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Evaluation of X-ray densitometry to identify tree-ring boundaries of two deciduous species from semi-arid forests in Brazil

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ABSTRACT

The presence of visible annual rings in semi-arid tropical trees may allow the application of dendrochronological methods. However, variation in water availability may cause the formation of narrow, irregular ill- or non-defined annual rings hindering the correct dating of tree-ring series. We aimed to evaluate X-ray densitometry as a method to identify tree rings of two deciduous tree species from the Caatinga forest, a semi-arid region in the northeast of Brazil, and compare with two other methods commonly used in dendrochronology, the sliding-stage micrometer and image analysis. Xylem was observed macro- and microscopically and wood anatomical features were assessed in *Aspidosperma pyrifolium* and *Poincianella pyramidalis* trees. In both species, tree-ring boundaries were identified considering intra-annual density patterns and wood anatomical features. No significant differences in tree-ring widths were found among methods. X-ray densitometry measurements showed a positive correlation with the measurements obtained with image analysis and sliding-stage micrometer in *A. pyrifolium* and *P. pyramidalis*, revealing the high reliability of the methods used. However, inter-correlation of tree-ring width series showed differences in the accuracy of crossdating across measuring methods. The maximum, mean and minimum density values were species-dependent, with mean wood density of *A. pyrifolium* lower than *P. pyramidalis*. Our results highlight X-ray densitometry as an important and complementary tool to identify tree-rings boundaries in semi-arid tree species, especially in *A. pyrifolium*. Along with other measuring methods, it may provide higher accuracy in dendrochronological studies in semi-arid or subtropical environments.

1. Introduction

The presence of annual rings in tropical trees may allow the application of dendrochronological methods to determine age, growth rates and climate-growth relationships (Stahle, 1999). In semi-arid tropical trees, tree-rings are visible when the cambial dormancy is induced by annually climatic events, such as drought (Worbes, 1995; Stahle, 1999; Cherubini et al., 2003; Wils et al., 2009). However, seasonal and monthly variation in water availability may cause the formation of indistinct, narrow and irregular rings with ill- or non-defined annual rings, hindering tree-ring dating and the construction of chronologies (Worbes 2002; Cherubini et al., 2003; Schöngart et al., 2006; Cherubini et al., 2013).

Crossdating, one of the basic principles in dendrochronology (Baillie, 1995; Stokes and Smiley, 1996), depends on the identification of similar growth patterns within and between trees in a population. The correct identification of tree-ring boundaries is fundamental to obtain accurate tree-ring width measurements and reliable growth patterns to cross-date. The explanatory power of chronologies and the quality of environmental reconstructions based on tree rings depend not only on crossdating but also in the accuracy of the measurements (Maxwell et al., 2011).

Standard dendrochronology approaches use direct methods to measure tree-ring widths, such as the sliding-stage micrometer (Pilcher, 1989; Nutto et al., 2012). A more recent method is the use

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of digital processing techniques where measurements are obtained in images scanned at high resolution with specific software to get the tree-ring width (Hietz, 2011; Maxwell et al., 2011). In both cases, intra-annual variations or false rings can hinder the accurate identification of annual growth and the process of crossdating becomes extensive, especially when working with long sequences or when trees form very narrow rings (Levanič, 2007).

X-ray densitometry is a method that can be useful to identify the boundaries of tree-rings and to build chronologies (Schweingruber et al., 1978; Ferreira and Tomazello Filho, 2009; Castro et al., 2014). This method shows tree growth characteristics by means of the intra-annual changes in wood density (Polge, 1970; Schweingruber et al., 1978; Tomazello Filho et al., 2008). Wood density values are measured in micron ranges, and the high resolution reveals the intra- and inter-ring growth variations, and thus enables the identification of the boundaries of tree-rings. This method has been used for the construction of chronologies and climatological studies in temperate regions (e.g. Wang et al., 2001; Koga and Zhang, 2002; Xiang et al., 2014; Klusek et al., 2015) highlighting its advantages in the identification of tree-ring boundaries and false rings. X-ray densitometry also provides the minimum, mean and maximum density values of the early- and latewood, which can be used to build chronologies of wood features (e.g. Ferreira and Tomazello Filho, 2009; Castro et al., 2014; De Mil et al., 2016; Klusek et al., 2015; Klusek and Grabner, 2016).

In the Brazilian semi-arid region named Caatinga, trees can display annual rings (Tsuchiya, 1990, 1995; Silva et al., 2009; Dias Leme and Gasson, 2012; Pagotto et al., 2015). In this region, the climate is characterized by a rainy and a dry season, with high spatial and temporal variability in rainfall distribution during the growing period which promotes the formation of both annual tree-rings and false rings (Pagotto et al., 2015). The aim of this study is assessing the X-ray densitometry as a powerful method to identify tree-rings boundaries for dendrochronological studies in semi-arid trees. The specific objectives were (i) identifying the radial-growth variation by measuring wood density of two Caatinga tree species, and (ii) comparing X-ray densitometry with direct measuring and image analysis methods for building tree-ring chronologies. We also discussed X-ray densitometry contribution to the development of dendrochronological techniques in semi-arid environments.

2. Material and methods

2.1. Study area

The study was conducted in Caatinga forest, located in the Sergipe state (09° 48′ 17” S, 37° 41′ 06” W), Brazil (Fig. 1). The climate is hot semi-arid (Bsh; Köppen, 1948), with 560 mm of mean annual precipitation and 25.6 °C of mean annual temperature. The precipitation presents a seasonal pattern, with a rainy season from April to July, and a dry season from August to December (Fig. 1). Climate from January to March is relatively dry (Magalhães, 2012), although high rainfall variation is observed among years due to the heavy downpours that may occur at any time during this period (Nobre, 2012; Fig. 1).

Caatinga vegetation in the studied area is hiperxerophytic deciduous shrubby-arboreal type, with tree size varying from 6 to 12 m height, consisting mainly in deciduous angiosperms. Due to the historical timber exploration and the establishment of rural settlements for agriculture and livestock grazing, the vegetation of the study area is a mosaic of habitats at different stages of regeneration, with few patches of well-preserved natural vegetation (Ribeiro and Mello, 2007; Maia, 2012). The site is also characterized by an intermittent flowing rivers and shallow soils, up to one meter deep, usually associated with rocky outcrops, high erodibility, wide range of fertility and the reduced water storage capacity (Silva and Silva, 1997; Embrapa, 2006). The soils are classified as leptosols and luvisols, with sandy texture and water percolation limitations (Embrapa, 2006).

2.2. Species characterization and sample collection

Aspidosperma pyrifolium Mart. (Apocynaceae) and *Poincianella pyramidallis* (Tul.) L. P. Queiroz (Leguminosae) are thornless, endemic deciduous tree species widely distributed in the Caatinga (Maia, 2012). They are abundant in several regions of the Caatinga and commercially valuable for timber and firewood across northeastern Brazil (Tsuchiya, 1990, 1995; Silva et al., 2009; Dias Leme and Gasson, 2012; Pagotto et al., 2015). They shed in the dry season and start to sprout at the beginning of the rainy season. Flowering occurs during the transition dry-rainy and also during the rainy season, followed by fructification (Tsuchiya, 1995; Maia, 2012).

These two species were chosen for dendrochronological studies because they present visible tree-rings. Nine *A. pyrifolium* and eight *P. pyramidalis* trees were randomly sampled from healthy, straight trunks with no visible imperfections in order to increase the reliability of the tree-ring width measurements. The samples were collected by either a non-destructive method, using a motorized Stihl BT45 wood-boring drill, with a single radial core being collected from each tree, or a destructive method, with a disk obtained at 1.30 m above the ground. In the latter method, two radii from the same disk were used for analysis. A total of 11 radii of *A. pyrifolium* (seven cores and two disks) and 12 radii of *P. pyramidalis* (four cores and four disks) and were analyzed.

2.3. Wood density profiles

In the disks, wood samples were cut with a handsaw in prism shapes (with 1 cm width, 1 cm high and variable length according to its size). These samples and the wood cores from the non-destructive method were glued onto wooden mounts with the fibers in the horizontal direction. The samples were cut in the transverse orientation with 2 mm of thickness using double circular saws. The thin wood samples were stored in a conditioning chamber (12 h, 20 °C, 50% relative humidity) until reaching 12% moisture content (Tomazello Filho et al., 2008). The samples were fitted in a metallic support, inserted in the shielded internal compartment of the QTRX-01X (Quintek Measurement Systems, EUA) and radial scanning carried out over the transversal surface of the wood by a collimated X-ray beam. The X-ray values that cross the sample were converted into apparent density (hereafter density) recorded every 80 μm, using QMS software (QMS, 1999). This technique dispenses the use of radiographic film and produces a permanent record of exact density values (Ferreira and Tomazallo Filho, 2009; Castro et al., 2014; Surdi et al., 2014). Using the wood densitometry profile, it is possible to calculate other parameters, such as mean, maximum, and minimum densities for every tree-ring (Polge, 1970; Schweingruber et al., 1978; Tomazello Filho et al., 2008).

2.4. Anatomical description

Macro and microscopic cross-sections of *A. pyrifolium* and *P. pyramidalis* were analyzed to aid in the interpretation of the wood density profiles. A standard methodology of wood anatomy, in accordance with Johansen (1940) and Franklin (1937), was followed to describe the microscopic features (see Supplementary Material S1).