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A CONTRIBUTION TO THE IDENTIFICATION OF CHARCOAL ORIGIN IN BRAZIL I – ANATOMICAL CHARACTERIZATION OF CORYMBIA AND EUCALYPTUS

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ABSTRACT

Charcoal is one of the main forestry products and Brazil is the world's largest producer. Its production from native species is estimated at 30-35% of total output. One of the major problems of the iron and steel industry is charcoal consumption, especially in terms of environmental and social aspects. Therefore, the use of reforestation species must be increased. Considering most of the energy forests in Brazil are planted with eucalyptus, the present work aims to contribute to the identification of charcoal origin through anatomical analysis of *Eucalyptus* and *Corymbia*. The wood samples were carbonized in a muffle furnace during 7h to a maximum of 450ºC. Anatomical analysis was done according to IAWA Committee. We found few works with charcoal anatomy and the species analyzed were not characterized. The results on charcoal are very close to previous studies of wood anatomy. But, we recommend the comparison of materials of similar features, enhancing the visual acuity, particularities of each material and modifications that might happen. We believe that this analysis is an accurate tool to identify the source of charcoal and can help to guarantee the sustainability of the charcoal supply chain.

Keywords: Anatomy, charcoal, eucalyptus, sustainability.

INTRODUCTION

Sustainability has been a popular subject in recent years, attracting attention from researchers, environmentalists and leaders, including at important global events such as "Rio +20". Sustainable development can be defined as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). The application of this concept in forestry should consider a close association between nature conservation and forest management based on technology as well as economic and social considerations.

Charcoal is one of the main forestry products and Brazil is the world's largest producer (FAO 2012). This biofuel is very important in the national energy mix and almost 90% of production goes to the iron and steel industry (Brasil 2012a). When charcoal is produced from planted forests, carbon credits are generated along with income in a politically correct way (ABRAF 2012). Despite this, the charcoal supply chain still has negative features, e.g.: (i) unspecialized workers, including children, often working under slave-like conditions; and (ii) illegal cutting of native forests (Carneiro 2008, IOS 2011a, IOS2011b).

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The production of charcoal from native species in Brazil is estimated to account for 30-35% of total output (IBGE 2010, ABRAF 2012). Considering the size of the country and additionally the difficulty of effective control of deforestation, we believe that the percentage of charcoal produced from illegally cut native species is even higher. In fact, one of the major problems of the iron and steel industry is charcoal production. In practice, there is no selection on native species for charcoal production, practically all the species goes to the carbonization oven. It is problematic in terms of environmental and social aspects, so the use of reforestation species must be increased (IOS 2011b, Brasil 2012b).

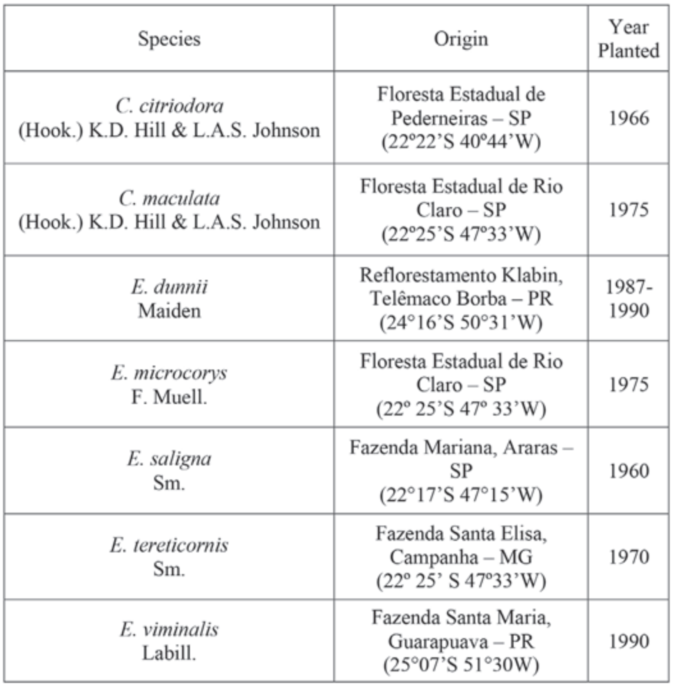
Brazil had 4,87 million hectares of planted eucalypts forests in 2011, using 18,4% of it to produce charcoal for the steel sector (ABRAF 2012). In general, the term “eucalyptus” is used to refer to about 900 species distributed in two major lineages: (i) *Angophora and Corymbia*; (ii) *Eucalyptus “sensu stricto”* – with the subgenera *Eudesmia, Symphyomyrtus and Monocalyptus*; *Eucalyptus* and *Corymbia* are the most abundant genera, having over 700 and about 130 species, respectively (Hill and Johnson 1995, Rozefelds 1996, Euclid 2006).

The present work aims to contribute for the control of charcoal production from native forests in Brazil through anatomical characterization of charcoal made from species of *Eucalyptus* and *Corymbia*. It is justified by: (i) the need to increase the use of planted species for charcoal production; (ii) the fact that most energy forests in Brazil are planted with eucalyptus; (iii) the importance of controlling the illegal production of charcoal from native species.

MATERIAL AND METHODS

Wood samples of *Corymbia* spp and *Eucalyptus* spp lumber were donated by Prema - a forestry firm in the city of Rio Claro, São Paulo state. Table 1 shows the data on the species studied.

Table 1. Data on the species.



Species	Origin	Year Planted
C. citriodora (Hook.) K.D. Hill & L.A.S. Johnson	Floresta Estadual de Pederneiras – SP (22º22’S 40º44’W)	1966
C. maculata (Hook.) K.D. Hill & L.A.S. Johnson	Floresta Estadual de Rio Claro – SP (22º25’S 47º33’W)	1975
E. dunnii Maiden	Reflorestamento Klabin, Telêmaco Borba – PR (24°16’S 50°31’W)	1987-1990
E. microcorys F. Muell.	Floresta Estadual de Rio Claro – SP (22º 25’S 47º 33’W)	1975
E. saligna Sm.	Fazenda Mariana, Araras – SP (22°17’S 47°15’W)	1960
E. tereticornis Sm.	Fazenda Santa Elisa, Campanha – MG (22º 25’ S 47º33’W)	1970
E. viminalis Labill.	Fazenda Santa Maria, Guarapuava – PR (25°07’S 51°30W)	1990

For the carbonization, we took random parts of the lumbers and cut samples of ~3-5x10-6 m³. Lumber was randomly sampled from the trees simulating the real conditions of charcoal identification in the field. The samples were wrapped in aluminum foil and carbonized in a muffle furnace (Gonçalves *et al.* 2012). The carbonization process lasted 5 h, with a final temperature of 450 °C and heating rate of 1,66 °C/min; the samples remained at the final temperature for 2 h (Muñiz *et al.* 2012). The resulting charcoal samples were manually broken and analyzed with a Zeiss Discovery V12 stereomicroscope. Images of the charcoal samples were processed by the Axio Vision Release 4.7 software and measurements of anatomical features were made using them. For the scanning electron microscope (SEM) micrographs the charcoals were fixed with a conductive carbon double-side tape into traditional SEM stubs. The images were obtained directly from the material, without coating, in a Hitachi TM-1000 tabletop microscope.

The descriptions and measurements of wood and charcoal anatomy followed the IAWA Committee (1989) recommendations. Tangential vessel diameter (µm) was calculated from 25 measurements; 10 measurements were taken for vessel frequency (vessels /mm²), ray frequency (rays/mm), ray width (µm), and ray height (µm). The results are presented as mean values (minimum-maximum), standard deviation and unit.

The charcoals micrographs of transverse section (a), longitudinal tangential (b) and radial (c) planes follow the descriptions. We use arrows to show some ruptures.

RESULTS

The anatomical characterization is presented for each species in the sequence. All the pictures are after the descriptions, they are close to each other to facilitate the comparison between the species. The anatomical characteristics of main importance are summarized in table 2.

Plate 1: *Corymbia citriodora* (Hook.) K.D. Hill & L.A.S. Johnson (Figures 1a, 1b, 1c)
Growth rings: present, demarcated by thick-walled and radially flattened fibers.

Vessels: wood diffuse-porous; diagonal pattern; solitary and multiples; 133 (83-212) 29 µm; 12 (8-19) 4 vessels/mm²; tyloses present; simple perforation plates; alternate intervessel pits, vestured.

Axial parenchyma: mostly vasicentric, confluent, diffuse and diffuse-in-aggregates, tendency to form lines, few lozenge-aliform; 4-8 cells per strand.

Rays: 1-2-seriate; 23 (11-38) 8 µm width; 193 (120-317) 60 µm height; 12 (7-17) 2 rays/mm; all cells procumbent.

Fibers: non-septate; very thin to thick-walled.

Mineral inclusions: prismatic crystals in chambered axial parenchyma cells and fibers.

Ruptures: present in rays.

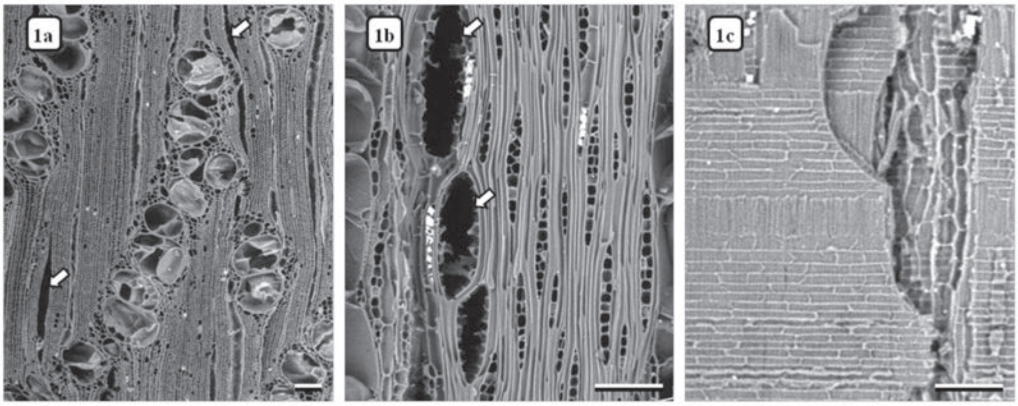


Figure 1. Plate 1. *Corymbia citriodora.* Charcoal micrographs. Arrows show the ruptures. Sections (a) Transverse, (b) Tangential Longitudinal, (c) Radial Longitudinal. Bars: 100µm.

Plate 2: *Corymbia maculata* (Hook.) K.D. Hill & L.A.S. Johnson (Figures 2a, 2b, 2c)
Growth rings: present, demarcated by thick-walled and radially flattened fibers.

Vessels: wood diffuse-porous; diagonal pattern; solitary and multiples; 149 (102-202) 25 µm; 11 (8-16) 2 vessels/mm²; tyloses present; simple perforation plates; alternate intervessel pits, vestured.

Axial parenchyma: few distinct, vasicentric, diffuse, few confluent and lozenge-aliform; 3-7 cells per strand.

Rays: mostly 1-seriate, few locally 2-seriate; 15 (12-18) 2 µm width; 169 (100-237) 47 µm height; 14 (8-17) 2 rays/mm; all cells procumbent, or with body cells procumbent with 1 to 2 rows of upright and square marginal cells.

Fibers: non-septate; thin to very thick-walled.

Mineral inclusions: prismatic crystals in chambered axial parenchyma cells.

Ruptures: present in rays and in fibers; especially in heartwood.

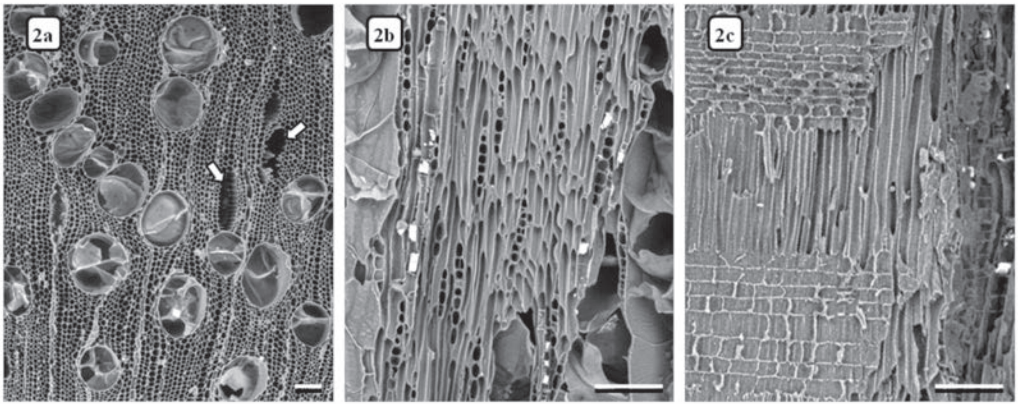


Figure 2. Plate 2. *Corymbia maculata.* Charcoal micrographs. Arrows show the ruptures. Sections (a) Transverse, (b) Tangential Longitudinal, (c) Radial Longitudinal. Bars: 100µm.

Plate 3: *Eucalyptus dunnii* Maiden (Figures 3a, 3b, 3c)

Growth rings: present, demarcated by thick-walled and radially flattened fibers.

Vessels: wood diffuse-porous; diagonal pattern; exclusively solitary (90% or more); 112 (70-173) 23 µm; 11 (8-20) 9 vessels/mm²; tyloses present; simple perforation plates; alternate intervessel pits, vestured.

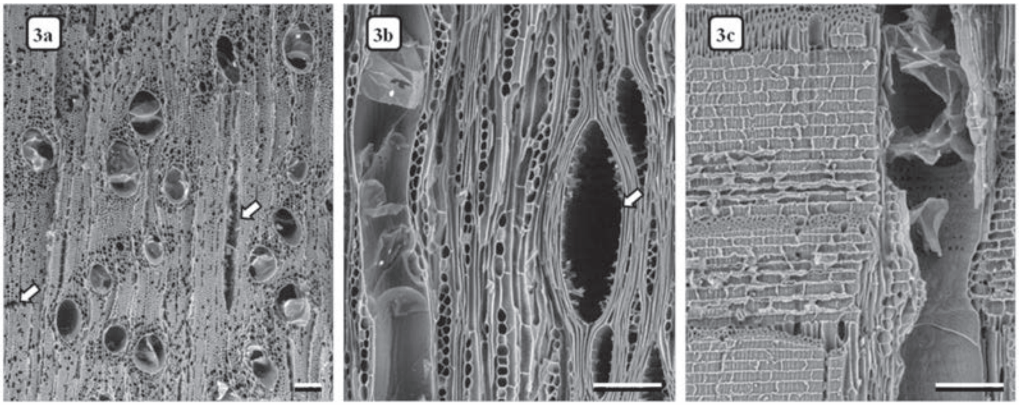
Axial parenchyma: abundant, vasicentric, confluent, diffuse and diffuse-in-aggregates; 2-7 cells per strand.

Rays: 1-2-seriate, mostly 2-seriate; 15 (10-23) 4 µm width; 173 (105-311) 59 µm height; 14 (10-18) 2 rays/mm; all cells procumbent.

Fibers: non-septate; thin to very thick-walled.

Mineral inclusions: few prismatic crystals in tyloses and in chambered axial parenchyma cells.

Ruptures: present in rays and in few axial parenchyma cells; especially in sapwood.



Figures 3. Plate 3. *Eucalyptus dunnii.* Charcoal micrographs. Arrows show the ruptures. Sections (a) Transverse, (b) Tangential Longitudinal, (c) Radial Longitudinal. Bars: 100µm.

Plate 4: *Eucalyptus microcorys* F. Muell. (Figures 4a, 4b, 4c)

Growth rings: present, demarcated by thick-walled and radially flattened fibers.

Vessels: wood diffuse-porous; diagonal and radial pattern; solitary and multiples; 121 (119-168) 26 µm; 17 (11-22) 15 vessels/mm²; rare tyloses; simple perforation plates; alternate intervessel pits, vestured.

Axial parenchyma: vasicentric, confluent, lozenge-aliform, diffuse and diffuse-in-aggregates; 4-8 cells per strand.

Rays: 1-2-seriate, mostly 1-seriate; 14 (9-18) 3 µm width; 208 (147-275) 47 µm height; 16 (11-20) 2 rays/mm; all cells procumbent.

Fibers: non-septate; thick to very thick-walled.

Mineral inclusions: prismatic crystals in chambered axial parenchyma cells, more than one crystal per cell.

Ruptures: absent.

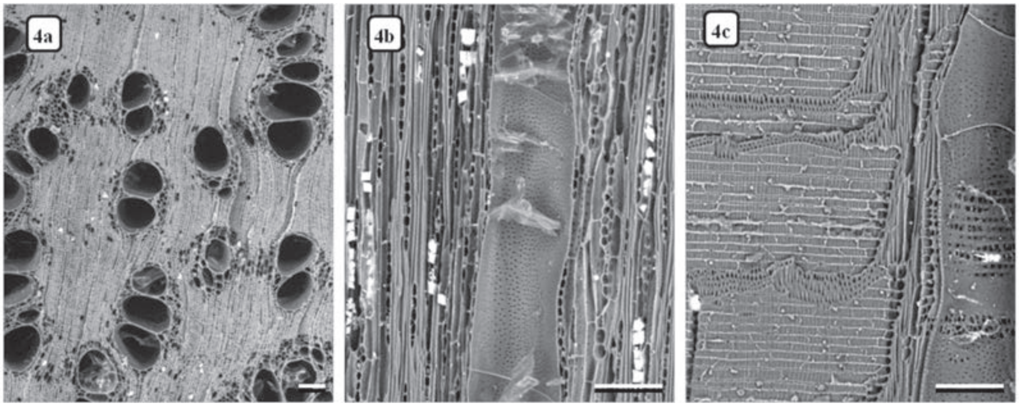


Figure 4. Plate 4. Eucalyptus microcorys. Charcoal micrographs.
Sections (a) Transverse, (b) Tangential Longitudinal, (c) Radial Longitudinal. Bars: 100µm.

Plate 5: *Eucalyptus saligna* Sm. (Figures 5a, 5b, 5c)

Growth rings: present, demarcated by thick-walled and radially flattened fibers.

Vessels: wood diffuse-porous; diagonal pattern, fewer distinct in microscopy; exclusively solitary (90% or more); 161 (110-212) 30 µm; 11 (5-14) 7 vessels/mm²; tyloses present; simple perforation plates; alternate intervessel pits, vestured.

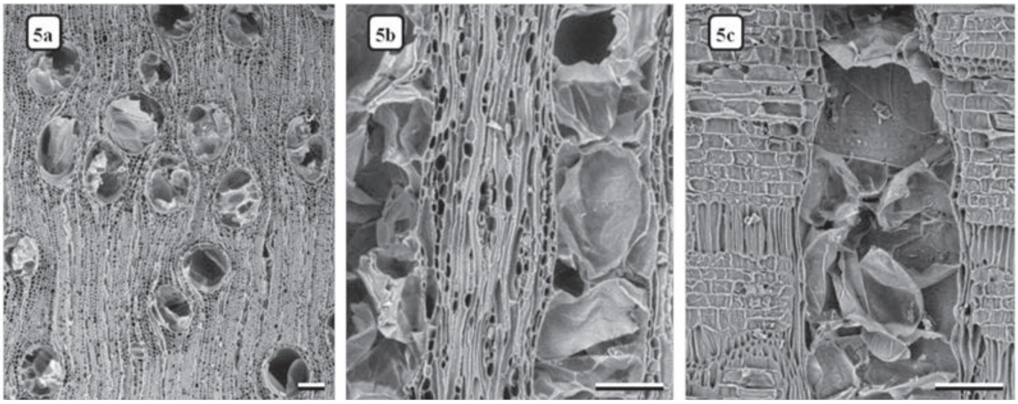
Axial parenchyma: mostly vasicentric, but also confluent, diffuse and diffuse-in-aggregates, few lozenge-aliform; 3-8 cells per strand.

Rays: 1-2-seriate; 33 (18-46) µm width; 172 (130-224) µm height; 13 (9-17) 2 rays/mm; all cells procumbent.

Fibers: non-septate; thick to very thick-walled.

Mineral inclusions: rare prismatic crystals.

Ruptures: absent.



Figures 5. Plate 5. *Eucalyptus saligna.* Charcoal micrographs.
Sections (a) Transverse, (b) Tangential Longitudinal, (c) Radial Longitudinal. Bars: 100µm.

Plate 6: *Eucalyptus tereticornis* Sm. (Figures 6a, 6b, 6c)

Growth rings: present, demarcated by thick-walled and radially flattened fibers.

Vessels: wood diffuse-porous; diagonal pattern; exclusively solitary (90% or more); 166 (124-218) 27 µm; 9 (5-13) 2 vessels/mm²; tyloses present; simple perforation plates; alternate intervessel pits, vestured.

Axial parenchyma: vasicentric, confluent, diffuse and diffuse-in-aggregates, few lozenge-aliform; 4-8 cells per strand.

Rays: 1-3-seriate, mostly 2-seriate; 34 (23-44) 7 µm width; 176 (132-224) 35 µm height; 12 (6-15) 2 rays/mm; all cells procumbent.

Fibers: non-septate; thick to very thick-walled.

Mineral inclusions: rare prismatic crystals.

Ruptures: rare in rays.

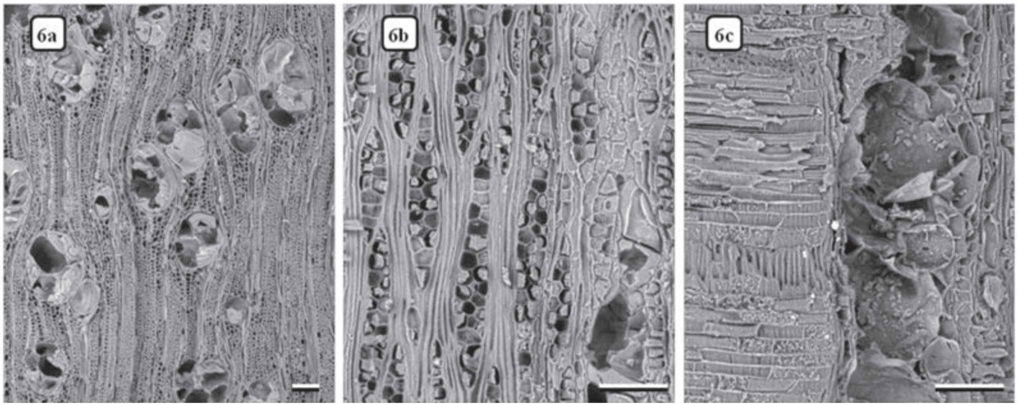


Figure 6. Plate 6. Eucalyptus tereticornis. Charcoal micrographs.
Sections (a) Transverse, (b) Tangential Longitudinal, (c) Radial Longitudinal.Bars: 100µm.

Plate 7: *Eucalyptus viminalis* Labill. (Figures 7a, 7b, 7c)

Growth rings: present, demarcated by thick-walled and radially flattened fibers.

Vessels: wood diffuse-porous; diagonal pattern; exclusively solitary (90% or more); 147 (97-187) 20 µm; 10 (5-13) 2 vessels/mm²; tyloses present; simple perforation plates; alternate intervessel pits, vestured.

Axial parenchyma: few celled, vasicentric, confluent, diffuse and diffuse-in-aggregates and few lozenge-aliform; 3-7 cells per strand.

Rays: 1-seriate; 19 (16-21) 2 µm width; 213 (121-312) 60 µm height; 12 (7-17) 4 rays/mm; all cells procumbent.

Fibers: non-septate; thin to thick-walled.

Mineral inclusions: rare prismatic crystals.

Ruptures: present in rays.

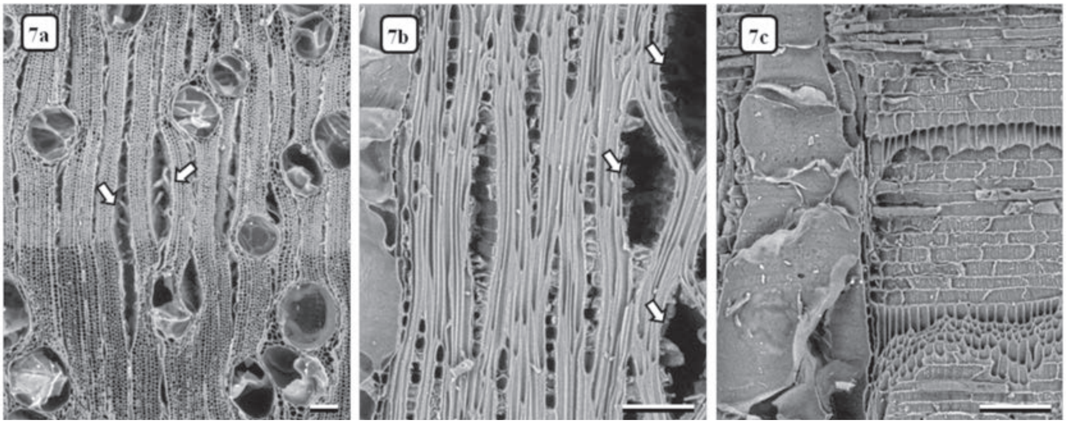
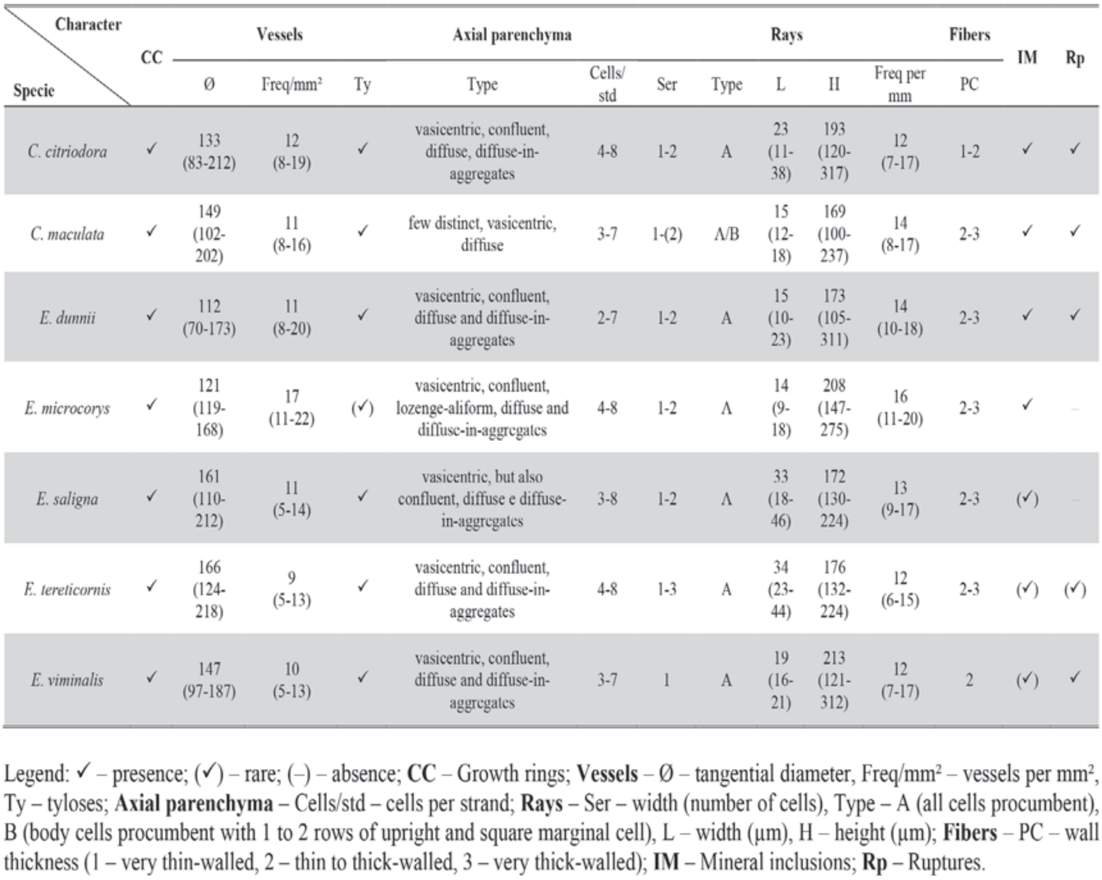


Figure 7. Plate 7. *Eucalyptus viminalis.* Charcoal micrographs.
Arrows show the ruptures. Sections (a) Transverse, (b) Tangential Longitudinal, (c) Radial Longitudinal. Bars: 100µm.

Table 2. Anatomical characters of the species analyzed.



Character / Specie	CC	Vessels			Axial parenchyma		Rays				Fibers		IM	Rp
		Ø	Freq/mm²	Ty	Type	Cells/std	Ser	Type	L	H	Freq per mm	PC		
C. citriodora	✓	133 (83-212)	12 (8-19)	✓	vasicentric, confluent, diffuse, diffuse-in-aggregates	4-8	1-2	A	23 (11-38)	193 (120-317)	12 (7-17)	1-2	✓	✓
C. maculata	✓	149 (102-202)	11 (8-16)	✓	few distinct, vasicentric, diffuse	3-7	1-(2)	A/B	15 (12-18)	169 (100-237)	14 (8-17)	2-3	✓	✓
E. dunnii	✓	112 (70-173)	11 (8-20)	✓	vasicentric, confluent, diffuse and diffuse-in-aggregates	2-7	1-2	A	15 (10-23)	173 (105-311)	14 (10-18)	2-3	✓	✓
E. microcorys	✓	121 (119-168)	17 (11-22)	(✓)	vasicentric, confluent, lozenge-aliform, diffuse and diffuse-in-aggregates	4-8	1-2	A	14 (9-18)	208 (147-275)	16 (11-20)	2-3	✓	–
E. saligna	✓	161 (110-212)	11 (5-14)	✓	vasicentric, but also confluent, diffuse e diffuse-in-aggregates	3-8	1-2	A	33 (18-46)	172 (130-224)	13 (9-17)	2-3	(✓)	–
E. tereticornis	✓	166 (124-218)	9 (5-13)	✓	vasicentric, confluent, diffuse and diffuse-in-aggregates	4-8	1-3	A	34 (23-44)	176 (132-224)	12 (6-15)	2-3	(✓)	(✓)
E. viminalis	✓	147 (97-187)	10 (5-13)	✓	vasicentric, confluent, diffuse and diffuse-in-aggregates	3-7	1	A	19 (16-21)	213 (121-312)	12 (7-17)	2	(✓)	✓

Legend: ✓ – presence; (✓) – rare; (–) – absence; **CC** – Growth rings; **Vessels** – Ø – tangential diameter, Freq/mm² – vessels per mm², Ty – tyloses; **Axial parenchyma** – Cells/std – cells per strand; **Rays** – Ser – width (number of cells), Type – A (all cells procumbent), B (body cells procumbent with 1 to 2 rows of upright and square marginal cell), L – width (μm), H – height (μm); **Fibers** – PC – wall thickness (1 – very thin-walled, 2 – thin to thick-walled, 3 – very thick-walled); **IM** – Mineral inclusions; **Rp** – Ruptures.

DISCUSSION

We could not find previous works reporting the anatomical characterization of charcoal made from the species analyzed in this work. The few works identifying charcoal samples from Eucalyptus spp have a special focus on the paleoenvironment (e.g. Hopkins *et al.* 1990).

Charcoal structure normally retains all the qualitative wood anatomy features. It presents few changes, especially in quantitative values (Prior and Gasson 1993, Gonçalves 2010). In a study of the effect of carbonization on wood structure of five species from the Brazilian cerrado, the quantitative changes found were: (i) reduction of tangential vessel diameter, (ii) increase of vessel frequency, and (iii) increase of ray frequency. But only the tangential vessel diameter differences were statistically significant, corroborating the strong basis for charcoal identification (Gonçalves *et al.* 2012).

The results of charcoal anatomy are very close to previous studies of wood anatomy in both qualitative and quantitative features. We compared the other species using the specialized literature and the Inside Wood database. The main differences are: (i) growth ring boundaries indistinct or absent – *C. citriodora* (Dadswell 1972), *C. maculata* (Kribs 1968, Dadswell 1972), *E. microcorys* (Kribs 1968); (ii) vessels exclusively solitary – *E. microcorys* (Kribs 1968, Alfonso 1987); (iii) ray width exclusively 1-seriate – *E. saligna* (Alzate 2009); (iv) ray width 1 to 3 cells – *C. maculata* (Kribs 1968, Dadswell 1972), *E. viminalis* (Dadswell 1972, Ammon 2011). These differences are common within genera (Metcalfe and Chalk 1950, Carlquist 2001), and especially in the case of growth rings, they are also influenced by ecological factors, particularly water supply (Carlquist 2001, Schweingruber 2007). Although, we strongly recommend comparing materials of similar features, enhancing the visual acuity, highlighting particularities of each material and modifications that might happen (ruptures, e.g.)

Ruptures were present in rays of *C. citriodora, C. maculata, E. dunnii, E. tereticornis* and *E. viminalis.* There are also a few ruptures in axial parenchyma cells in *E. dunnii.* The analysis of *Quercus alba* L. revealed radial splits as the second most characteristic macroscopic feature in charcoal, similar in appearance to honeycombed wood (McGinnes et al. 1971). In *Q. variabilis* BL. charcoal prepared at different temperatures, the honeycombed appearance became more severe with increasing charring temperature. One of the explanations for this behavior is that an increasing charring temperature leads to a decreases cell wall thickness, volumetric shrinkage and possible ruptures. This occurred especially in multiseriate rays (Kim and Hanna 2006). The multiseriate rays in *Q. robur* also presented ruptures; they appeared “exploded” as if a sudden release of pressure had occurred through this region of relatively weak tissue (Braadbaart and Poole 2008). The same did not occur in *Pinus sylvestris*; the authors believe that it is probably due to the uniseriate rays (Braadbaart and Poole 2008). Our results demonstrate no difference between uniseriate and multiseriate rays, since the ruptures occurred in both cases. Samples of *Mimosa tenuiflora* and *M. ophthalmocentra* charcoal made at 400ºC and higher temperatures present fissures especially among the fibers; one speculation for this behaviour is the presence of crystals may influence this fissuring (Dias Leme *et al.* 2010). We found ruptures only in the fibers of *Corymbia maculata* and we cannot associate them with the presence of crystals. Most of the species ruptures occur mainly in rays. More studies and other correlations are necessary to understand why some charcoals present these ruptures. This is particularly important in charcoal identification because sometimes the sample can be so damaged that it is hard to identify the species.

CONCLUSIONS

There is a strong need to associate charcoal production with nature conservation and reduction of deforestation. The present work aims to contribute to control of charcoal production from native forests, by facilitating the identification of that made from eucalyptus. Considering the homogeneity of the wood anatomy of *Corymbia* and *Eucalyptus* we have not attempted to distinguish between them. We aimed to show different species of eucalypts and how to differentiate these Australian trees from native Brazilian species. We defend the sustainable use of charcoal. It might be not only from eucalyptus species but also from native species that are under sustainable forest management. We believe that charcoal anatomy is an effective tool to identify the origin of charcoal in Brazil and help to guarantee the sustainability of the charcoal supply chain.

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