Dendrochronologia 42 (2017) 42–50

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro

ORIGINAL ARTICLE

X-ray microdensitometry of wood: A review of existing principles and devices

Philippe Jacquin [a], Fleur Longuetaud [a], Jean-Michel Leban [b], Frédéric Mothe [a,*]

[a] LERFoB, UMR1092, INRA, AgroParisTech, F-54280 Champenoux, France
[b] INRA, IGN, LIF, F-54280 Champenoux, France

ARTICLE INFO

Article history:
Received 1 August 2016
Received in revised form 5 January 2017
Accepted 5 January 2017
Available online 27 January 2017

Keywords:
Radiography
Computed tomography
Density profile
Dendrochronology
Tree ring analysis

ABSTRACT

Wood microdensitometry is the analysis of radial variations of density at the annual or intra-annual growth ring level. Density is related to wood quality, biomass, carbon content, tree growth and climate. Wood microdensitometry is particularly used in dendrochronology and climatology studies. The present study focuses on X-ray based methods used in wood microdensitometry analyses and provides a review of the main available devices. An exhaustive review of 75 works published on this topic in 2014 and 2015 showed that film-based equipment is still commonly used. The three other most popular devices, SilviScan, Itrax and QTRS, are also based on X-ray radiography and deliver results with comparable accuracy, below 50 μm per pixel. X-ray tomography (CT) is still rarely used in wood densitometry. Medical CT scanners currently offer a lower accuracy (above 100 μm per pixel) that is insufficient in most cases for ring or intra-ring scales. Micro-CT scanners offer good performance at the cost of much longer acquisition and reconstruction times.

1. Introduction

Density is certainly the most universally measured property of wood. Wood density is a good predictor of several quality features of the wood material such as mechanical properties (Zhang, 1997; Mamdy et al., 1999; Rozenberg et al., 1999), dimensional stability (Chafe, 1986; Sotelo Montes et al., 2007) or calorific value (Munalula and Meincken, 2009; Antwi-Boasiako and Acheampong, 2016). It is a crucial variable in carbon cycle research and biomass estimation (Knapic et al., 2014; Bouriaud et al., 2015; Pompa-García and Venegas-González, 2016). It is related to tree growth through relationships with tree physiology and ecology (Hacke et al., 2001; Chave et al., 2009), and with climate (Franceschini et al., 2013). Due to this relationship with climate, wood density is used in dendrochronology and dendroclimatology studies to determine past climate from trees (Schweingruber et al., 1978; Briffa et al., 1995).

Wood microdensitometry is a powerful method that allows one to obtain wood density profiles or images for analysing density variations along a wood sample (in general, a radial[1] wood sample). It can be used non-destructively from increment cores extracted from standing trees. For tree species with rhythmic growth and showing annual growth rings, it allows one to obtain the density profile of each ring, making it possible to correlate wood properties to tree age or to the year of wood formation. Moreover, annual density profiles allow one to determine the transition between earlywood and latewood within each annual growth ring (Mothe et al., 1998; Koubaa et al., 2002).

In wood and forest sciences, microdensitometry allows analysis of the variability of wood quality (Groot and Luther, 2015), to assess the effects of forest management (Jaakkola et al., 2006; Mäkinen et al., 2015) or to provide models predicting wood density within and among trees from dendrometric or ecological factors (Berges et al., 2008; Filipescu et al., 2013; Auty et al., 2014). Radial profiles of density allow analysis of features such as ring width, latewood proportion, width and density of earlywood and latewood (Cown and Clement, 1983; Mothe et al., 1998; Kumar, 2002), or in the case of tropical species, to identify seasonal growth markers (Jacoby, 1989; Worbes, 1995; Moya-Roque and Tomazello Filho, 2009) and the relationships with anatomical features (Moya-Roque and Tomazello Filho, 2007). It is widely accepted that density

* Corresponding author.
E-mail addresses: philippe.jacquin@inra.fr (P. Jacquin), fleur.longuetaud@inra.fr (F. Longuetaud), jean-michel.leban@inra.fr (J.-M. Leban), frederic.mothe@inra.fr (F. Mothe).

[1] The terms radial, tangential and longitudinal used through this paper refer to the usual longitudinal-radial-tangential coordinate system for wood.

http://dx.doi.org/10.1016/j.dendro.2017.01.004
1125-7865/

characteristics of tree rings are related to climate. Schweingruber et al. (1978) analysed the relationships with monthly temperatures of maximum ring density (*MXD*), minimum ring density, earlywood and latewood widths and concluded that *MXD* was the best variable for reconstructing past temperatures. *MXD* was especially used as a temperature proxy in coniferous species for trees that have grown at the treeline or at high latitudes, where growth is limited by low temperatures (Briffa et al., 1998, 2004). More recently, ring density profiles were used to propose proxies of adaptive traits linked to the resistance to drought (Britez et al., 2014).

In the literature, several methods were investigated for measuring wood density at the tree ring or intra-tree ring levels: beta rays (Cameron et al., 1959; Phillips, 1960), gamma rays (Woods and Lawhon, 1974) and X-rays (Polge, 1966); high-frequency (HF) densitometry that is based on the dielectric properties of wood (Schinker et al., 2003; Boden et al., 2012); some optical methods including the use of the blue intensity (*BI*) component (McCarroll et al., 2002; Campbell et al., 2007; Dolgova, 2016); neutron imaging (Lehmann et al., 2001; Mannes et al., 2007) and mechanical drilling (Rinn, 2012).

X-ray wood densitometry is considered the reference method in dendrochronology. It was initiated in the 1960s by Polge (1966, 1978). Today, X-ray based methods are the most suitable and the most used worldwide for measuring wood density at the ring or intra-ring levels. In the beginning, only radiographic films were used. Later, several direct scanning devices based on X-rays (emitted by electrical X-ray tubes) or gamma rays (radiation similar to X-rays emitted by radioactive nuclei) were described (Woods and Lawhon, 1974; Ferraz, 1976; Cown and Clement, 1983; Hoag and McKimmy, 1988; Jonsson et al., 1990; Clauson and Wilson, 1991). These precursor systems were progressively replaced by the devices described in Section 3.

New methods that are not based on X-rays are still under study. The objective in developing new methods is to reduce the cost and time needed for the density measurements in comparison with X-ray methods.

Among the possible alternative methods, the *BI* component appears to be an interesting surrogate for wood density. However, there are still some limitations due to wood discolouration between samples or within samples, for example for species showing a difference in colour between heartwood and sapwood, or between deadwood samples and living-wood samples (Björklund et al., 2014; Rydval et al., 2014). Consequently, *BI* cannot yet be considered suitable as a climate proxy on centennial or longer scales. However, recent works propose special adjustments for dealing with this problem and open new possibilities for further climatic studies on long scales (Björklund et al., 2015).

HF densitometry was also used for studying relative density variation profiles (Schinker et al., 2003). The first calibration attempt in terms of true density values was performed by Wassenberg et al. (2014). This method was much less studied than the one based on the *BI* component and should be further studied, in particular regarding the calibration procedure and some technical aspects such as sample preparation and other aspects related to the characteristics of the dielectric probes used (Wassenberg et al., 2015).

In this study, the choice was made to focus on X-ray based methods used for measuring wood density at the ring or intra-ring levels. We carried out an inventory, which was as exhaustive as possible, of the scientific works published in 2014 and 2015 making use of X-ray based methods for measuring wood density at the annual ring level. From this inventory, a shortlist of the methods actually used by the scientific community was issued. Apart from X-ray films, which are still in use in many laboratories, three main devices have emerged and are described in detail in Section 3: SilviScan (CSIRO, Melbourne, Australia), Itrax (Cox Analytical Systems, Gothenburg, Sweden) and QTRS (QMC, Knoxville, USA). In addition, we present several more exploratory works based on X-ray computed tomography (CT) applied to wood densitometry.

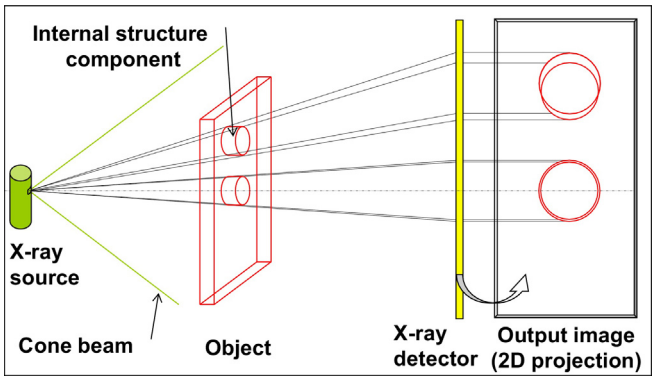

Fig. 1. X-ray conical beam.

2. Principles of densitometric measurements based on X-rays

There are two principles based on X-rays absorption for measuring density: radiography and tomography.

2.1. Radiography

X-ray radiography is the acquisition of the projection of an object by means of an X-ray beam passing through the object. An image is obtained by using a photographic film or a digital detector. In this image, grey levels depend on the attenuation of X-rays which is related to the atomic number and the quantity of atoms that are in the beam path. The atomic composition of wood being relatively constant, the radiography of a wood sample of constant thickness depends essentially on the density variations, making the device easy to calibrate for measuring wood density.

X-ray sources generate divergent beams, which enable magnifications by moving the sample between the X-ray source and the detector.

Depending on the angle of incidence of the X-rays and the thickness of the object, a blur may appear. In Fig. 1, the structural elements of the object are oriented in the same direction as the main axis of the X-ray beam. In this usual configuration, the farther the crossed area is from the main axis, the greater the blur effect appears.

To avoid this blur, an effort is usually made to make the X-rays more parallel, at the expense of losing the magnification effect (Fig. 2). The simplest method for that is to place the X-ray source as far as possible from the object and use only the central part of the cone beam. The drawback is that the device occupies a large space and requires specific protection on all sides against X-ray radiation. Another method employs collimators to reduce the beam aperture. This method enables small detectors to be used, which are cheaper, and in addition, are limiting radiation to a small area. The drawback is that the field of view (FOV) is also reduced, which means that for analysing large objects several views are needed and software for combining the images is required. The radiographic devices dedicated to wood science all use one of these two methods. Parallel X-rays can also be obtained by X-ray optical focusing methods (Yamanoi and Nakazawa, 2000; Croudace et al., 2006; Kang et al., 2011) but, to our knowledge, these techniques have not begun to be used in wood science.