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How do trees grow? Response from the graphical and quantitative analyses of computed tomography scanning data collected on stem sections

Comment les arbres poussent-ils ? Réponse des analyses graphique et quantitative de données de tomodensitométrie pour des sections de la tige

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ABSTRACT

Tree growth, as measured via the width of annual rings, is used for environmental impact assessment and climate back-forecasting. This fascinating natural process has been studied at various scales in the stem (from cell and fiber within a growth ring, to ring and entire stem) in one, two, and three dimensions. A new approach is presented to study tree growth in 3D from stem sections, at a scale sufficiently small to allow the delineation of reliable limits for annual rings and large enough to capture directional variation in growth rates. The technology applied is computed tomography scanning, which provides – for one stem section – millions of data (indirect measures of wood density) that can be mapped, together with a companion measure of dispersion and growth ring limits in filigree. Graphical and quantitative analyses are reported for white spruce trees with circular vs non-circular growth. Implications for dendroclimatological research are discussed.

RÉSUMÉ

La croissance des arbres, mesurée via l'épaisseur des cernes annuels, est utilisée pour évaluer les impacts environnementaux et rétroprédire le climat. Ce processus naturel fascinant a été étudié dans la tige à des échelles variées, en une, deux et trois dimensions. Une nouvelle approche est présentée pour étudier la croissance des arbres en 3D à partir de sections de la tige, à une échelle suffisamment petite pour attribuer des limites fiables aux cernes annuels et assez large pour capturer la variation directionnelle dans les taux de croissance. La technologie appliquée est la tomodensitométrie assistée par ordinateur, qui produit – pour une section de tige – des millions de données qui peuvent être cartographiées avec une mesure de leur variabilité et des limites des cernes de croissance en filigrane. Des analyses graphique et quantitative sont rapportées pour des épinettes blanches à croissance circulaire et non circulaire. Des implications pour la recherche dendroclimatologique sont discutées.

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1. Introduction

The measurement of tree growth with the purpose of relating it to environmental and genetic factors has long been the subject of intensive research, from a variety of perspectives, including dendrochronology [1] and wood technology [2]. While photosynthesis and the companion recycling of atmospheric carbon dioxide occur at the level of the leaves in trees, annual increments of the stem circumference, which are reflected by annual rings in temperate and boreal climates, and troughs and peaks in the fluctuations of wood density, depending on whether the wood is produced earlier or later in a given year, are more easily traceable indicators of tree growth [3–6].

The characterization of wood properties inside a tree stem [7–11] has motivated the development and use of a plethora of measurement techniques. Many of these are based on the X-ray technology: computed tomography (CT) scanning [12–17]; microdensitometry [18]; and others [19,20]. Rarely, though, was a three-dimensional (3D) analysis of the data really performed; when this was the case, the focus was on the detection of branch knots, known as rameal traces [16,17] and compression wood [21] in the tree stem, rather than the measurement of tree growth via wood density variations within and among annual rings. In two dimensions, an automated but essentially graphical procedure involving multiple processing stages has been proposed to generate tree-ring profiles from the CT image showing the cross-section of a piece of wood [22]; in one dimension, one curve of raw CT numbers showing peaks corresponding to different years, from bark to bark, has been presented in [23], together with one 2D CT image of the stem of a *Pinus nigra* tree at breast height.

Hereafter, we explain how measurements are possible in 3D by CT scanning stem sections (Fig. 1d,e). In doing so, we shall explore the content and nature of tree stem sections (Fig. 1b,c) and identify growth layers and rings in a large number of directions in 3D. After integration along the vertical axis z (over successive CT images), the resulting maps of means (Fig. 1f) and corresponding standard deviations of wood density estimates will be presented, with the horizontal x–y plane (perpendicular to the stem) as support. A novelty of our approach is that it allows the extraction of "virtual cores" (Fig. 1g) from the wood CT scan dataset, which in turn provides the basis for:

(i) plotting curves of wood density estimates in multiple directions;
(ii) measuring the width of annual rings in each direction;
(iii) assessing the variations in ring width as a function of year and direction.

For illustration, we use stem sections from two white spruce trees (see, e.g., Fig. 1a), with circular vs non-circular stem growth patterns. Then, we discuss the pros and cons of the approach and define the conditions of application for future studies. From the dendrochronological perspective, when the aim is back-forecasting the climate, we address the implications of measuring tree growth from radial wood cores instead of wood volumes (i.e. discs with a thickness) analyzed for their inner part rather than their surface [21], and make suggestions regarding possible field equipment for the on-site collection of CT scan data for the latter.

2. Materials and methods

The wood discs, for which results of graphical and quantitative analyses of CT scan data will be presented to illustrate the new approach proposed, are stem sections of two white spruces (*Picea glauca* (Moench) Voss), grown in natural forest stands of Québec (Canada) and harvested in October 2009 (Tree 1) and September 2009 (Tree 2). These two trees were chosen for their very different stem growth patterns (circular, Tree 1 vs non-circular, Tree 2), from a number of white spruces harvested the same year in a broader region (Tree 1: 45°26′11″N, 70°54′45″W; Tree 2: 46°45′25″N, 79°04′41″W). They grew in the same climatic zone (Nordic temperate) but a different vegetation area, composed of other white spruces and balsam firs (*Abies balsamea* (L.) Mill.) for Tree 1 vs trembling aspens (*Populus tremuloides* Michx.) and white birches (*Betula papyrifera* Marsh.) for Tree 2. They also differed in site topography, 14° slope exposure relative to magnetic north and at the bottom of a 5% slope (Tree 1) vs a 144° slope exposure and mid-way of an 8% slope (Tree 2).

The high-resolution X-ray CT scanner used in this study is the same as the one used in [24–26], where technological details about some of our previous plant science applications (i.e. canopies and wood sticks) can be found. In the CT scanning of Tree 1 and Tree 2 stem sections, the following parameter values were used: 50 mA (tube current), 120 kV (tube voltage), 1 mm (X-ray beam width), and 18 cm (field of view) for Tree 1 and 24 cm (field of view) for Tree 2; no zoom factor was applied. Using the Helical Scan option with a 0.3-mm thickness, CT images were first constructed every 0.3 mm in the tree stem direction (z-axis), each CT image (x–y plane) consisting of a 512×512 matrix of CT numbers. Then, CT numbers were converted to wood density estimates using the calibration equation, density = $0.993 \times$ CT number + 1015, for not oven-dried wood in [12] (see also [26]); our wood samples were not oven-dried and the estimated 95% confidence interval for moisture content (4.6 ± 1.8%) included the lower bound of 6% in [12]. To capture the variability in 3D and represent it graphically, one map of means and one map of corresponding standard deviations (in the x–y plane) were computed from the wood density estimates obtained from 25 CT images (along the z-axis) for each of the two wood discs. The functions *mean* and *std* of the MATLAB programming language were used to compute 2D arrays of values of the two statistics, which were mapped with the function *mesh* (The MathWorks, Inc., Natick, MA, USA). The bark was excluded from the computations. For each wood disc, bark exclusion from map production was made by visual inspection of the 25 CT images, which were processed individually with the MATLAB function *imtool*. Specifically, since bark is much more dense than most of the interior part of the stem section with the exception of rameal traces, peripheral voxels appearing in white or very light grey in a CT image (see, e.g., Fig. 1e), thus,