Computers and Electronics in Agriculture 127 (2016) 50–55

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

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

Original papers

Estimating the density of coast Douglas-fir wood samples at different moisture contents using medical X-ray computed tomography

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ARTICLE INFO

Article history:
Received 29 December 2015
Received in revised form 1 June 2016
Accepted 2 June 2016

Keywords:
Wood density
Medical imaging
Douglas-fir

ABSTRACT

Wood density (ρ) is an indicator of Douglas-fir (*Pseudotsuga menziesii*) forest product performance and past and present tree ecophysiology. Models describing the spatial variation in this wood property will require a considerable sampling effort. Medical X-ray computed tomography (CT) has been identified as one technology for rapidly estimating ρ of Douglas-fir wood. The density of Douglas-fir can be predicted from CT Hounsfield units through a linear relationship ($R^2 : 96\%$). The moisture content of wood samples has an additional linear effect on estimating Douglas-fir wood density ($0.0015\ \mathrm{g/cm^3}$) and also has a practically minor ($2.8E - 06\ \mathrm{g/cm^3}$), but significant, interactive relationship with CT Hounsfield units. While the effect of moisture content explains only a small percentage of the variance in ρ, accounting for this effect my be important to avoid prediction biases. Finally, X-ray tube current (mA) may also impose a small effect ($0.00003\ \mathrm{g/cm^3}$) on estimating wood density. In contrast to other factors, the filtered back-projection algorithm used to produce CT scanning images does not have an strong effect on estimating ρ. While it is important to account for scanner settings and moisture content, 74% of the variance in predicting ρ can be explained by CT Hounsfield units with 21% explained by accounting for moisture content and X-ray tube current. Independent estimates of wood sample volume for validation can be achieved in several ways, each with possible systematic biases. This experiment found volume of wood samples conditioned to different moisture content could be estimated similarly using volumetric displacement or dimension measurement by caliper. The absolute mean deviance of estimated sample volume from caliper measurement relative to volumetric displacement was 0.45 cm^3 or 2.6%. CT scanning can be used to rapidly estimate Douglas-fir at a resolution of 1-mm using unprepared samples.

1. Introduction

Wood density (ρ) in coast Douglas-fir (*Pseudotsuga menziesii*) results from a complex of interacting ecophysiological processes that influence rate of meristematic cell division and the growth in cell diameter, cell length and cell wall thickness (Larson, 1969). Wood density integrates the effect of these attributes on important wood properties that in turn affect the performance of most wood products. In the wood of Douglas-fir, ρ largely depends on the dimensions of longitudinal tracheids, which are long, skinny, tubular cells with pinched ends, usually arranged parallel to the stem, branch or root axis (Côté, 1968). Within the annual growth ring, tracheid development and final dimensions vary with season of formation. Earlywood is formed at the onset of growth in spring, and is characterized by relatively short longitudinal tracheid cells with large lumens and thin cell walls. Earlywood transitions to latewood during the latter part of the growing season and is apparently driven by one or more environmental factors that also synchronize with the end of terminal growth (Larson, 1969). For example, latewood production can be related to the onset of soil moisture deficit (Kantavichai et al., 2010). The timing of transition to latewood is probably an adaptation to water and other environmental stresses, so this trait would be expected to exhibit some level of genetic heritability along environmental gradients (Rozenberg et al., 2001). Latewood is characterized by relatively long, thick walled longitudinal tracheids with decreased cell diameter and lumen size. Within an annual growth ring, ρ is less in earlywood than latewood. Tracheid developmental pattern also varies spatiotemporally along the longitudinal and radial direction within the tree bole. As the longitudinal distance from the tree tip

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http://dx.doi.org/10.1016/j.compag.2016.06.003
0168-1699/

increases, the transition from earlywood to latewood is found to be more abrupt in Douglas-fir (Emmingham, 1977).

The radial profile of ρ at breast height (1.37 m) for managed Douglas-fir trees in the Pacific Northwest United States can be predicted partly from conventional tree dimensions and growing site conditions (Filipescu et al., 2013; Kantavichai et al., 2010). Future goals in modeling ρ for managed Douglas-fir trees are to predict spatial variation within the tree bole in the longitudinal and radial direction, to represent response of ρ to silvicultural treatment, and to account for geographic trends induced by environmental influences. Meeting these goals may require deploying a mixture of technologies to estimate density of a large number of wood samples. X-ray densitometry has supported the development of current models for predicting density in Douglas-fir (Filipescu et al., 2013). This high resolution scanning technique (usually at 25μ) will continue to support modeling of within and between growth ring variation of ρ, especially to establish causal mechanisms related to local climate and other site conditions like soil attributes. Many other approaches could be deployed to estimate the density of Douglas-fir wood, each with its own unique costs and benefits (Wei et al., 2011). Several authors have demonstrated that medical X-ray computed tomography (CT) can be used to rapidly estimate the density of wood, when a 1-mm scanning resolution is acceptable (Freyburger et al., 2009; Steffenrem et al., 2014).

The goal of this study was to provide a regionally applicable equation to estimate Douglas-fir wood density (g/cm^3) based upon imagery produced by medical CT scanning. Output of CT scanning includes Hounsfield units (H), a transformation of a radiation attenuation coefficient into a linear scale between distilled water (0 m) and air (−1000 m). The goal of the study would clearly be met most expediently if ρ could be estimated on unprepared Douglas-fir wood cores, sample blocks, or whole tree sections. Most significantly, use of unprepared samples would mean that moisture content would not confound density estimates to the extent that the quick and efficient potential of CT scanning would be negated by complicated, time consuming, and expensive characterization of average moisture content or spatial variation of moisture content in larger samples. Moisture content was expected to have a significant effect on predicting ρ, due to different X-ray absorption coefficients for water and wood (Lindgren, 1991). Our work follows that of Freyburger et al. (2009) who developed an equation to predict ρ using wood from several tree species, but not including Douglas-fir.

The specific objectives of the work reported here were to: (1) test the hypothesis that CT scanning would provide a significantly accurate estimate of Douglas-fir wood density, ρ; and (2) develop an estimation equation that could be applied to a large regional sample of Douglas-fir to create a database for modeling radial and longitudinal variation in ρ under varying site conditions and silvicultural regimes. A regional model predicting the magnitude and spatial pattern of wood density in Douglas-fir would be useful for marketing logs and for developing manufacturing technology that would optimize the value recovered from a given log.

2. Methods and materials

Developing an equation to estimate Douglas-fir ρ from CT Hounsfield units required four steps: (1) collecting wood core and cube samples covering the expected range of ρ for intensively managed Douglas-fir trees; (2) conditioning samples to three targeted moisture contents; (3) scanning those samples using a combination of CT scanner settings at each targeted moisture content; (4) measuring sample volume and weight; and (5) converting CT scanning images into a modeling dataset for regression analysis. As described below, targeted moisture contents were specified to ensure the desired range, but moisture content of each sample was measured to determine its specific content at time of CT scanning.

2.1. Collecting wood core and block samples

Thirty 1.27-cm diameter wood cores were drawn from a 30-year old coastal Douglas-fir spacing trial established by the Stand Management Cooperative near Corvallis, Oregon (914-Lewisburg Saddle) (Maguire et al., 1991). Ten samples were collected from each of three spacing blocks planted at 485 trees ha^{-1}, 190 trees ha^{-1}, and 40 trees ha^{-1}. Samples were drawn across the widest possible range in initial spacing to represent the potentially largest range in ρ, owing to differences in timing of crown closure, average rate of diameter growth, degree of stem differentiation, and onset of suppression mortality (Fig. 1). Within each experimental plot, sample trees were randomly selected across the diameter distribution, so that all social classes within each spacing were represented. At breast height (1.37 m) on each sample tree, a single 12.7-mm diameter wood core was extracted with an increment borer from a random azimuth around the bole.

Eighty Douglas-fir wood blocks of approximately the same dimensions (2.5-cm^3) were cut from sawn lumber to extend the range of ρ for analysis (Fig. 1). The wood cubes were sawn from several Douglas-fir studs purchased at a local hardware store and planks from a local wood pile. The wood blocks were purposefully selected to represent the widest possible range in Douglas-fir ρ, implied by relative proportions of earlywood and latewood along the exposed cross-sectional area. Between the 30 wood cores and 80 wood cubes, the sample ρ ranged from 0.40 to 0.84 g/cm^3 (Table 1).

2.2. Laboratory methods

Each of the wood cores and cubes were scanned using a TOSHIBA Aquillion medical CT scanner, located at the Oregon State University, College of Veterinary Medicine (VETMED). For each scan the X-ray voltage (120 kVp), slice thickness and interval (1-mm) and pixel resolution (0.544-mm^2) was fixed. The targeted level of sample moisture content and X-ray tube current (mA) and reconstructive backfilter algorithm used to process imagery was varied (Table 2). As Freyburger et al. (2009) mention, filters are provided by the CT scanner manufacturer on an as-is basis without technical details and are designed for imaging different parts of the human body. For each scanning session, wood samples were arranged as accurately as possible to move through the scanner with the growth rings oriented in a vertical position, i.e., with the sample cross-section facing up. Wood cores were scanned in a balsa wood cassette, using a method adapted from Steffenrem et al. (2014), and wood cubes were oriented in a square matrix on a glass plate placed on the scanner bed (Fig. 2).

The 0-percent moisture content was achieved by drying samples in an air-circulated oven set to 103 °C for 24-hours (Table 1). To maintain a 0-percent moisture content during transportation to the medical imaging facility, samples were transferred directly from the oven into a glass desiccator lined with silica cobbles. The time between unloading samples from the desiccator and completing the CT scans was around ten minutes. After the first scanning session was completed, wood samples were conditioned to a targeted moisture content of 10-percent. A 10-percent moisture content was achieved by allowing samples to reach equilibrium in a climate chamber maintained at 65-percent relative humidity and temperature of 20 °C. To maintain the final moisture condition, samples were placed in the glass desiccator without sil-