Effect of carbonization on wood anatomy of three Fabaceae species from an Araucaria forest stand in Southern Brazil

Efecto de la carbonización en la anatomía de la madera de tres especies de Fabaceae del Bosque de Araucaria, sur de Brasil

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SUMMARY

The aim of this study was to measure and compare some anatomical elements of wood and charcoal of *Inga vera*, *Machaerium paraguariense* and *Muellera campestris* to support identification of the materials seized by regulatory authorities. For each species, three trees were analyzed. After wood evaluation, all samples (moisture content of 12 ± 1 %) were wrapped in aluminum foil and carbonized in a muffle furnace for 8 hours with final temperature of 450 °C and a heating rate of 1.66 °C/min. The number of measurements was based on 30 readings regarding tangential diameter and vessel density, along with frequency, height and width of rays (in micrometers). After carbonization, changes in cell dimensions and different behavior were observed in the Fabaceae species evaluated. In all species, vessel diameter declined; vessel density decreased in *Inga vera* and increased in the other species; ray height decreased in *Inga vera* and *Muellera campestris*, and increased in *Machaerium paraguariense*; and ray width and frequency increased in all species. We concluded that due to the conservation of wood anatomical structures after carbonization, the inclusion of this species in a database would be effective to support efforts to control deforestation in the south of Brazil.

Key words: *Inga vera*, *Machaerium paraguariense*, *Muellera campestris*, anatomical characteristics, charcoal.

RESUMEN

El objetivo de este estudio fue medir y comparar algunos elementos anatómicos de madera y carbón vegetal de *Inga vera*, *Machaerium paraguariense* y *Muellera campestris* con el fin de apoyar la identificación de los materiales incautados por las autoridades reguladoras. Para cada especie, se analizaron tres árboles. Después de la evaluación de la madera, todas las muestras (contenido de humedad de 12 ± 1 %) se envolvieron en papel de aluminio y se carbonizaron en un horno de mufla durante 8 horas con una temperatura final de 450 °C y una velocidad de calentamiento de 1,66 °C/min. El número de mediciones se basó en 30 lecturas con respecto al diámetro tangencial y densidad de los vasos, junto con frecuencia, altura y ancho de los radios (en micrómetros). Después de la carbonización, se observaron cambios en las dimensiones celulares y diferentes comportamientos en las especies de Fabaceae evaluadas. En todas las especies, el diámetro del vaso disminuyó; la frecuencia de los vasos disminuyó en *Inga vera* y aumentó en otras especies; la altura de los radios disminuyó en *Inga vera* y *Muellera campestris*, y aumentó en *Machaerium paraguariense*; y el ancho y la frecuencia de los radios aumentaron en todas las especies. Concluimos que debido a la conservación de las estructuras anatómicas de la madera después de la carbonización, la inclusión de esta especie en una base de datos sería efectiva para apoyar los esfuerzos para controlar la deforestación en el sur de Brasil.

Palabras clave: *Inga vera*, *Machaerium paraguariense*, *Muellera campestris*, características anatómicas, carbón vegetal.

INTRODUCTION

Charcoal is an important raw material for iron and steel making. A potential problem is identification of its origin, which can be from planted forests or illegal wood from native forests (Gonçalves and Schell-Ybert 2012). Sometimes illegal logging is hidden by making charcoal because carbonization makes it harder to identify species. Additiona-
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Ly, charcoal from native wood is often mixed, for example, with charcoal from *Eucalyptus* L’Hér., a species planted for charcoal production. On this basis, it is necessary to know which anatomical changes that occur during carbonization are related to each species. In general, qualitative characteristics remain unchanged, while some variations occur in dimensions and frequency of vessels and rays (Gonçalves et al. 2012, Gonçalves and Scheel-Ybert 2016). Similarly, Osterkamp et al. (2018) reported that during carbonization, chemical and physical processes occur that result in changes in wood cell dimensions, although general anatomical characteristics remain without major alterations. Therefore, based on wood anatomy, it is possible to distinguish most species after burning (Muñiz et al. 2012b).

Literature reports wood and charcoal anatomy for some species in Brazil, such as macro or microscopic description of *Copaifera c. langsdorffii* Desf. and *Dipteryx odorata* (Aubl.) Willd (Nisgoski et al. 2012); *Cedrelinga cateniformis* (Ducke) Ducke and *Enterolobium schomburgkii* (Benth.) Benth. (Muñiz et al. 2012a); *Pouteria macrophylla* (Lam.) Eyma and *Micropholis guianensis* (A.D.C.) Pierre (Muñiz et al. 2013); *Byrsonima spicata* (Cav.) DC., *Calophyllum brasiliense* Cambess., *Cecropia sciadophylla* Mart., *Cochlospermum orinocense* (Kunth) Steud. and *Schefflera morototoni* (Aubl.) Maguire et al. (2014); *Brosimum acutifolium* Huber, *Ficus citrifolia* Mill., *Hyeronima laxiflora* (Tul.) Müll. Arg. and *Sapium glandulatum* (Vell.) Pax. (Nisgoski et al. 2015); *Anacardiaceae* species (Gonçalves and Scheel-Ybert 2016); *Mimosa scabrella* Benth., *Miconia cinnamomifolia* (DC.) Naudin, *Cecropia glaziiovii* Sneathl, *Hyeronima alchorneoides* Allemão and *Pera glabrata* (Schott) Baill. (Carvalho et al. 2017); and angelim species (Muñiz et al. 2016); besides 80 species described in an anthracology atlas (Scheel-Ybert and Gonçalves 2016).

The Araucaria forest stands in Santa Catarina State, Brazil, are composed of approximately 925 species, from 439 genera in 116 botanical families (Gasper et al. 2013). One of the most important is the Fabaceae family, with 58 species recorded (Gasper et al. 2013), some with high commercial importance, such as *Inga vera* Willd. and *Muellera campestris* (Mart. ex Benth) M. J. Silva et A. M. G. Azevedo (Richter and Dallwitz 2000), while others are listed by the Environmental Ministry as endangered in Brazil, such as 12 species from the genus *Inga* Mill. and one from *Machaerium* Pers. (MMA 2014).

Considering the extraordinary biological diversity in Brazil, as well as the difficulties related to the inspection of environmental crimes, a reference collection and database with a large number of samples is necessary to facilitate efficient identification of wood and charcoal by regulatory authorities. The aim of this study was to verify wood and charcoal anatomical characteristics in different radial positions of three Fabaceae species (*Inga vera*, *Machaerium paraguariense* Hassl and *Muellera campestris*) to contribute with information to a database for these species evaluation.

**METHODS**

Wood samples from *Inga vera*, *Machaerium paraguariense* and *Muellera campestris* were obtained from trees cut by Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) in a region that is now inundated by a reservoir (San Roque hydroelectric plant) in Santa Catarina State. For each species, three trees were collected. Specimens of the botanical material were deposited at Lages Herbarium of Santa Catarina State University – LUSC (table 1). The access to the botanical material was registered under the code AF3EDDC with the Genetic Heritage Management Council (CGEN/SISGEN).

For each tree, we selected a disc with no defects at breast height (DBH) for evaluation and wedge obtainability. The material was divided into three samples oriented in anatomical sections (transversal, longitudinal radial, longitudinal tangential), with dimensions of 2 x 2 x 2 cm, codified as near pith (next to the pith, though not including it), intermediate (exactly halfway between near bark and near pith) and near bark (in the outermost part of the disc) (figure 1). Radial sampling was done to cover most anatomical variation that can interfere in wood identification, since results will be added to a database for posterior practical application in forest supervision. Samples were from heartwood, transition and sapwood, varying depending on tree diameter. For characterization, samples were smoothed with #1200 sandpaper.

Wood and charcoal analyses were performed on the same samples. After wood evaluation, all samples (moisture content of 12 ± 1 %) were wrapped in aluminum foil and carbonized in a muffle furnace, as described by Muñiz et al. (2012b), with final temperature of 450 °C (two hours at final temperature) and a heating rate of 1.66 °C min⁻¹, totaling eight hours. Description of wood and charcoal was based on images obtained with a Discovery V12 stereomicroscope (Zeiss) with the Axio Vision Rel. 4.7 software. Charcoal details were observed with a Hitachi

![Figure 1. Illustration of sampling disk diagram of *Muellera campestris*, where B: near bark, I: intermediate, P: near pith.](image-url)

**Diagrama de muestreo en disco de *Muellera campestris*, donde: B: próximo a la corteza; I: intermedio; P: próximo a la médula.**

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**Table 1.** Identification of the botanical material deposited at the Lages Herbarium of Santa Catarina State University – LUSC (IBAMA).<ref>
Table 1. Species and record numbers.

| Species/Record number | DBH (cm) | Coordinates (WGS84) | Altitude (m) |
|-----------------------|----------|---------------------|--------------|
| **Inga vera**         |          |                     |              |
| LUSC 6225            | 26.0     | lat: -27.484728 long: -50.805003 | 701          |
| LUSC 6226            | 18.0     | lat: -27.484378 long: -50.805603 | 851          |
| LUSC 6227            | 17.5     | lat: -27.484228 long: -50.805753 | 731          |
| **Machaerium paraguariense** | | | |
| LUSC 6243            | 18.3     | lat: -27.489997 long: -50.805392 | 734          |
| LUSC 6244            | 12.9     | lat: -27.489997 long: -50.805417 | 734          |
| LUSC 6245            | 11.0     | lat: -27.490006 long: -50.805433 | 734          |
| **Muellera campestris** | | | |
| LUSC 6237            | 31.2     | lat: -27.496892 long: -50.810606 | 692          |
| LUSC 6238            | 25.1     | lat: -27.497081 long: -50.810536 | 696          |
| LUSC 6239            | 15.0     | lat: -27.483572 long: -50.808342 | 740          |

TM-1000 tabletop scanning electron microscope (SEM) directly from the material, without coating. The description of the anatomical elements of wood and charcoal samples followed procedures from International Association of Wood Anatomists (IAWA, 1989) and 30 measurements were made for tangential diameter and vessel density, as well as frequency, height and width of rays (dimensions in micrometers).

A statistical analysis was performed considering the kind of material (wood or charcoal) and different positions in the disk (near bark, intermediate, near pith), resulting in a 2 x 3 factorial analysis. Differences in data between wood and charcoal were evaluated by the Scott-Knott test at 95% probability, using the Sisvar software.

RESULTS

Qualitative characteristics. *Inga vera*. In wood samples, growth ring boundaries were distinguished by differences in fiber zones. Vessels: diffuse porosity, solitary vessels (68%) and in radial multiples 2-5 (14%, 9%, 2%, 7%, respectively for multiples of 2, 3, 4 and more than 4) (figure 2A), simple perforate plates (figure 2H), intervessel pits alternate, gums and other deposits present (figure 2A). Axial parenchyma: lozenge-aliform and confluent (figure 2A). Rays homogeneous, all ray cells procumbent, 1-3 cells wide, not storied (figure 2B). After carbonization, most qualitative characteristics remained intact (figure 2C) and it was also possible to observe not storied rays (figure 2D), some ray cells with ruptures (figure 2E) and cells in uniseriate and multiseriate rays (figure 2F). The presence of crystals in axial parenchyma cells was verified (figure 2G, H).

*Machaerium paraguariense*. In wood samples, growth ring boundaries were little distinguished by fiber zones (figure 3A). Vessels: diffuse porous, mostly solitary vessels (84%) (figure 3A), in radial multiples 2-4 present, simple perforate plate (figure 3H), alternate intervessel pits. Axial parenchyma: winged-aliform and confluent; diffuse-in-aggregates. Rays: heterogeneous, with procumbent body ray cell and 1-2 rows of square marginal cells, 1-3 cells wide, storied (figure 3B). In charcoal, qualitative characteristics remained, such as solitary vessels (figure 3C), storied rays (figure 3D), aliform axial parenchyma (figure 3E), heterogeneous rays (figure 3G) and simple perforate plate and alternate intervessel pits (figure 3H) and crystals in axial parenchyma cells were also observed (figure 3F).

*Muellera campestris*. In wood samples, growth ring boundaries were distinct, marked by thin lines from marginal parenchyma (figure 4A). Vessels: diffuse porous with irregular distribution, solitary vessels (62%) or in radial multiples 2-4 (24%, 9%, 2%, respectively for multiples of 2, 3 and 4), simple perforate plate, alternate intervessel pits, gums and other deposits present. Axial parenchyma: lozenge-aliform and confluent, vasicentric, unilateral present (figure 4A). Rays: homogeneous, multiseriate and storied (figure 4B). Carbonization resulted in more distinct vessels (figure 4C), more evident irregular distribution, and some contrast in storied rays (figure 4D). It was possible to observe more contrast of axial parenchyma in more detailed images (figure 4E), presence of crystals in axial parenchyma cells (figure 4F), homogeneous rays (figure 4G), simple perforate plate (figure 4H) and alternate intervessel pits (figure 4F).
Quantitative characteristics. In wood samples, increase in vessel diameter and decrease in vessel density from near pith to near bark (table 2) were observed. Ray dimensions showed no linear tendency of variation and ray frequency was not influenced by radial position in trunk (table 3). In charcoal, changes in structural dimensions were different depending on species characteristics (tables 2 and 3).

**DISCUSSION**

*Tangential diameter of vessels.* In the wood of all species, we observed an increase in vessel diameter from the region of near pith towards near bark, being more accentuated in *Muellera campestris*. In *Inga vera* wood, mean vessel diameter was 129 µm, similar to all species of the genus *Inga*.

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**Figure 2.** Images of *Inga vera* wood (A, B) and charcoal (C, D). SEM images of charcoal (E-H). (A, C) transversal section, (B, D, F) tangential section, (E) transversal section, arrow indicates splits in rays; (G, H) radial section, arrow indicates crystals and simple perforation plate.

*Figura 2.* Imágenes de la madera (A, B) y carbón (C, D) de *Inga vera*. MEB imágenes del carbón (E-H). (A, C) sección transversal; (B, D, F) sección tangencial; (E) sección transversal, la flecha indica grietas en los radios; (G, H) sección radial, la flecha indica cristales y placa de perforación simples.
published in Inside Wood, along with the study of Ortega et al. (1988), who also analyzed *Inga vera*. Furthermore, the results of this study are comparable to those reported by Richter and Dallwitz (2000), with values varying from 60-130-200 µm, for material collected in Mexico, and those reported by Vieira et al. (2019), with a mean value of 141 µm. In *Machaerium paraguariense* wood, mean vessel diameter was 107 µm, within the range presented in Inside Wood for the same genus. The results for both *Machaerium paraguariense* and *Muellera campestris* wood are proportionate to those of Marchiori et al. (2009), Richter and Dallwitz (2000) and Vieira (2017), although these authors did not ascertain differences from pith to bark.

In charcoal, differences in vessel diameter from near pith to near bark regions were not linear in accordance with position and varied among the species. After carbo-

![Figure 3](image-url)

**Figure 3.** Images of *Machaerium paraguariense* wood (A, B) and charcoal (C, D). SEM images of charcoal (E-H). (A, C) Transversal section, (B, D) tangential section, (E) transversal section, arrow indicates axial parenchyma; (F) tangential section, arrow indicates crystals in parenchyma cells; (G, H) radial section, arrow indicates simple perforate plate and intervessel pits.

Imágenes de la madera (A, B) y carbón (C, D) de *Machaerium paraguariense*. MEB imágenes de lo carbón (E-H). (A, C) Sección transversal; (B, D) sección tangencial; (E) sección transversal, la flecha indica parénquima axial aliforme; (F) sección tangencial, la flecha indica cristales en lo parénquima axial; (G, H) sección radial, la flecha indica la placa de perforación simple y las punteaduras intervasculares.
nization, we observed a reduction in vessel diameter for all positions and species. The contraction of cells was more evident in the intermediate position of *Machaerium paraguariense* (32.99 %) and less pronounced in the intermediate position of *Muellera campestris* (14.41 %). Regarding reduction of mean vessel diameter by species after carbonization, *Machaerium paraguariense* had the most important contraction (32.04 %) followed by *Inga vera* (25.41 %) and *Muellera campestris* (20.36 %). Reduction in vessel diameter after carbonization is related to anatomical features, such as the wall thickness of fibers and disposition of axial parenchyma cells, as well as processing conditions such as heating rate. These changes were also reported in other species, such as four Myrtaceae

**Figure 4.** Images of *Muellera campestris* wood (A, B) and charcoal (C, D). SEM images of charcoal (E-H). (A, C) Transversal section, (B, D) tangential section, (E) transversal section, arrow indicates the axial parenchyma; (F) tangential section, arrow indicates intervessel pits and crystals in parenchyma cells; (G, H) radial section, arrow indicates simple perforate plate.

Imágenes de la madera (A, B) y carbón (C, D) de *Muellera campestris*. MEB imágenes de lo carbón (E-H). (A, C) Sección transversal; (B, D) sección tangencial; (E) sección transversal, la flecha indica el parénquima axial; (F) sección tangencial, la flecha indica punteaduras intervasculares y cristales en las células del parénquima axial; (G, H) sección radial, la flecha indica placa de perforación simples.
Table 2. Mean values and standard deviation of tangential diameter and vessel density of studied species.

| Species                  | Material | Near Bark | Intermediate | Near Pith |
|--------------------------|----------|-----------|--------------|-----------|
|                          |          | Vessel diameter (µm) |              |           |
|                          |          |              |              | Control   |
| Inga vera*               | Wood     | 139.88 Aa (21.91) | 136.38 Aa (25.26) | 109.17 Ab (31.92) |
|                          | Charcoal | 106.24 Ba (25.49) | 96.44 Bb (28.30) | 84.18 Bc (28.96) |
| Machaerium paraguariense| Wood     | 119.82 Aa (23.18) | 103.04 Aa (18.34) | 97.85 Ab (20.69) |
|                          | Charcoal | 81.52 Ba (22.91) | 69.05 Bb (17.72) | 67.34 Bb (17.55) |
| Muellera campestris*     | Wood     | 118.27 Aa (33.21) | 105.33 Ab (23.26) | 94.73 Ac (15.87) |
|                          | Charcoal | 83.90 Bb (25.53) | 90.15 Ba (23.28) | 78.05 Bb (20.95) |

|                          | Vessel density (n/mm²) |              |              |           |
|--------------------------|                        |              |              |           |
| Inga vera                | Wood                   | 6.00 Ab (3.42) | 5.77 Ab (3.01) | 7.58 Aa (4.35) |
|                          | Charcoal               | 5.76 Aa (2.62) | 5.46 Aa (2.32) | 6.49 Aa (4.49) |
| Machaerium paraguariense| Wood                   | 4.18 Bb (1.69) | 5.53 Ba (2.29) | 5.76 Ba (1.85) |
|                          | Charcoal               | 7.64 Aa (2.70) | 7.89 Aa (2.13) | 8.18 Aa (2.38) |
| Muellera campestris*     | Wood                   | 8.42 Ab (3.51) | 7.61 Ab (2.71) | 10.38 Ba (3.55) |
|                          | Charcoal               | 7.49 Ab (2.85) | 7.84 Ab (2.59) | 12.22 Aa (5.08) |

*Species where interaction between material and position was not significant at 95 % probability. For each species, equal letters in means do not present statistical differences by the Scott-Knott test at 95 % probability. Capital letters in column refer to changes after carbonization and small letters are related to radial position in disk (near bark, intermediate, near pith).

species (Stange et al. 2018), in angelim species (Muñiz et al. 2016) and other species from the Fabaceae family (Nisgoski et al. 2012). Another factor that can influence vessel diameter is the possible change in circular shape of cells after carbonization (Gasson et al. 2017).

**Vessel density.** Decrease in vessel density was observed in wood from the regions near the pith towards the bark, with statistical significance from the intermediate to near pith region, except in *Machaerium paraguariense*, which had differences between the regions near the bark towards intermediate (33.3 %). In *Inga vera* wood, mean vessel density was 6, similar to the numbers reported by Richter and Dallwitz (2000) and Vieira et al. (2019). In wood from *Machaerium paraguariense*, the mean value observed was comparable to that reported by Vieira et al. (2019), while for *Muellera campestris* it was similar to that reported by Marchiori et al. (2009), Richter and Dallwitz (2000) and Vieira (2017).

In charcoal, changes were only observed in *Muellera campestris*, with decrease in radial direction (33.3 % from near pith towards intermediate and 41.7 % from near pith towards near bark). In other species, there were no differences based on radial position. In a study with Myrtaceae species, Stange et al. (2018) also verified that changes in vessel density were not linear regarding position and occurred in accordance with species. Carbonization had little influence on vessel density. Samples from all positions of *Machaerium paraguariense* and the near pith region of *Muellera campestris* had significant increase. The highest change was near the bark for *Machaerium paraguariense* (82.78 %), although considerable values were noted in the other locations (42.68 % in intermediate and 42.01 % near the pith region). This parameter seems to be influenced by species intrinsic characteristics, since Stange et al. (2018) observed increases in vessel density in all positions after carbonization of four Myrtaceae species.

Regarding mean vessel density, large divergence was observed among the species. A reduction of 7.92 % occurred in *Inga vera* after carbonization, and increase of 10.60 % in *Muellera campestris* and 32.76 % in *Machaerium paraguariense* were detected. Stange et al. (2018) observed values much higher than for the species studied here with samples of *Eugenia pyriformis* Cambess (92.3 %), *Campomanesia xanthocarpa* (Mart.) O. Berg (60.3 %) and *Myrcia retorta* Cambess (50.7 %). Likewise, the influence of species characteristics on changes in vessel density after carbonization has also been reported in literature, such as for Anacardiaceae (Gonçalves and Scheel-Ybert 2016) and Fabaceae species (Muñiz et al. 2016). The release of volatile matter and formation of some cracks and voids can also interfere in vessel density (Assis et al. 2016).
Table 3. Mean values and standard deviation of ray dimensions and frequency of studied species.

| Species                  | Material | Near bark | Intermediate | Near pith |
|--------------------------|----------|-----------|--------------|-----------|
|                          |          | Ray height (µm) |              |           |
| Inga vera                | Wood     | 189.14 Aa (67.94) | 190.39 Aa (77.81) | 163.39 Ab (68.56) |
|                          | Charcoal | 165.59 Ba (60.18) | 168.22 Ba (55.47) | 155.26 Aa (78.27) |
| Machaerium paraguariense| Wood     | 107.41 Aa (21.22) | 109.63 Aa (28.49) | 108.86 Aa (21.42) |
|                          | Charcoal | 112.05 Aa (18.31) | 111.65 Aa (16.99) | 110.71 Aa (28.75) |
| Muellera campestris      | Wood     | 145.84 Aa (33.82) | 137.60 Aa (37.88) | 139.51 Aa (29.42) |
|                          | Charcoal | 127.58 Ba (27.96) | 116.28 Bb (22.66) | 118.15 Ba (18.19) |

| Species                  | Material | Ray width (µm) |              |           |
|--------------------------|----------|---------------|--------------|-----------|
| Inga vera*               | Wood     | 20.08 Aa (6.81) | 20.32 Aa (8.46) | 15.54 Bb (5.14) |
|                          | Charcoal | 22.81 Aa (9.05) | 18.95 Ab (6.32) | 23.02 Aa (16.93) |
| Machaerium paraguariense| Wood     | 16.33 Ba (4.73) | 14.13 Bb (5.18) | 15.77 Ba (5.73) |
|                          | Charcoal | 25.45 Aa (9.16) | 24.73 Aa (6.04) | 25.28 Aa (7.98) |
| Muellera campestris      | Wood     | 30.17 Ba (11.31) | 26.69 Ab (8.07) | 24.21 Ab (9.69) |
|                          | Charcoal | 33.23 Aa (6.27) | 28.74 Ab (6.32) | 25.90 Ac (7.07) |

| Species                  | Material | Ray frequency (n/mm) |              |           |
|--------------------------|----------|----------------------|--------------|-----------|
| Inga vera                | Wood     | 8.40 Ba (2.07)       | 8.46 Ba (1.93) | 8.35 Ba (2.13) |
|                          | Charcoal | 10.42 Aa (1.91)      | 10.62 Aa (2.07) | 10.31 Aa (1.76) |
| Machaerium paraguariense| Wood     | 7.54 Ba (1.24)       | 7.33 Ba (1.18) | 6.90 Bb (1.16) |
|                          | Charcoal | 9.20 Aa (1.27)       | 9.36 Aa (1.45) | 9.46 Aa (1.37) |
| Muellera campestris      | Wood     | 8.88 Ba (1.87)       | 8.64 Ba (2.01) | 8.84 Ba (1.61) |
|                          | Charcoal | 10.68 Ab (1.88)      | 10.82 Ab (1.70) | 12.54 Aa (1.93) |

*Species where interaction between material and position was not significant at 95 % probability. For each species, equal letters in means do not present statistical differences by the Scott-Knott test at 95 % probability. Capital letters in columns refer to changes after carbonization and small letters are related to radial position in disk (near bark, intermediate, near pith).

Ray height. In wood, no linear pattern was observed in all three species and the variation among positions was from 0.65 % to 5.99 %. The highest discrepancy (14.18 %) was from intermediate towards the near pith of Inga vera. The same species had mean ray height of 181 µm, lower than the 500 µm observed by Richter and Dallwitz (2000). Moreover, in Machaerium paraguariense, mean ray height was 109 µm, lower than the values observed by Vieira et al. (2019). For Muellera campestris wood, the mean value was 141 µm, similar to those obtained by Marchiori et al. (2009) in wood from Rio Grande do Sul, and smaller than those observed by Richter and Dallwitz (2000).

In charcoal, reduction in ray height occurred from the near pith towards the intermediate region in Muellera campestris. In other species, there was no influence of position on ray height. Carbonization did not statistically influence ray height in Machaerium paraguariense. For Muellera campestris, all positions presented reduction in ray height from wood to charcoal (12.52 % near bark, 15.49 % intermediate and 15.31 % near pith), probably as a result of the higher quantity of parenchyma cells in comparison to the other two species. In Inga vera, only in the near pith region were there no substantial changes in dimension, while for other positions, reductions of 12.45 % in the near bark position and 11.64 % for intermediate region were observed. According to Muñiz et al. (2012), rays are laterally connected to fibers, which limit rays movement, since the contraction of the fibers in the axial direction is small during the carbonization process. On the other hand, Stange et al. (2018) described reduction of ray height in Campomanesia xanthocarpa and Eugenia pyriformis and increase in Myrcia retorta species in all radial positions.

With regard to mean ray height values by species, a contrast was observed after carbonization, with reduction of 9.69 % in Inga vera and 14.44 % in Muellera campestris, and with increase of 2.62 % in Machaerium pa-
Ray width. For ray width, a difference was observed in wood from near pith towards near bark, nevertheless there was no pattern in all species. Significant increase was observed from near pith towards the bark region in *Inga vera* (23.52 %). The same pattern was also noted from near pith to intermediate (9.29 %) and to near bark (11.54 %) region in *Muellera campestris*. In *Machaerium paraguariense*, the intermediate region had thinner rays than those of the near pith (10.40 %) and near bark regions (13.47 %). Stange *et al.* (2018) also observed divergence in this characteristic in the radial position of Myrtaceae species, with predomiance of thinner rays in the near pith region.

In charcoal, there was no difference in ray width concerning sample position in *Machaerium paraguariense*. Increase was observed from near pith towards near bark in *Muellera campestris* (22.06 %). In *Inga vera* charcoal, ray width was lower in the intermediate position when compared to the other regions (16.92 % near bark and 17.68 % near pith). After carbonization, there was significant increase in ray width in all samples of *Machaerium paraguariense*, with variation of 35.83 % for near bark, 42.86 % in intermediate wood and 37.62 % for near pith. Correspondingly, the same behavior was observed for near pith (32.49 %) and near bark (11.97 %) in *Inga vera* and near bark in *Muellera campestris* (10.14 %). According to Stange *et al.* (2018), these results may be related to ruptures that occur due to the expansion of cell walls.

Regarding mean ray width values, increase was observed in all species, varying from 8.27 % in *Muellera campestris* to 38.77 % in *Machaerium paraguariense*, and intermediate in *Inga vera*, with 17.07 % increase. These differences can be the result of multiserate and uniseriate ray percentage. Literature reports divergent behavior of species related to chemical changes in substances stored in parenchyma cells: decrease in ray width in the Fabaceae family was reported in *Enterolobium schomburgkii* (Muñiz *et al.* 2012a), *Dipteryx odorata* (Nisgoski *et al.* 2012) and *Parkia pendula* (Muñiz *et al.* 2016); while increase in ray width was observed in *Cedrelinga catenaeformis* (Muñiz *et al.* 2012a), *Hymenolobium petraeum* and *Vatairea paraensis* (Muñiz *et al.* 2016). Moreover, increase in ray width was observed in Cerrado (savanna) species (Gonçalves *et al.* 2012) and Myrtaceae species (Stange *et al.* 2018).

Ray frequency. Ray frequency in wood, in general, was not influenced by radial position in the trunk. Only the near pith region of *Machaerium paraguariense* had a value lower (12.5 %) than that presented by the other regions. In *Inga vera* wood, mean ray frequency was 8 / mm, in the range reported by Richter and Dallwitz (2000) and Vieira *et al.* (2019). In *Machaerium paraguariense*, mean ray frequency was 7 / mm, higher than what was observed by Vieira *et al.* (2019). For *Muellera campestris*, 9 rays / mm were observed, lower than what was reported by Marchiori *et al.* (2009), who found mean ray frequency of 12 (10-15) in wood from Rio Grande do Sul, and similar to the value obtained by Vieira (2017).

In charcoal, ray frequency showed reduction of 15.38 % from near pith towards the intermediate/near bark region in *Muellera campestris*, and 9.09 % from intermediate to near pith and near bark of *Inga vera*. In all species and positions, carbonization affected ray frequency. Regarding mean values, ray frequency increased by similar values: 24.35 % in *Inga vera*, 29.12 % in *Muellera campestris* and 28.94 % in *Machaerium paraguariense*. In other species of the Fabaceae family, Muñiz *et al.* (2016) verified significant increase in ray frequency in *Diplotropis purpurea*, *Hymenolobium petraeum* and *Vatairea guianensis*. Different behavior was observed by Ávila *et al.* (2017) regarding mass loss and cell contraction after carbonization, attributed to the influence of intra-specific and ecological characteristics.

CONCLUSIONS

The changes in cell dimensions caused by the carbonization process were confirmed. In all species, the vessel diameter decreased; vessel density decreased in *Inga vera*, though it increased in the other species; ray height decreased in *Inga vera* and *Muellera campestris*, however increased in *Machaerium paraguariense*; and ray width and frequency increased in all species.

Despite the alterations resulting from carbonization, cell arrangement and type were not influenced, therefore the inclusion of these species in a database would be effective to support efforts to control deforestation in the south of Brazil. Charcoal anatomy can be applied for species characterization, and in comparison, with reference data, can support illegal logging control.

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