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Mapping site index and age by linking a time series of canopy height models with growth curves

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ABSTRACT

Site index (SI) is one of the main measures of forest productivity in North America. For monospecific even-age stands, it is defined as the height of dominant trees at a given reference age or presented as an age–height curve. SI normally reflects the overall effect of all the environmental parameters that determine height growth locally. However, measuring SI can only be achieved though field observations and is, for this reason, limited to sample plots. In this study, we propose a new method for quantifying and mapping SI and age based on known age–height curves and time series of canopy height models (CHMs) produced using digital photogrammetry and lidar. Digital surface models (DSMs) are created by applying an automated stereo-matching algorithm to scanned aerial photographs. The canopy height is obtained by subtracting the lidar ground elevations from the DSM. Using aerial photographs covering the 1945–2003 interval and a recent lidar coverage, CHMs could be reconstructed retrospectively for a period of over 58 years. Regionally calibrated age–height curves were fitted to observations that were extracted cell-wise from the historical CHMs to estimate SI and age values for all undisturbed locations. Results demonstrate that SI and age of jack pine (*Pinus banksiana* [Lamb.]) stands can be quantified respectively with an average bias of 0.76 m (2.41 m root mean squared error, RMSE) and 1.86 years (7 years RMSE). The method can be used to produce quasi-continuous maps of SI and age and to estimate productivity in a spatially explicit way.

1. Introduction

Site index (SI) is a widely used forest management tool for quantifying the productivity of forests. In even-aged stands, SI expresses the relationship between the height of dominant and/or codominant trees and age (Skovsgaard and Vanclay, 2008). It integrates the combined effects of the most important environmental determinants of tree growth such as topography, soil characteristics, and climate (Perron et al., 1996). The age–height data used for building SI curves are normally derived from measurements on sample trees within large sets of temporary or permanent sample plots, or from stem analyses (García, 2005; Raulier et al., 2003). It is assumed that the selected trees grew relatively free of suppression or competition and were not affected by damage from insects, diseases, or severe weather (Sturtevant and Seagle, 2004). Anamorphic or polymorphic curves, i.e., mathematical functions having SI as one of their parameters, are fitted to the height–age observations (Raulier et al., 2003; Huang and Titus, 1993). For the region concerning this study, i.e., the province of Quebec, Canada, a generalized model for predicting SI for most of the commercial tree species was developed by Pothier and Savard (1998) based on large temporary sample plot datasets. Once the curves are established, the SI at a given location (plot, stands, etc.) is estimated by measuring the height and age of selected sample trees (Mailly et al., 2004) and by subsequently extracting the SI value from the calibrated curve that best fits the observed age–height values (Carmean et al., 2001).

Quantifying the spatial variation of forest productivity requires upscaling field measurements to a spatially explicit level. In Canada, the height and age data extracted from large-scale (e.g. 1: 25,000) forest stand maps is sometimes used for this purpose (Fournier et al., 2003). However, the resulting estimations, aggregated into broad classes, may be not well suited to detect local growing variations reported within stands of same SI and resulting from local interactions between climate, soil, stand density, and origin (Huang et al., 2004; Lussier et al., 2002; MacFarlane et al., 2000; Wang and Huang, 2000). Furthermore, high-resolution height and age mapping

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may be helpful in some specific areas to assess and monitor changes in forest productivity driven by global changes (Fries et al., 2000). To address these problems, methods that would rely on repeated measurements at short time intervals and with a high spatial resolution should be developed (Chen et al., 2002).

The improvements of automated image-matching algorithms within digital photogrammetry software and the wider use of lidar to precisely map terrain topography open up new possibilities for accurately measuring forest height at different moments in time in a spatially explicit way (Véga and St-Onge, 2008; Itaya et al., 2004). Image-matching algorithms solve the image correspondence problem by automatically extracting homologous points from a stereo-pair using area- or object-oriented approaches (Brown et al., 2003). The elevation of these points is then calculated based on their parallax difference (Hartley and Sturm, 1997). A digital surface model (DSM) describing the absolute elevation of the surface of objects visible on aerial photographs can be obtained by interpolating the resulting XYZ points. In the case of closed forests, the DSM corresponds to the canopy surface. Image matching over forested areas yields canopy DSMs with elevation biases ranging from 0.5 to 5.5 m (St-Onge et al., 2008; Itaya et al., 2004; Næsset, 2002), except for localized blunders that can reach 20 m in areas where occlusion or shade provoke local matching errors (Miller et al., 2000). The height of the forest canopies can then be extracted from these DSMs provided the elevation of the ground topography can also be measured accurately—which is impossible by photogrammetry alone when the canopy is closed. However, lidar pulses have the capacity to penetrate most forest covers to produce returns (XYZ data) at ground level. Once non-ground hits are filtered out using classification algorithms (Sithole and Vosselman, 2004), interpolating the remaining returns produces a bare earth digital terrain model (DTM) with an elevation accuracy of approximately 30 cm (Hodgson and Bresnahan, 2004). St-Onge and Achaichia (2001) presented a novel approach for mapping forest height consisting of combining a lidar DTM with a DSM extracted from aerial photographs to create a photo-lidar canopy height model (CHM). Véga and St-Onge (2008) generalized the method for processing archive photographs—available in many areas from at least the middle of the 20th century with a high temporal frequency—to reconstruct CHMs time series. They showed that the height extracted from the resulting retrospective photo-lidar CHMs allowed to estimate dominant tree height with a 2 m accuracy at four different points in time during the 1945–2003 period in 20 $\times$ 20 m cells covering a boreal forest landscape. The results are of the same quality as those obtained by Itaya et al. (2004) combining DSM time series with a DTM derived from a field survey for a limited area. Such CHM time series were successfully used to quantify and map height growth and to detect disturbances that affect canopy height (clear cuts, windthrows, gaps openings, etc.) (Véga and St-Onge, 2008; Fujita et al., 2003; Itaya et al., 2004). However, to translate the extracted height data from such CHM time series to age–height curves and SI values, additional detailed information on forest species composition and age is required.

The main hypothesis tested in this study is that the SI and age of even-age jack pine stands (*Pinus banksiana* [Lamb.]) can be established by combining reconstructed height data extracted from historical photo-lidar CHMs encompassing a few decades. Fitting established species-specific age–height curves (parameterized with height, age, and SI) with the reconstructed year–height observations would then yield both age and SI. We begin by summarizing the methods for establishing the photo-lidar CHMs for the 1945–2003 period. We then explain how the jack pine stands were extracted and the age–height curves were fitted based on the time series of photo-lidar CHMs, and present an error assessment.

2. Study site and data

2.1. Study site

The study site is a 4.5 km^2 forested sector located in the managed part of the Training and Research Forest of Lake Duparquet. It is located approximately 75 km north of Rouyn-Noranda, Quebec (79° 22′W, 48° 30′N) and is part of the Canadian shield, characterized by soils dominated by argillaceous deposits of lacustrine origin (Brais and Camiré, 1992). The undulating topography varies from 234 to 348 m and supports a vegetation characteristic of the balsam fir-paper birch climate domain (*Abies balsamea* [Mill.] – *Betula papyrifera* [Marsh.]). The study area is dominated by jack pine (*P. banksiana* [Lamb.]) and trembling aspen (*Populus tremuloides* [Michx.]) growing in pure stands. The site composition and dynamics are driven by fire activity, and the area burned in 1923. Since the late 1970s, the landscape evolution was affected mostly by human activities (logging, road building). For the purpose of this study, only the jack pine stands were considered.

2.2. Image Data

Diapositives of archived black-and-white aerial photographs were acquired for the years 1945 (1:12,000), 1965 (1:15,840) and 1983 (1:15,000) (Table 1) at dates providing leaf-on conditions. The diapositives were scanned at 1600 dpi using an Epson Expression 1640XL scanner, producing nominal ground pixel sizes between 19.1 and 25.1 cm. The datasets were each composed of 6–15 images distributed on two parallel and overlapping flight lines. The internal orientation data corresponding to the diapositives was obtained from the concomitant calibration reports.

For the purpose of mapping jack pine stands, a Standard 2A level OrthoReady Quickbird image bundle composed of panchromatic and multispectral channels was acquired on June 13, 2004 with a sun azimuth and elevation of 146.4° and 61.7°, respectively. The pixel size of the panchromatic channel was 0.6 m, while that of the blue, green, red, and infrared channels was 2.4 m. The image-to-ground coordinates relation was described by 80 rational polynomial coefficients and 10 offset and scale parameters.

2.3. Lidar Data

Lidar data were acquired by LaserMap Image Plus Inc. (Boisbriand, QC, Canada) between August 14 and 16, 2003 using an ALTM 2050 sensor (Optech, Toronto, Canada), flown at 1000 m above ground level (AGL). The sensor recorded the first and last

Table 1
Aerial photograph characteristics.

Acquisition year	Acquisition date	Camera type	Focal length (mm)	Photo scale	Ground resolution (cm)	Base-height ratio	Image quality rank*
2003	22 May	Wild RC10	153.507	1:15,000	23.8	0.58	4
1983	17 June	Wild RC8	152.285	1:15,000	23.8	0.60	1
1965	17 July	Wild RC8	152.29	1:15,840	25.1	0.56	2
1945	24 August	Fairchild	200.9	1:12,000	19.1	0.34	3

* Relative image quality: (1) best–(4) worst based on visual appraisal