing of tips can migrate to medial needle regions leading to necrosis/senescence over time, and is generally observed in canopy tops (Stone, 1953; Will, 1978; Turner et al., 1979; Beets & Jokela, 1994; Mitchell et al., 2003). Thus, observed values and symptoms lead to two likely conclusions: 1) deficiency was present throughout the site, but not at critical level for expression of symptoms; or 2) the critical limit reported in the literature requires adjustments since symptoms were not observed in all VARI classes. Based on our study, we believe the second assumption is more plausible, and suggest adjusting the critical limit for needle Mg to 0.30 g kg^{-1}.

Trends ($0.5 < p \leq 0.10$) of variation among VARI classes for needle Ca concentration (0.86 to 1.98 g kg^{-1}) highlight that Ca can play a role in chlorosis and growth heterogeneity. Some needle Ca concentrations were below suggested critical levels [3.0 g kg^{-1}, Gonçalves (2005); 2.6 g kg^{-1}, Vogel et al. (2018); and 1.5 g kg^{-1}, Sypert (2006) and Albaugh et al. (2010)] (Table S12). However, if one considers the critical level of 0.8 g kg^{-1} proposed by Reissmann (1981), the lowest value remained close to this critical level (Table S12).

Similar to influence of needle Mg and Ca concentrations on chlorosis and heterogeneity, fine root concentrations showed a wide range for Mg (0.11 to 0.23 g kg^{-1}) and Ca (0.56 and 1.37 g kg^{-1}) among VARI classes. Confirming our observations, Consalter et al. (2021b) showed that roots in litter can be very sensitive to Ca and Mg additions (liming) and that addition enhanced concentrations of Mg (0.23 to 2.7 g kg^{-1}) and Ca (1.28 to 7.9 g kg^{-1}) (Table S12). Additionally, Adam et al. (2021) reported concentrations of 0.10 g kg^{-1} (Mg) and 0.20 g kg^{-1} (Ca) without liming compared to 2.7 g kg^{-1} (Mg) and 8.3 g kg^{-1} (Ca) for the complete treatment (macro- and micronutrients and lime) (Table S12). Since Adam et al. (2021) studied low growth sites with needle chlorosis and attained values close to ours, this suggests a possible link to lack of Mg in our study. Fine root analysis proved to be a good indicator for nutritional assessment of *P. taeda* since levels found in roots were in accordance with chlorotic symptoms observed in needles.

High levels of Al in roots can diminish Mg and Ca concentrations well before Al levels impact seedling growth (Raynal et al., 1990). This suggests that high Al levels could contribute to lower levels of Mg and Ca. This could also explain the lowest Ca/Al ratio in the Very Low class (0.77) and the higher ratio in the High class (1.66) (Table S5). However, our observed values were higher than the Ca/Al critical limit of 0.2 for fine roots suggested by Vanguelova et al. (2007). Thus, possibly Al did not threaten root growth, neither Ca absorption, but it may have affected nutrition by reducing Mg absorption. In regards to K/Mg ratios, the lowest value (5.38, High VARI class) was still considered high for *P. taeda*. Excess K in relation to Mg may contribute to Mg deficiency in plantation cultures since these elements have an antagonistic relationship (Beets & Jokela, 1994; Sun & Payn, 1999; Xie et al., 2021).

As with needles and roots, results for bark showed Mg and Ca enhancement in accordance with class and growth. However, class effects occurred above and below 25% of commercial height for Mg and Ca, respectively with trends ($0.5 < p \leq 0.10$) at other heights. Changes in bark concentrations as a result of soil management were also noted by Wit et al. (2010) and Pereira et al. (2022). Wit et al. (2010) found that Al amendment increased its concentration and diminished Mg in the inner bark with a similar trend for the outer bark of spruce (*Pinus abies*), but Ca was not impacted. This finding suggests that low soil availability of Ca and Mg combined with high Al values can be a major factor leading to lack of these elements. Evaluating bark from 22 year-old *P. taeda*, Dedecek et al. (2008) found a variation of 0.20 to 0.55 g kg^{-1} for Mg and 0.25 to 1.56 g kg^{-1} for Ca (Table S12). These values were relatively close to those observed in our study, except for Mg where a minimum value of 0.05 g kg^{-1} was obtained. Additionally, the attained Mg value was well below the 0.4 g kg^{-1} value reported by Albaugh et al. (2008) (Table S12). Pereira et al. (2022) found levels of 0.15 to 0.19 g kg^{-1} for Mg and 0.42 to 0.69 g kg^{-1} for Ca in *P. taeda* bark (7 year-old), which were close to the Very Low VARI class (Table S12). In the same culture at 12 years old, Zhao et al. (2014) reported 0.4 g kg^{-1} as the average Mg value (Table S12), which was closer to our highest VARI class. For Ca, they reported a value of 1.6 g kg^{-1}, which was approximately four times higher than that found in the Very Low class and greater than all values found in other classes.

Indications that tree bark can be affected by soil management was reported by Pereira et al. (2022). Observing bark and needle Mn concentrations, they were able to establish groups with low and high annual average increments for *P. taeda* amended with residue. These results suggest that bark can be useful to help evaluate tree nutrition and growth under some conditions, but a standardize sample height could facilitate this process.

Unlike other tissues, wood did not show differences among classes. Calcium (0.33 to 0.36 g kg^{-1}) and Mg (0.07 to 0.10 g kg^{-1}) in wood tissue obtained at DBH showed low variation. In a study of 11 to 15 year-old *P. taeda* in Texas, Angel et al. (2019) found Ca values approximately three times higher (0.9 g kg^{-1}) and 20 times higher for Mg (1.4 g kg^{-1}) (Table S12) when compared to findings of our study. Wood from 12 year-old *P. taeda* evaluated by Zhao et al. (2014) had levels of 0.6 g kg^{-1} for Ca and 0.3 g kg^{-1} for Mg, which was greater that observations in our study but lower than observations by Angel et al. (2019) (Table S12). Working with different rates of industrial residue applied to 7 years-old *P. taeda* in Paraná (southern Brazil), Pereira et al. (2022) found Mg wood concentrations closer to those of our study (ranging from 0.16 to 0.18 g kg^{-1}) while Ca values were higher (ranging from 0.46 to 0.56 g kg^{-1}) (Table S12). Thus, Ca and Mg concentrations found in our study were lower due to possible differences in soil conditions.

In relation to other needle elements, Cr in the Very Low class was low (Table 1). However, Cr deficiency has not identified in pine and no critical limit exists in the literature. In all classes and canopy positions, B was close to 3 mg kg^{-1} (Table 1), which is considered low based on previous reports of 15 mg kg^{-1} (Reissmann, 1981), 12 mg kg^{-1} (Gonçalves, 2005), and 10 mg kg^{-1} (Sypert, 2006) (Table S12). As observed in some trees in our study, B deficiency can cause symptoms such as bifurcated trees, and curved or coiled branches/stems (Will, 1978; Turner et al., 1979; Martinez et al., 1989). Phosphorus, Fe, Zn, and Cu were within critical limits based on literature reports (Table S12) (Reissmann, 1981; Sypert, 2006; Albaugh et al., 2010; Vogel et al., 2018). Although soil P level was low, needle levels were adequate likely due to tree roots absorbing P from organic or inorganic fractions due to solubilization by mycorrhizal activity (Will, 1985; Shane & Lambers, 2005; Castro-Delgado et al., 2020). Needle Mn ranged from 139 to 287 mg kg^{-1}, which was far above the limit range of 20 to 40 mg kg^{-1} suggested by Albaugh et al. (2010) (Table S12). Although high, our values were below the 395 mg kg^{-1} reported by Carlson et al. (2014). Gomes et al. (2019) suggested that excess Mn could cause problems in cultures since it is more sensitive to toxicity and imbalance compared to Al.

Low levels of Ca, Mg, and B and high levels of Mn (on average, 207 mg kg^{-1}) in needles can cause greater tree nutritional problems, since simultaneous deficiency of more than one nutrient can make *in loco* interpretation of symptoms difficult. This was observed in a *P. caribaea* plantation located in the Cerrado region (Chaves & Corrêa, 2003; 2005). These authors observed chlorotic symptoms and needle senescence. When analyzed, symptomatic needle levels of Mn, Ca, and Mg (96.5 mg kg^{-1}, 0.02 g kg^{-1}, and 0.01 g kg^{-1}, respectively) were lower than in needles from healthy trees (177 mg kg^{-1}, 0.10 g kg^{-1}, and 0.04 g kg^{-1}, respectively).

In our study, K was the most abundant element in needles and ranged from 4.54 to 5.02 g kg^{-1}, which was close to values (3.00 to 5.47 g kg^{-1}) reported by Dedecek et al. (2008) (Table S12). Similar to our study, they found that nutrient levels in needles followed a decreasing order of K > Ca > P > Mg. In relation to needle K, limits suggested in the literature were 3.5 g kg^{-1} (Albaugh et al., 2010), 4 g kg^{-1} (Reissmann, 1981), 6 g kg^{-1} (Gonçalves, 2005), and 8.7 g kg^{-1} (Vogel et al., 2018) (Table S12). Thus, our results were in the mid-range of these reported values. When comparing K and Mg, a study by Mitchell et al. (2003) with *P. radiata* found that the K/Mg ratio was always below 15, which was higher than in our Medium and High classes (12 to 14) but lower than our Very Low and Low classes (16 to 25) (Table 1). Therefore, a nutritional imbalance may also be occurring in the Very Low and Low classes where higher K may have negatively influenced Mg.

Wood tissue composition at DBH also showed low variation, and there were no differences between classes for P (0.08 to 0.13 g kg^{-1}) and K (0.65 to 0.88 g kg^{-1}). In 11 to 15 year-old *P. taeda* in Texas, Angel et al. (2019) found P and K levels in wood close to our study (0.1 and 0.9 g kg^{-1}, respectively) (Table S12). With different clones of *P. taeda* in Florida, Villacorta et al. (2015) obtained wood tissue values higher and/or close to values in our study for B (2.9 to 3.3 mg kg^{-1}) and Zn (7.6 to 8.8 mg kg^{-1}) (Table S12). However, Mn values reported by these authors ranged from 7.5 to 10.5 mg kg^{-1}, while values in our study ranged from 38.41 to 49.25 mg kg^{-1}.

Litter accumulation showed an inverse relationship with VARI, which corroborated with Reissmann and Wisniewski (2015) who found higher amounts of litter on poor sites due to low litterfall decomposition. Regardless of class, litter amounts observed in our study (42 to 64 Mg ha^{-1}) could be considered high and were similar to reports of Adam et al. (2021) (43.9 to 52.1 t ha^{-1}), Pereira et al. (2022) (29 to 52 Mg ha^{-1}), and Rabel et al. (2021) (35.8 to 42.1 Mg ha^{-1}) for poor and medium quality growth sites in southern Brazil. However, these amounts were well above values found at good sites (9 to 11 Mg ha^{-1}) in the same region (Quadros et al., 2021). In contrast, Ca and Mg enrichment was directly related to the greater than 2 mm litter fraction class with a similar trend ($0.5 < p \leq 0.10$) for the less than 2 mm litter fraction class. Since neither fertilizer nor lime were applied, litter was able to adequately supply both elements from aboveground tree inputs. Understanding nutrient dynamics between litter and trees is a potentially important concept for understanding chlorosis.

Nutrient concentration in litter can be directly or indirectly affected by soil management (Rabel et al., 2021). In their study of different rates of alkaline residues of recycled paper applied to a *P. taeda* forest, litter layers (greater than 2 mm) representing residues with and without roots showed variations of 0.59 to 1.28 g kg^{-1} for Mg and 0.67 to 3.30 g kg^{-1} for Ca (Table S12). These Mg levels were higher than those observed in our study (0.16 to 0.24 g kg^{-1}) for all VARI classes, while their Ca levels were close to our study (0.62 to 1.07 g kg^{-1}). Evaluating nutrient accumulation in a 16 year-old *P. taeda* cultivation, Sixel et al. (2015) found 9 kg ha^{-1} of Mg in litter; this was similar to that observed in our study (9.81 kg ha^{-1}). However, their observations of Ca (27 kg ha^{-1}), K (9 kg ha^{-1}), and P (12 kg ha^{-1}) were much lower than our study (34.83, 46.81, and 28.36 kg ha^{-1}, respectively); this may indicate that the classes studied had difficulty cycling nutrients present in litter.

4.5 INFLUENCE OF LANDSCAPE AND SOIL PEDOLOGY ON FOREST HETEROGENEITY

Our pine production area was located on complex hilly terrain composed of soil originating from acid eruptive rock parent material (rhyodacite/rhyolite); slopes ranged between 1 and 22% with *solum* depths between 40 and more than 100 cm. Despite site variations, soil type, *solum* depth, and surface horizon thickness (Table 2 and S11) differences had less influence on pine growth and separation of VARI classes. However, in contrast, studies by Horst et al. (2018) and Horst-Heinen et al. (2021) noted that solum depth and surface horizon thickness were directly related to pine growth where deeper *solum* with thicker surface horizons had the largest trees.

In our study, we observed variations in slope and plot positioning on the landscape. The four High class plots were located in the middle and lower thirds of the slope; three plots were on landscapes that favored accumulation of water (a geomorphic dip), and the fourth was on a slope with gentle relief (7%) (Table 2). Horst et al. (2018) noticed that areas on the lower third of the slope (i.e., closer to the drainage network) tended to have the largest trees. Santos Filho and Rocha (1987) stated that lower development of *P. taeda* usually occurred on sandy soils in landscape positions that favor nutrient leaching and low water retention capacity. In general, our High class occupied landscape positions that were more conservative in terms of water and nutrient loss since gentle slopes and slow drainage reduced losses that may have favored pine development compared to VARI classes with sharper reliefs and faster-draining landscapes.

5 CONCLUSION

VARI efficiently captured tree growth heterogeneity, with a direct relationship noted between VARI and tree growth (height, DBH, volume, and trunk mass). Despite the productivity of the area (generally considered normal for this region), portions of the area classified as Very Low VARI had smaller tree growth, as well as symptoms of needle chlorosis similar to reports of Mg deficiency (yellowing of needle tips to medial regions). Needle Mg concentration was well below values considered to be critical (0.8 g kg^{-1}), and our results suggest reestablishing the critical level as 0.3 g kg^{-1}. Low concentrations of Mg in fine roots and tree bark supported needle observations. Similar findings were noted for litter, with the lowest Mg values and highest accumulation of litter found in low growth stands (lower VARI). Thus, needles, fine roots, bark and litter (> 2 mm) showed to be good indicators of the nutritional status of the plant. In addition, the low concentration of nutrients in the parental material, associated with high values of Al^{+3} combined with low Mg^{+2} in soil, the intense leaching and depletion of the soil by the export of nutrients may have favored the occurrence of Mg deficiency in trees and than cause the chlorotic symptoms. Another factor that could have contributed to occurrence of Mg deficiency was the low concentrations of Ca^{+2} in soil, tree tissues, and litter. Therefore, it is suggested that the area be managed as a whole, and be submitted to liming with dolomitic limestone.

6 SUGGESTIONS FOR FUTURE RESEARCH

As suggestions for future research, it is suggested that the available water content in the soil should also be analyzed, as well as meteorological data collected in the study area. Also, verify if there are fractures in the rock below the *solum*. In addition, if possible, the number of plants per hectare should be determined for better notions of yield and productivity. Response to fertilization and liming for each VARI class should give a better indication of nutrients limitation.

7 REFERENCES

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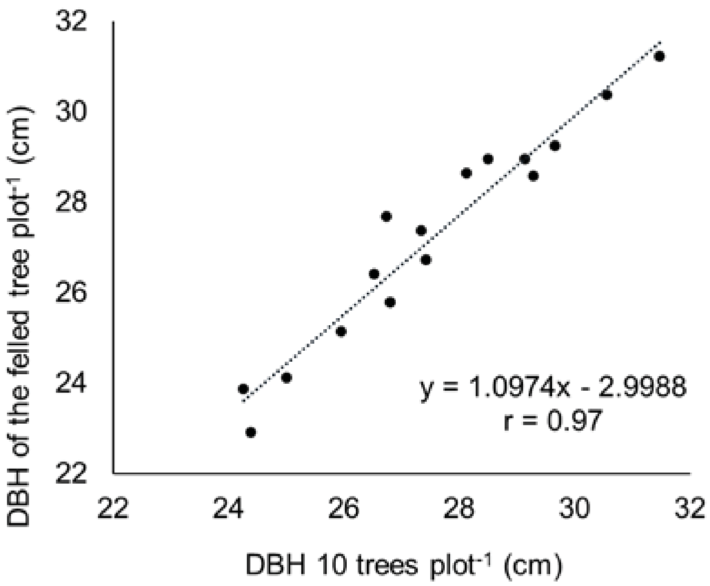
APPENDIX 1 – SUPPLEMENTARY MATERIAL

FIGURE S1 – EVALUATION IMAGES OF THE STUDY AREA OF A 14-YEAR-OLD *Pinus taeda* CULTIVATION IN BITURUNA, PARANÁ, BRAZIL.

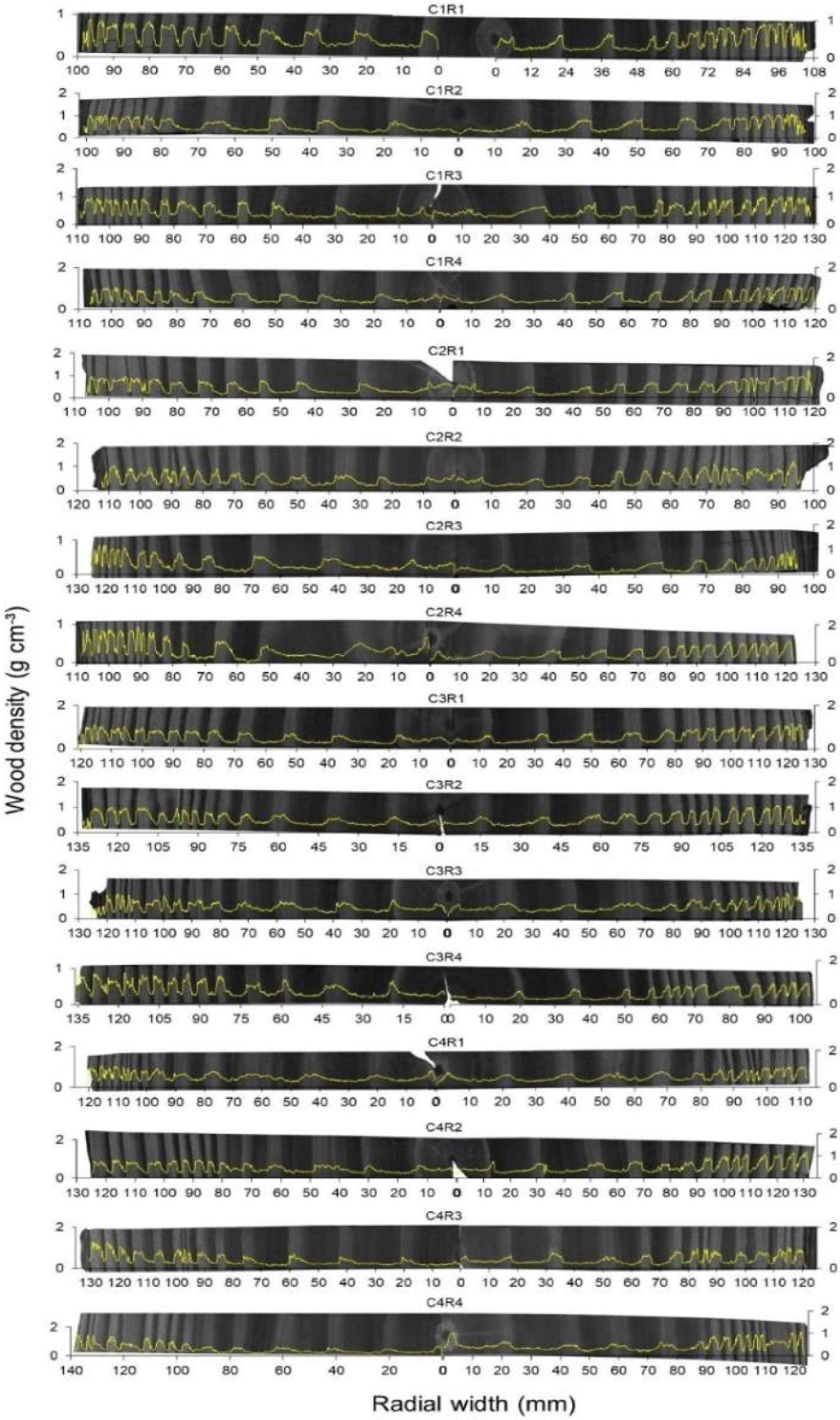
SOURCE: The author (2023).
LEGEND: Evaluation of the circumference at breast height (CBH) of the trees (a), height measurement (total and commercial) (b), cross sections collected from the tree trunk (c), needles collected and separated (d), litter sampled (e) , fine roots of *Pinus taeda* separated from the litter (f), soil trading (g), observation of plot location in the landscape (h), soil classification - morphological description (i).

FIGURE S2 – CORRELATION GRAPH BETWEEN *Pinus taeda* VALUES OF DIAMETER AT BREAST HEIGHT (DBH) WITHIN PLOTS (10 TREES PLOT^{-1}) AND THE FELLED TREE (r = 97%).



SOURCE: The author (2023).

FIGURE S3 – DENSITY PROFILE OF GROWTH RINGS OF 14 YEAR-OLD *Pinus taeda* TREES IN DIFFERENT VARI CLASSES (C1 - VERY LOW, C2 – LOW, C3 - MEDIUM AND C4 - HIGH) EVALUATED AT BITURUNA, PARANÁ, BRAZIL.



SOURCE: The author (2023).

TABLE S1 – APPARENT WOOD DENSITY OF GROWTH RINGS (EARLY + MATURE, EARLY AND MATURE) OF *Pinus taeda* TREES ACROSS 14 YEARS IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) IN BITURUNA, PARANÁ, BRAZIL.

Classes	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Mean
	------ g cm^{-3} ------														
	Growth ring density (early wood + late wood)														
Very Low	0.43 a	0.39 a	0.42 a	0.46 a	0.48 a	0.59 a	0.56 a	0.65 a	0.64 a	0.65 a	0.73 a	0.69 a	0.78 a	0.60 a	0.58 a
Low	0.33 a	0.28 a	0.31 a	0.34 a	0.39 a	0.45 a	0.52 a	0.57 a	0.53 a	0.60 a	0.59 a	0.69 a	0.69 a	0.66 a	0.50 a
Medium	0.39 a	0.36 a	0.39 a	0.43 a	0.49 a	0.57 a	0.56 a	0.61 a	0.62 a	0.59 a	0.66 a	0.63 a	0.78 a	0.68 a	0.55 a
High	0.41 a	0.37 a	0.40 a	0.41 a	0.43 a	0.54 a	0.55 a	0.63 a	0.64 a	0.58 a	0.67 a	0.66 a	0.79 a	0.75 a	0.56 a
	Early wood density														
Very Low	0.37 a	0.33 a	0.33 a	0.34 a	0.37 a	0.38 a	0.38 a	0.41 a	0.41 a	0.41 a	0.49 a	0.49 a	0.50 a	0.38 a	0.40 a
Low	0.30 a	0.21 b	0.21 a	0.22 a	0.24 b	0.27 a	0.29 a	0.33 a	0.32 a	0.35 a	0.34 a	0.38 a	0.43 a	0.33 a	0.31 a
Medium	0.35 a	0.31 ab	0.31 a	0.35 a	0.35 ab	0.39 a	0.38 a	0.37 a	0.38 a	0.38 a	0.42 a	0.38 a	0.47 a	0.38 a	0.38 a
High	0.35 a	0.31 ab	0.32 a	0.32 a	0.33 ab	0.38 a	0.37 a	0.40 a	0.38 a	0.35 a	0.42 a	0.40 a	0.50 a	0.41 a	0.38 a
	Late wood density														
Very Low	0.56 a	0.61 a	0.65 a	0.68 a	0.73 a	0.73 a	0.75 a	0.81 a	0.77 a	0.81 a	0.86 a	0.79 a	0.86 a	0.76 a	0.74 a
Low	0.45 a	0.47 b	0.55 a	0.58 a	0.62 a	0.66 a	0.70 a	0.76 a	0.71 a	0.71 a	0.72 a	0.79 a	0.80 a	0.83 a	0.68 a
Medium	0.56 a	0.55 ab	0.61 a	0.62 a	0.70 a	0.71 a	0.74 a	0.75 a	0.77 a	0.78 a	0.82 a	0.82 a	0.91 a	0.83 a	0.74 a
High	0.52 a	0.55 ab	0.55 a	0.60 a	0.62 a	0.71 a	0.79 a	0.83 a	0.83 a	0.77 a	0.87 a	0.81 a	0.98 a	0.93 a	0.75 a

Means followed by different letters in the columns within each subdivision (early wood + late wood, early and late wood) differ statistically from each other by Kruskal-Wallis with Nemenyi mean test ($p \leq 0.05$).
SOURCE: The author (2023).

TABLE S2 – WIDTH OF GROWTH RINGS (EARLY WOOD + LATE WOOD, EARLY AND LATE WOOD) OF *Pinus taeda* TREES ACROSS 14 YEARS IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) IN BITURUNA, PARANÁ, BRAZIL.

Classes	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Mean
	------------------------------------ cm ------------------------------------														
	Early and late wood width														
Very Low	1.82 a	1.89 a	1.44 a	1.25 a	0.97 a	0.60 a	0.42 a	0.46 a	0.35 a	0.36 a	0.32 a	0.23 a	0.23 a	0.26 a	0.75 a
Low	2.18 a	2.03 a	1.46 a	1.11 a	0.80 a	0.62 a	0.39 a	0.34 a	0.23 a	0.29 a	0.28 a	0.36 a	0.27 a	0.27 a	0.76 a
Medium	1.89 a	2.11 a	1.80 a	1.26 a	0.92 a	0.67 a	0.49 a	0.49 a	0.52 a	0.52 a	0.46 a	0.42 a	0.29 a	0.39 a	0.87 a
High	1.92 a	2.00 a	1.79 a	1.49 a	0.99 a	0.70 a	0.39 a	0.37 a	0.32 a	0.48 a	0.53 a	0.55 a	0.31 a	0.43 a	0.88 a
	Early wood width														
Very Low	1.47 a	1.48 a	1.04 a	0.81 a	0.67 a	0.26 a	0.22 a	0.19 a	0.12 a	0.14 ab	0.12 a	0.08 a	0.05 a	0.10 a	0.48 a
Low	1.79 a	1.53 a	1.02 a	0.77 a	0.47 b	0.34 a	0.20 a	0.14 a	0.10 a	0.08 b	0.09 a	0.06 a	0.07 a	0.08 a	0.48 a
Medium	1.51 a	1.53 a	1.29 a	0.86 a	0.55 ab	0.29 a	0.24 a	0.18 a	0.20 a	0.24 a	0.19 a	0.17 a	0.08 a	0.13 a	0.53 a
High	1.61 a	1.53 a	1.18 a	1.02 a	0.65 ab	0.37 a	0.21 a	0.17 a	0.12 a	0.21 ab	0.24 a	0.19 a	0.12 a	0.14 a	0.55 a
	Late wood width														
Very Low	0.35 a	0.41 a	0.40 a	0.44 a	0.30 a	0.34 a	0.20 a	0.27 a	0.22 ab	0.21 a	0.20 a	0.15 a	0.18 a	0.16 a	0.27 a
Low	0.39 a	0.49 a	0.45 a	0.34 a	0.33 a	0.29 a	0.28 a	0.20 a	0.13 b	0.21 a	0.20 a	0.30 a	0.20 a	0.19 a	0.28 a
Medium	0.38 a	0.51 a	0.50 a	0.40 a	0.37 a	0.38 a	0.25 a	0.32 a	0.32 a	0.27 a	0.28 a	0.25 a	0.20 a	0.26 a	0.34 a
High	0.32 a	0.47 a	0.61 a	0.47 a	0.34 a	0.33 a	0.18 a	0.20 a	0.20 ab	0.26 a	0.29 a	0.36 a	0.19 a	0.29 a	0.32 a

Means followed by different letters in the columns within each subdivision (early wood + late wood, early and late wood) differ statistically from each other by Kruskal-Wallis with Nemenyi mean test ($p \leq 0.05$).
SOURCE: The author (2023).

FIGURE S4 – SYMPTOMS OF CHLOROSIS OBSERVED IN NEEDLES OF A 14 YEAR-OLD *Pinus taeda* TREE PRESENT IN THE VERY LOW VARI CLASS EVALUATED IN BITURUNA, PARANÁ, BRAZIL.

SOURCE: The author (2023).

LEGEND: Symptoms can be observed in branches with one and two year-old needles (a) and on branches of the felled tree (b); also note the thinning of the tree crown (c).

TABLE S3 – CONCENTRATIONS OF NUTRIENTS AND ALUMINUM IN WOOD TISSUE OF A 14 YEAR-OLD *Pinus taeda* CULTIVATION IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) IN BITURUNA, PARANÁ, BRAZIL

Classes	Part	Ca	Mg	P	K	Al	B	Ba	Cu	Fe	Mn	Zn
		g kg^{-1}				mg kg^{-1}						
Very Low	Base	0.37 a	0.09 a	0.21 a	1.25 a	47.84 a	4.85 a	1.20 ab	0.75 a	6.63 b	45.65 a	12.73 a
Low	Base	0.43 a	0.11 a	0.17 a	1.19 a	30.44 ab	1.37 ab	0.87 b	1.97 a	52.73 a	50.41 a	11.30 a
Medium	Base	0.52 a	0.11 a	0.16 a	1.19 a	34.07 ab	1.12 ab	2.18 ab	1.05 a	23.33 ab	39.59 a	9.29 ab
High	Base	0.37 a	0.10 a	0.11 a	0.71 a	16.09 b	0.74 b	2.53 a	0.57 a	2.77 b	37.70 a	3.67 b
Very Low	DBH	0.33 a	0.07 a	0.13 a	0.88 a	31.36 a	3.53 a	1.29 ab	0.94 a	1.97 a	49.25 a	8.83 a
Low	DBH	0.33 a	0.07 a	0.10 a	0.87 a	19.76 a	1.09 ab	0.66 b	1.31 a	8.15 a	44.04 a	7.28 ab
Medium	DBH	0.36 a	0.08 a	0.08 a	0.73 a	14.18 a	0.75 b	1.26 ab	1.06 a	6.75 a	39.96 a	6.22 ab
High	DBH	0.33 a	0.10 a	0.08 a	0.65 a	13.55 a	0.65 b	2.07 a	0.07 a	3.69 a	38.41 a	2.80 b
Very Low	25% comercial height	0.34 ab	0.07 a	0.13 a	0.89 a	25.56 a	1.36 a	0.99 ab	1.12 ab	4.44 a	47.78 a	8.25 a
Low	25% comercial height	0.40 a	0.09 a	0.11 a	0.92 a	28.52 a	1.14 ab	0.70 b	1.67 a	7.02 a	47.54 a	8.46 a
Medium	25% comercial height	0.33 ab	0.07 a	0.07 a	0.64 a	8.68 a	0.67 b	0.96 ab	0.65 ab	1.91 a	35.97 a	5.12 ab
High	25% comercial height	0.27 b	0.09 a	0.06 a	0.57 a	8.99 a	0.66 b	1.93 a	0.08 b	0.41 a	35.10 a	1.87 b
Very Low	50% comercial height	0.35 a	0.07 a	0.12 a	0.93 a	19.28 a	2.02 a	1.03 ab	0.83 a	6.26 a	41.76 a	8.45 a
Low	50% comercial height	0.32 a	0.07 a	0.09 a	0.76 a	10.73 a	0.94 ab	0.65 b	1.71 a	25.23 a	42.46 a	6.06 ab
Medium	50% comercial height	0.31 a	0.07 a	0.06 a	0.70 a	8.84 a	0.66 b	0.77 ab	1.35 a	7.69 a	35.34 a	6.19 ab
High	50% comercial height	0.32 a	0.10 a	0.07 a	0.56 a	9.67 a	0.61 b	1.82 a	0.19 a	2.92 a	41.71 a	3.98 b
Very Low	75% comercial height	0.31 a	0.08 a	0.09 a	0.80 a	12.09 a	1.35 a	1.00 a	0.92 ab	7.10 ab	42.74 a	7.00 a
Low	75% comercial height	0.35 a	0.08 a	0.09 a	0.80 a	13.39 a	0.97 ab	0.68 a	2.21 a	32.71 a	43.15 a	6.82 a
Medium	75% comercial height	0.34 a	0.09 a	0.07 a	0.69 a	7.02 a	0.66 b	0.75 a	1.05 ab	1.69 b	40.39 a	6.06 a
High	75% comercial height	0.31 a	0.11 a	0.08 a	0.93 a	20.03 a	0.80 ab	2.73 a	0.06 b	7.80 ab	39.08 a	4.21 a
Very Low	100% comercial height	0.35 a	0.10 a	0.11 a	0.91 a	15.10 a	1.51 a	0.73 a	1.36 ab	8.81 a	54.02 a	18.69 a
Low	100% comercial height	0.39 a	0.11 a	0.11 a	1.45 a	16.62 a	1.03 ab	0.64 a	2.31 a	51.92 a	49.84 a	10.40 a
Medium	100% comercial height	0.37 a	0.11 a	0.09 a	0.78 a	7.27 a	0.77 b	1.07 a	1.27 ab	3.52 a	46.02 a	7.55 a
High	100% comercial height	0.33 a	0.13 a	0.09 a	0.85 a	13.71 a	0.96 ab	1.28 a	0.38 b	6.21 a	45.22 a	5.32 a

Means followed by different letters in the columns within each part subdivision differ statistically from each other by Kruskal-Wallis with Nemenyi mean test ($p \leq 0.05$).
SOURCE: The author (2023).

TABLE S4 – CONCENTRATIONS OF NUTRIENTS AND ALUMINUM IN BARK OF A 14 YEAR-OLD *Pinus taeda* CULTIVATION IN DIFFERENT VARI CLASSES VLUE (VERY LOW, LOW, MEDIUM, AND HIGH) IN BITURUNA, PARANÁ, BRAZIL

Classes	Part	P	K	Al	B	Ba	Cu	Fe	Mn	Zn
		-------- g kg^{-1} --------		mg kg^{-1}						
Very Low	Base	0.14 a	0.74 a	546 a	1.61 a	1.69 ab	1.61 a	48.38 a	25.05 a	6.39 a
Low		0.11 a	0.72 a	425 a	1.80 a	1.14 b	2.77 a	44.45 a	25.08 a	7.06 a
Medium		0.13 a	0.93 a	337 a	1.94 a	1.92 ab	2.62 a	34.63 a	30.01 a	7.04 a
High		0.13 a	0.72 a	411 a	2.19 a	3.10 a	1.99 a	35.55 a	28.72 a	5.23 a
Very Low	DBH	0.20 a	0.97 a	688 a	2.01 a	2.33 ab	2.09 a	51.58 a	37.25 a	12.70 a
Low		0.16 a	1.15 a	516 a	2.47 a	1.68 b	2.75 a	28.52 a	29.84 a	13.57 a
Medium		0.17 a	1.10 a	443 a	2.40 a	2.85 ab	2.67 a	24.01 a	33.19 a	13.03 a
High		0.15 a	0.92 a	526 a	2.33 a	4.19 a	2.65 a	23.67 a	30.92 a	7.26 a
Very Low	25% comercial height	0.19 a	1.06 a	718 a	1.86 a	2.34 ab	2.27 a	104 a	36.31 a	13.81 a
Low		0.14 a	0.90 a	504 a	1.98 a	1.24 b	2.57 a	53.45 a	39.89 a	12.50 a
Medium		0.18 a	1.25 a	467 a	2.61 a	2.18 ab	2.93 a	51.14 a	37.90 a	17.22 a
High		0.24 a	1.55 a	548 a	2.70 a	4.58 a	2.72 a	33.20 a	49.88 a	13.91 a
Very Low	50% comercial height	0.38 a	2.17 a	628 a	2.67 a	2.50 a	2.58 a	41.10 a	65.28 a	35.76 a
Low		0.30 a	2.13 a	497 a	2.67 a	1.50 a	2.96 a	46.18 a	57.62 a	31.58 a
Medium		0.25 a	1.77 a	478 a	3.03 a	2.25 a	2.91 a	40.25 a	51.22 a	31.28 a
High		0.33 a	1.94 a	516 a	2.95 a	3.73 a	2.18 a	34.12 a	54.98 a	89.26 a
Very Low	75% comercial height	0.50 a	2.93 a	662 a	3.49 a	2.19 a	3.01 a	27.18 b	59.87 a	63.48 a
Low		0.43 a	3.05 a	477 a	3.38 a	1.48 a	3.01 a	46.09 ab	67.67 a	53.46 a
Medium		0.42 a	2.72 a	497 a	3.68 a	2.11 a	3.05 a	71.46 a	71.33 a	58.78 a
High		0.50 a	3.04 a	529 a	3.89 a	3.21 a	2.96 a	58.79 ab	65.45 a	38.05 a
Very Low	100% comercial height	0.70 a	3.97 a	590 a	4.69 a	1.68 a	5.74 a	83.66 a	87.22 a	76.45 a
Low		0.70 a	4.45 a	438 a	4.83 a	1.30 a	3.48 a	46.51 a	83.22 a	77.98 a
Medium		0.70 a	4.09 a	432 a	5.35 a	1.44 a	3.63 a	63.00 a	92.57 a	79.12 a
High		0.75 a	3.76 a	492 a	5.50 a	2.96 a	3.61 a	66.07 a	91.90 a	50.29 a

Means followed by different letters in the columns within each part subdivision differ statistically from each other by Kruskal-Wallis with Nemenyi mean test ($p \leq 0.05$).
SOURCE: The author (2023).

TABLE S5 – ELEMENT CONCENTRATIONS AND RATIOS OF K/Mg AND Ca/Al IN FINE ROOTS OF A 14 YEAR-OLD *Pinus taeda* CULTIVATION IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) IN BITURUNA, PARANÁ, BRAZIL.

Classes	**P**	**K**	**Al**	**B**	**Ba**	**Cr**	**Cu**	**Fe**	**Mn**	**Ni**	**V**	**Zn**	**K/Mg**	**Ca/Al**
	g kg^{-1}		mg kg^{-1}											
Very Low	0.48 a	0.85 a	775 a	0.95 a	5.45 a	0.49 a	2.87 a	362 a	52.61 a	1.01 a	0.81 a	15.86 a	7.68 a	0.77 a
Low	0.51 a	1.29 a	723 a	1.10 a	4.93 a	0.22 a	1.61 a	281 a	65.66 a	0.92 a	0.65 a	17.61 a	8.72 a	1.33 a
Medium	0.48 a	1.01 a	831 a	1.08 a	5.91 a	0.19 a	4.81 a	215 a	85.65 a	0.76 a	0.59 a	16.44 a	5.94 a	1.50 a
High	0.47 a	1.21 a	827 a	1.22 a	6.45 a	0.22 a	5.85 a	379 a	95.52 a	0.94 a	0.71 a	14.89 a	5.38 a	1.66 a

Means followed by different letters in the columns differ statistically from each other by Kruskal-Wallis with Nemenyi mean test ($p \leq 0.05$).
SOURCE: The author (2023).

TABLE S6 – CONCENTRATIONS AND CONTENTS OF ELEMENTS IN LITTER OF A 14 YEAR-OLD *Pinus taeda* CULTIVATION IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) IN BITURUNA, PARANÁ, BRAZIL.

Classes	**P**	**K**	**Al**	**B**	**Ba**	**Cr**	**Cu**	**Fe**	**Mn**	**Ni**	**V**	**Zn**
	g kg^{-1}		mg kg^{-1}									
	Concentration of the elements in the fraction > 2 mm											
Very Low	0.51 a	0.92 a	3397 a	1.32 a	8.94 a	2.24 a	5.76 a	2266 a	96.65 a	1.82 a	6.60 a	12.63 a
Low	0.51 a	1.12 a	1738 a	0.99 a	5.81 a	2.09 a	4.03 a	819 a	92.06 a	1.42 a	2.16 a	10.01 a
Medium	0.48 a	0.87 a	2357 a	1.28 a	7.90 a	2.35 a	4.23 a	1614 a	121 a	1.86 a	3.76 a	9.99 a
High	0.50 a	0.80 a	2265 a	1.32 a	8.75 a	2.16 a	3.90 a	1393 a	158 a	1.77 a	3.23 a	11.84 a
	Concentration of the elements in the fraction < 2 mm											
Very Low	0.63 a	0.97 a	6686 a	2.29 a	14.47 a	6.72 a	7.60 a	5169 a	79.46 a	3.47 a	14.4 a	13.73 a
Low	0.63 a	1.06 a	5883 a	1.80 a	11.84 a	1.25 a	6.39 a	3952 a	75.69 a	2.05 a	9.85 a	14.47 a
Medium	0.68 a	0.85 a	6464 a	1.67 a	15.00 a	10.76 a	7.30 a	4564 a	120 a	4.26 a	11.50 a	16.45 a
High	0.67 a	0.88 a	6411 a	1.64 a	15.71 a	1.38 a	7.36 a	4080 a	133 a	1.92 a	10.96 a	15.16 a
	Elements content (kg ha^{-1})											
Very Low	36.13 a	59.93 a	339 a	0.12 a	0.77 a	0.27 a	0.44 a	253 a	5.44 a	0.17 a	0.72 a	0.84 a
Low	30.36 ab	58.83 a	202 a	0.07 a	0.47 a	0.09 a	0.28 a	128 a	4.47 a	0.09 a	0.32 a	0.66 a
Medium	22.30 b	33.10 a	172 a	0.06 a	0.44 a	0.25 a	0.23 a	120 a	4.53 a	0.12 a	0.30 a	0.51 a
High	24.65 ab	35.39 a	183 a	0.06 a	0.52 a	0.07 a	0.24 a	116 a	5.87 a	0.08 a	0.30 a	0.55 a

Means followed by different letters in the columns within each subdivision (> 2 mm, < 2 mm and elements content) differ statistically from each other by Kruskal-Wallis with Nemenyi mean test ($p \leq 0.05$).
SOURCE: The author (2023).

TABLE S7 – CHEMICAL FERTILITY AND LIME RECOMMENDATIONS (LR) FOR THREE SOIL DEPTHS (0 – 0.20, 0.20 – 0.40, AND 0.40 – 0.60 m) OF A 14 YEAR-OLD *Pinus taeda* CULTIVATION IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) IN BITURUNA, PARANÁ, BRAZIL

Classes	pH $CaCl_2$	C	Ca^{2+}	Mg^{2+}	K^+	H + Al	Al^{3+}	Na^+	SB(1)	CEC eff(2)	CEC pH 7.0(3)	P	m(4)	V(5)	LR(6)
		g dm^{-3}	cmol$_c$ dm^{-3}									mg dm^{-3}	%		t ha^{-1}
0 – 0.20 m															
Very Low	3.17 a	69.68 a	0.22 a	0.10 a	0.12 a	28.08 a	4.00 a	0.03 a	0.47 a	4.47 a	28.55 a	1.92 a	90 a	1.63 a	1.68 ab
Low	3.18 a	71.93 a	0.11 b	0.10 a	0.12 a	29.23 a	4.01 a	0.04 a	0.37 a	4.38 a	29.60 a	1.93 a	92 a	1.26 a	1.78 a
Medium	3.25 a	89.73 a	0.14 ab	0.10 a	0.10 a	29.08 a	3.98 a	0.03 a	0.38 a	4.36 a	29.45 a	1.95 a	91 a	1.28 a	1.76 ab
High	3.37 a	81.10 a	0.21 a	0.11 a	0.11 a	28.65 a	3.50 a	0.04 a	0.48 a	3.98 a	29.13 a	3.09 a	88 a	1.65 a	1.67 b
0.20 – 0.40 m															
Very Low	3.37 a	49.23 a	0.18 a	0.07 a	0.08 a	24.78 a	3.62 a	0.03 a	0.37 a	3.99 a	25.14 a	1.61 b	91 a	1.43 a	1.74 a
Low	3.41 a	60.38 a	0.11 a	0.07 a	0.08 a	24.48 a	3.67 a	0.03 a	0.29 a	3.95 a	24.76 a	1.98 ab	93 a	1.17 a	1.82 a
Medium	3.50 a	64.70 a	0.12 a	0.07 a	0.06 a	23.80 a	3.35 a	0.03 a	0.27 a	3.62 a	24.07 a	1.49 b	92 a	1.13 a	1.82 a
High	3.64 a	72.40 a	0.16 a	0.08 a	0.26 a	22.30 a	2.85 a	0.03 a	0.53 a	3.38 a	22.83 a	4.55 a	84 a	2.38 a	1.76 a
0.40 – 0.60 m															
Very Low	3.52 a	42.05 a	0.20 a	0.06 a	0.10 a	22.65 a	3.16 a	0.02 a	0.38 a	3.55 a	23.03 a	2.40 a	90 ab	1.60 ab	1.74 a
Low	3.59 a	48.10 a	0.10 a	0.05 a	0.05 a	21.05 a	3.21 a	0.02 a	0.23 a	3.44 a	21.28 a	1.93 a	93 a	1.09 b	1.85 a
Medium	3.69 a	45.83 a	0.11 a	0.05 a	0.04 a	18.75 a	2.57 a	0.02 a	0.22 a	2.79 a	18.97 a	2.03 a	92 ab	1.19 ab	1.84 a
High	3.79 a	45.70 a	0.17 a	0.06 a	0.06 a	18.35 a	2.34 a	0.03 a	0.32 a	2.66 a	18.67 a	3.92 a	88 b	1.78 a	1.76 a

(1) SB = sum of bases (Ca^{2+} + Mg^{2+} + K^+ + Na^+); (2) CEC eff = effective cation exchange capacity (SB + Al^{3+}); (3) CEC pH 7.0 = pH 7.0 cation exchange capacity (SB + H + Al); (4) m = aluminum saturation (m% = ((Al^{3+} * 100)/CEC eff); (5) V = bases saturation (V% = ((SB * 100)/CEC pH 7.0); (6) Liming recommendation (LR = [2 – (Ca^{2+} + Mg^{2+})]).
Means followed by different letters in the columns within each subdivision of soil depths (0-0.20, 0.20-0.40 and 0.40-0.60 m) differ statistically from each other by Kruskal-Wallis with Nemenyi mean test ($p \leq 0.05$).
SOURCE: The author (2023).

TABLE S8 – MICRONUTRIENTS AND OTHER ELEMENTS AT THREE SOIL DEPTHS (0 – 0.20, 0.20 – 0.40, AND 0.40 – 0.60 m) IN A 14 YEAR-OLD *Pinus taeda* CULTIVATION IN DIFFERENT VARI CLASSES VALUE (VERY LOW, LOW, MEDIUM, AND HIGH) IN BITURUNA, PARANÁ, BRAZIL.

Classes	B	Ba	Cr	Cu	Fe	Mn	Mo	Ni	V	Zn
	---------- mg dm^{-3} ----------									
0 – 0.20 m										
Very Low	0.13 a	2.70 a	0.15 ab	5.66 a	376 a	10.60 a	1.66 a	0.25 a	0.49 a	2.56 a
Low	0.13 a	2.10 a	0.16 ab	5.33 a	367 a	2.45 a	2.40 a	0.23 a	0.44 a	1.85 a
Medium	0.10 a	2.27 a	0.13 b	5.01 a	286 a	2.36 a	1.24 a	0.24 a	0.48 a	2.61 a
High	0.10 a	2.87 a	0.19 a	4.48 a	298 a	3.65 a	2.80 a	0.27 a	0.81 a	2.24 a
0.20 – 0.40 m										
Very Low	0.13 a	2.57 a	0.19 ab	5.61 a	237 a	5.34 a	1.62 ab	0.23 a	0.44 a	1.87 a
Low	0.09 a	2.31 a	0.57 a	5.39 ab	209 a	3.34 a	2.62 ab	0.20 a	0.42 a	2.64 a
Medium	0.07 a	2.11 a	0.17 b	4.63 ab	171 a	2.94 a	1.47 b	0.18 a	0.51 a	2.13 a
High	0.07 a	3.17 a	0.22 ab	4.14 b	186 a	3.68 a	5.20 a	0.16 a	0.80 a	2.03 a
0.40 – 0.60 m										
Very Low	0.08 a	3.14 a	0.25 a	6.06 a	165 a	7.17 a	1.61 a	0.22 a	0.51 a	5.50 a
Low	0.07 a	2.48 a	0.21 a	5.38 ab	118 a	3.73 a	2.25 a	0.13 a	0.40 a	1.89 a
Medium	0.05 a	2.68 a	0.19 a	4.92 ab	103 a	2.19 a	1.33 a	0.12 a	0.54 a	3.36 a
High	0.05 a	4.36 a	0.49 a	4.55 b	112 a	2.58 a	2.23 a	0.11 a	0.70 a	1.71 a

Means followed by different letters in the columns within each subdivision of soil depths (0-0.20, 0.20-0.40 and 0.40-0.60 m) differ statistically from each other by Kruskal-Wallis with Nemenyi mean test ($p \leq 0.05$).
SOURCE: The author (2023).

TABLE S9 – CHEMICAL FERTILITY OF THE SURFICIAL SOIL HORIZON OF A 14 YEAR-OLD *Pinus taeda* CULTIVATION IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) IN BITURUNA, PARANÁ, BRAZIL.

Classes	**pH $CaCl_2$**	**C**	**Ca^{2+}**	**Mg^{2+}**	**K^+**	**H + Al**	**Al^{3+}**	**Na^+**	**SB(1)**	**CEC eff(2)**	**CEC pH 7.0(3)**	**P**	**m(4)**	**V(5)**
	-	g dm^{-3}	cmol$_c$ dm^{-3}									mg dm^{-3}	%	
Very Low	3.03 b	53.00 a	0.12 a	0.11 a	0.13 a	28.75 a	3.87 a	0.03 a	0.39 a	4.26 a	29.14 a	2.79 a	90.64 a	1.37 a
Low	2.99 b	53.35 a	0.13 a	0.11 a	0.11 a	30.75 a	4.04 a	0.03 a	0.38 a	4.42 a	31.13 a	2.42 a	91.32 a	1.23 a
Medium	3.17 ab	59.45 a	0.13 a	0.10 a	0.10 a	28.60 a	3.92 a	0.04 a	0.36 a	4.29 a	28.96 a	1.68 a	91.47 a	1.26 a
High	3.47 a	74.00 a	0.16 a	0.11 a	0.10 a	24.78 a	3.48 a	0.04 a	0.38 a	4.21 a	28.60 a	2.31 a	90.78 a	1.36 a

(1) SB = sum of bases (Ca^{2+} + Mg^{2+} + K^+ + Na+); (2) CEC eff = effective cation exchange capacity (SB + Al^{3+}); (3) CEC pH 7.0 = pH 7.0 cation exchange capacity (SB + H + Al); (4) m = aluminum saturation (m% = ((Al^{3+} * 100)/CEC eff); (5) V = bases saturation (V% = ((SB * 100)/CEC pH 7.0).
Means followed by different letters in the columns differ statistically from each other by Kruskal-Wallis with Nemenyi mean test ($p \leq 0.05$).
SOURCE: The author (2023).

TABLE S10 – MICRONUTRIENTS AND OTHER ELEMENTS IN THE SURFICIAL SOIL HORIZON OF A 14 YEAR-OLD *Pinus taeda* CULTIVATION IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) IN BITURUNA, PARANÁ, BRAZIL

Classes	**B**	**Ba**	**Cr**	**Cu**	**Fe**	**Mn**	**Mo**	**Ni**	**V**	**Zn**
	mg dm^{-3}									
Very Low	0.27 a	2.15 a	0.22 a	5.90 a	394 a	4.15 a	0.09 b	0.27 a	0.62 a	2.35 a
Low	0.17 ab	2.04 a	0.16 a	5.75 a	386 a	2.44 a	0.81 ab	0.24 a	0.51 a	1.77 a
Medium	0.13 ab	2.42 a	0.16 a	4.65 a	334 a	1.61 a	2.39 a	0.25 a	0.70 a	1.37 a
High	0.10 b	2.65 a	0.29 a	5.16 a	241 a	2.39 a	1.64 ab	0.38 a	0.66 a	3.55 a

Means followed by different letters in the columns differ statistically from each other by Kruskal-Wallis with Nemenyi mean test ($p \leq 0.05$).
SOURCE: The author (2023).

TABLE S11 – PEDOLOGICAL DESCRIPTION (HORIZON, UPPER, AND LOWER LIMIT), THICKNESS, COLOR, CLAY, AND TEXTURAL CLASS) OF THE SOIL PROFILES EVALUATED IN THE DIFFERENT VARI CLASSES (VERY LOW - VL, LOW - L, MEDIUM – M, AND HIGH - H) IN BITURUNA, PARANÁ, BRAZIL

Class - Repetition	Horizon	Limit		Thickness	Color	Clay	Textural class
		upper	lower				
		cm	cm	cm		g kg^{-1}	
VL - R1	O	-7	0	7	-	-	-
	Ap_1	0	35	35	Very Dark Brown (7.5YR 2.5/2)	600	Very clayey
	Ap_2	35	60	25	Dark Brown (7.5YR 3/3)	-	-
	BA	60	75	15	Dark Brown (7.5YR 3/4)	788	Very clayey
	Bi	75	100+	25	Strong Brown (7.5YR 4/6)	800	Very clayey
VL - R2	O	-13	0	13	-	-	-
	Ap	0	40	40	Black (5YR 2.5/1.5)	425	Clay
	BA	40	60	20	Dark Brown (7.5YR 3/2.5)	-	-
	Bi_1	60	80	20	Dark Brown (7.5YR 3/3.5)	763	Very clayey
	Bi_2	80	95+	15	Dark Brown (7.5YR 3/4)	775	Very clayey
	CR	95+	-	-	Red (2.5YR 4/6) Yellow Red (5YR 5/6)	-	-
VL - R3	O	-9	0	9	-	-	-
	Ap	0	35	35	Dark Reddish Brown (5YR 2.5/2)	750	Very clayey
	ABi	35	55	20	Very Dark Brown (7.5YR 2.5/3)	-	-
	Bi	55	100+	45	Strong Brown (7.5YR 4/6)	750	Very clayey
VL - R4	O	-8	0	8	-	-	-
	Ap	0	35	35	Dark Reddish Brown (5YR 2.5/2)	725	Very clayey
	AB	35	55	20	Dark Brown (7.5YR 3/3)	-	-
	BA	55	70	15	Dark Brown (7.5YR 3/4)	-	-
	Bi	70	100+	30	Brown (7.5YR 4/5)	788	Very clayey
L - R1	O	-10	0	10	-	-	-
	Ap	0	35	35	Dark Reddish Brown (5YR 2.5/2)	713	Very clayey
	AB	35	65	30	Very Dark Brown (7.5YR 2.5/3)	-	-
	Bi_1	65	80	15	Dark Brown (7.5YR 3/4)	800	Very clayey
	Bi_2	80	100+	20	Brown (7.5YR 4/5)	800	Very clayey
L - R2	O	-15	0	15	-	-	-
	Ap	0	30	30	Black (5YR 2.5/1.5)	575	Clay

	AB	30	45	15	Dark Reddish Brown (5YR 2.5/2)	-	-
	BA	45	55	10	Dark Reddish Brown (5YR 3/2.5)	-	-
	Bi	55	70	15	Dark Brown (7.5YR 3/3.5)	750	Very clayey
	BC	70	80	10	Dark Brown (7.5YR 3/3.5) Strong Brown (7.5YR 5/6) Red (2.5YR 4/8)	650	Very clayey
	CR	80	85+	5	Dark Brown (7.5YR 3/3.5) Strong Brown (7.5YR 5/6) Red (2.5YR 4/8)	-	-
L - R3	O	-20	0	20	-	-	-
	Ap	0	35	35	Black (5YR 2.5/1.5)	575	Clay
	C/A	35	40+	5	Yellow Red (5YR 4/6) Dark Reddish Brown (5YR 2.5/2)	-	-
L - R4	O	-10	0	10	-	-	-
	Ap	0	20	20	Dark Reddish Brown (5YR 2.5/2)	675	Very clayey
	AB	20	40	20	Dark Brown (7.5YR 3/3)	725	Very clayey
	Cr_1	40	50	10	Yellow Red (5YR 4/6) Reddish Brown (5YR 5/5) Dark Brown (7.5YR 3/3)	400	Sandy clay
	Cr_2	50	70	20	Yellow Red (5YR 4/6) Reddish Brown (5YR 5/5) Dark Brown (7.5YR 3/3)	400	Sandy clay
	Cr_3	70	80+	10	Pinkish Gray (5YR 6/2) Reddish Brown (5YR 5/5) Dark Brown (7.5YR 3/3)	400	Sandy clay
M - R1	O	- 10	0	10	-	-	-
	Ap	0	37	37	Dark Reddish Brown (5YR 2.5/2)	588	Clay
	AB	37	60	23	Very Dark Brown (7.5YR 2.5/3)	-	-
	BA	60	70	10	Dark Brown (7.5YR 3/4)	-	-
	Bi	70	100+	30	Brown (7.5YR 4/5)	763	Very clayey
M - R2	O	-4	0	4	-	-	-
	Ap	0	30	30	Black (5YR 2.5/1)	288	Clay loam
	AB	30	45	15	Dark Reddish Brown (2.5YR 3/3)	313	Clay loam
	BA	45	55	10	Dark Brown (7.5YR 3/3)	-	-
	Bi	55	89	34	Dark Yellowish Brown (10YR 4/6)	700	Very clayey

	C/B	89	91+	2	Yellow Red (5YR 5/8) Strong Brown (7.5YR 4/6)	-	-
M - R3	O	-10	0	10	-	-	-
	Ap	0	38	38	Black (5YR 2.5/1.5)	550	Clay
	AB	38	75	37	Dark Brown (7.5YR 3/3)	-	-
	Bi	75	97	22	Brown (7.5YR 4/5)	750	Very clayey
	CR	97	100+	3	Yellow Red (5YR 5/8)	-	-
M - R4	O	-12	0	12	-	-	-
	Ap	0	35	35	Dark Reddish Brown (5YR 2.5/2)	688	Very clayey
	AB	35	50	15	Dark Reddish Brown (5YR 2.5/2)	-	-
	BA	50	60	10	Dark Brown (7.5YR 3/3)	-	-
	Bi	60	98	38	Dark Yellowish Brown (10YR 4/5)	763	Very clayey
	CR	98+	-	-	Yellow-Red (5YR 5/8)	-	-
H - R1	O	-10	0	10	-	-	-
	Ap	0	47	47	Black (10YR 2/1.5)	338	Clay loam
	BA	47	60	13	Dark Brown (10YR 3/3)	-	-
	Bi	60	79	19	Yellowish Brown (10YR 5/4)	750	Very clayey
	CR	79+	-	-	Reddish Brown (5YR 4/5)	-	-
H - R2	O	- 13	0	13	-	-	-
	Ap	0	25	25	Black (5YR 2.5/1)	288	Clay loam
	BA	25	60	35	Dark Brown (10YR 3/3)	550	Clay
	C/B	60	70+	10	Yellow-Red (5YR 5/8)	-	-
H - R3	O	- 5	0	5	-	-	-
	Ap	0	45	45	Black (5YR 2.5/1)	588	Clay
	BA	45	55	10	Very Dark Brown (7.5YR 3.5/3)	-	-
	Bi_1	55	85	30	Yellowish Brown (10YR 5/6)	763	Very clayey
	Bi_2	85	90	5	Yellowish Brown (10YR 5/6)	-	-
	CR	90+	-	-	-	-	-
H - R4	O	-8	0	8	-	-	-
	Ap	0	45	45	Dark-Reddish-Brown (5YR 2.5/2)	663	Very clayey
	AB	45	65	20	Dark Brown (7.5YR 3/3)	-	-
	BA	65	75	10	Dark Brown (7.5YR 3/4)	-	-
	Bi	75	100+	25	Yellowish Brown (10YR 5/6)	775	Very clayey

SOURCE: The author (2023).

TABLE S12 – NUTRIENT CONCENTRATION IN NEEDLES, WOOD, BARK, FINE ROOTS, AND LITTER DESCRIBED IN THE LITERATURE THAT WERE USED AS A REFERENCE OR COMPARISON TO OUR STUDY OF A COMMERCIAL *Pinus taeda* CULTIVATION IN DIFFERENT VARI CLASSES (VERY LOW, LOW, MEDIUM, AND HIGH) IN BITURUNA, PARANÁ, BRAZIL

Component	P	K	Ca	Mg	Fe	Mn	Zn	B	Cu	Reference
	---- $g\ kg^{-1}$ ----				---- $mg\ kg^{-1}$ ----					
Needles[1]										
	1.3 - 1.4	7.0 - 11.0[2] (< 4.0)[3]	0.8 - 3.0 (< 0.5)	0.8 - 1.5 (< 0.8)	133 - 165	210 - 363	20.0 - 80.0 (< 10.0)	15.0 - 29.0	5 - 7	Reissmann (1981)
	-	-	-	0.6	-	-	-	-	-	Sun and Payn (1999)
	-	-	-	0.20 - 0.25	-	-	-	-	-	Laing et al. (2000)
	0.8 - 1.4	6.0 - 10.0	3.0 - 5.0	1.3 - 2.0	100 - 200	250 - 600	30.0 - 45.0	12.0 - 25.0	4 - 7	Gonçalves (2005)
	1.2	4.0	1.5	0.8	20.0	40.0	20.0	10.0	3.0	Sypert (2006)
	0.95 - 1.12	3.0 - 5.5	0.83 - 2.72	0.51 - 0.86	85.0 - 156	34.0 - 166	18.0 - 31.0	-	3.0 - 5.0	Dedecek et al. (2008)
	1.2	3.5 - 4.0	1.5	0.8	-	20.0 - 40.0	10.0 - 20.0	4.0 - 8.0	2.0 - 3.0	Albaugh et al. (2010)
	1.6	8.7	2.6	0.80	-	-	-	-	-	Vogel et al. (2018)
Wood[4]										
	0.1	0.7 - 0.9	0.6 - 0.7	0.2 - 0.3	-	-	-	-	-	Albaugh et al. (2008)
	0.1	0.5	0.6	0.3	-	-	-	-	-	Zhao et al. (2014)
	0.2	0.8 - 1.1	0.5 - 0.6	0.2 - 0.3	10.6 - 15.1	7.5 - 10.5	7.6 - 8.8	2.9 - 3.3	1.6 - 2.2	Villacorta et al. (2015)
	0.1	0.9	0.9	1.4	-	-	-	-	-	Angel et al. (2019)
	0.18 - 0.19	1.0 - 1.14	0.46 - 0.56	0.16 - 0.18	3.12 - 5.75	54.89 - 113.51	-	3.56 - 4.15	-	Pereira et al. (2022)
Fine roots[4]										
	0.7 - 1.1	2.3 - 3.4	1.6 - 1.8	0.6 - 0.9	-	-	-	-	-	Albaugh et al. (2008)
	0.22 - 0.38	0.6 - 0.8	1.28 - 7.9	0.23 - 2.7	-	-	-	25.0 - 35.0	-	Consalter et al. (2021b)
	0.85 - 1.12	0.3 - 0.4	0.2 - 8.3	0.1 - 2.7	432 - 620	18.4 - 172	-	-	-	Adam et al. (2021)
Bark[4]										
	0.16 - 0.29	0.31 - 1.09	0.25 - 1.56	0.20 - 0.55	40.0 - 106	39.0 - 114	13.0 - 48.0	-	3.0 - 5.0	Dedecek et al. (2008)
	0.3	0.7 - 0.9	1.0 - 1.9	0.3 - 0.4	-	-	-	-	-	Albaugh et al. (2008)
	0.4 - 0.5	3.3 - 4.0	1.0 - 1.8	0.5 - 0.7	19.3 - 31.9	18.6 - 25.3	27.6 - 43.8	8.9 - 10.2	2.1 - 2.6	Villacorta et al. (2015)
	0.2	0.6	1.6	0.4	-	-	-	-	-	Zhao et al. (2014)
	0.18 - 0.25	0.64 - 0.88	0.42 - 0.69	0.15 - 0.19	55.7 - 67.0	26.6 - 60.6	-	11.4 - 13.3	-	Pereira et al. (2022)
Litter[4]										
	0.39 - 0.50	0.57 - 1.09	0.67 - 3.30	0.59 - 1.28	1531 - 7242	46.1 - 163.9	7.4 - 22.0	-	2.9 - 5.3	Rabel et al. (2021)

(1) Levels of nutrients considered adequate in needles (dry matter) of *P. taeda* and *P. radiata* for interpretation. (2) Range of adequate contents; (3) Critical levels.
(4) Range of values found in the studies, without a qualification.
SOURCE: The author (2023).