Agricultural and Forest Meteorology 237–238 (2017) 184–195

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Research paper

A method to quantify canopy changes using multi-temporal terrestrial lidar data: Tree response to surrounding gaps

Martin-Ducup Olivier[a,*], Schneider Robert[a], Richard A. Fournier[b]

[a] Chaire de recherche sur la forêt habitée, Département de biologie, chimie et géographie, Université du Québec à Rimouski (UQAR), 300 allée des Ursulines, Rimouski, Québec, G5L 3A1, Canada
[b] Centre d'Applications et de Recherches en Télédétection (CARTEL), Département de géomatique appliquée, Université de Sherbrooke, 2500, boul. de l'université, Sherbrooke, Québec, J1 K 2R1, Canada

ARTICLE INFO

Article history:
Received 27 October 2016
Received in revised form 9 February 2017
Accepted 11 February 2017
Available online 20 February 2017

Keywords:
Canopy
Crown expansion
Primary growth
Tree architecture
Gap closure
Mixed stands

ABSTRACT

Branch growth and the resulting crown expansion play many roles in tree and forest processes. Crown expansion is difficult to measure on an adult tree due to the crown's complexity and inaccessibility. The present study proposes a method to quantify vegetation changes over time. It was applied to follow the tree crown response to gap formation for broadleaved (Sugar maple) and coniferous (Balsam fir) species. The method was developed using terrestrial laser scanner (TLS) data. It consists of identifying the vegetation boundaries at time t_0 and extracting the new material produced or displaced between time t_0 and time t_x. Changes in vegetation were quantified with four metrics, and vertical profiles of these metrics were analysed. Results show that Sugar maple has a stronger response to gap formation compared to Balsam fir because of the different crown architecture. Both species showed considerable downward space reoccupation within most of the crown two years after the release of competition. These results are probably a consequence of a mechanical rearrangement of the crown and highlight the importance of analysing canopy changes in both the vertical and horizontal directions. The developed methodology can be applied to both individual trees as well as to a group of trees bordering a gap, in order to get insight on how trees recolonize the space that is freed by local and large scale disturbances.

1. Introduction

The crown structure of a tree at a given time determines both the amount of light intercepted for its own growth and the amount of light available for neighbouring trees and the understory vegetation. Crown dimensions are also important inputs for models that simulate forest stand dynamics (Coates et al., 2003; Ligot et al., 2014; Medlyn, 2004). Moreover, canopy structure has major effects on rainfall interception and water availability. Canopies can intercept up to 50% of the annual precipitation in certain ecosystems (Carlyle-Moses and Gash, 2011). Finally, the vertical organization of the canopy structure is closely related to the fauna diversity by creating specific habitats and microclimates (Shaw, 2004). Tree crown dynamics, defined as the changes over time in crown shape and space occupancy by branches, twigs and leaves, ultimately define crown structure, which is important in understanding stand dynamics for forest ecology and improving forest management.

Silvicultural treatments such as fertilization and thinning can have important effects on crown dynamics (Weiskittel et al., 2007). For example, an increase in the growth of the lower part of the crown is observed after trees are released by thinning, due to the changes in the light environment. Furthermore, several studies conducted in managed stands have shown that crown length and width increase after the removal of competitors (Forrester et al., 2013; Gillespie et al., 1994). Crown length increases since self-pruning is reduced whereas crown width increases due to available space for lateral crown expansion. The intensity of the response after a significant structural change in the surrounding of the tree crown depends however on the species considered, the type of thinning and the age of the stand when it is thinned. For example, the growth in the lower part of the crown of Douglas fir increases more when it is thinned earlier (i.e. after precommercial thinning) than later (i.e. after commercial thinning) (Weiskittel et al., 2007). Moreover, crown dynamics will vary between species with shade tolerances, since self-shading is more important for shade tolerant species such as Douglas fir, when compared to certain shade intolerant

---

* Corresponding author.
E-mail addresses: olivier.martin01@uqar.ca (M.-D. Olivier), Robert.Schneider@uqar.ca (S. Robert), Richard.Fournier@USherbrooke.ca (F. Richard A.).

http://dx.doi.org/10.1016/j.agrformet.2017.02.016
0168-1923/

Pines (Ruha et al., 1997). A good understanding of how tree crowns respond to silvicultural treatments is a key component to predict growth and wood quality, both of which are directly related to crown attributes in managed stands (Achim et al., 2006; Kellomäki et al., 1999; Schneider et al., 2011).

In natural forest dynamics, tree crown response to gap formation has also important implications on canopy closure and thus on tree regeneration (McCarthy, 2001). In this context it has been shown that coniferous species have generally a lower ability to close a gap when compared to broadleaved species. This is probably due to the less flexible developmental mode of conifers (Getzin and Wiegand, 2007; Muth and Bazzaz, 2002). Vepakomma et al. (2011) observed a different response in boreal forests, where no difference between conifers and broadleaved species was observed. The location of the tree along the gap may also be important, where trees can exhibit higher crown expansion toward the south (Rouvinen and Kuuluvainen, 1997). On saplings or young trees, quantifying crown expansion has allowed a better understanding of how trees modulate their shape according to light availability and a more accurate assessment of species-specific plasticity and growth strategies (Beaudet and Messier, 1998; Canham, 1988; Petriţan et al., 2009). Finally, the importance of crown lateral extension in understanding tree growth, competition for space and persistence in canopy has also been highlighted in recent years (Kellner and Asner, 2014; Seidel et al., 2015a).

In spite of the major roles of crown dynamics on forest functioning and management, very few studies have tried to accurately follow the dynamics of the tree crown on a short time scale. An important reason for this shortcoming is that primary growth (Barthelemy and Caraglio, 2007) of the crown (e.g., shoot growth resulting in the elongation of the different axes) is difficult to quantify. Consequently, for practical reasons, the estimation of the primary growth of the tree crown usually focuses on the tree height increment. This reduces the problem to a unidirectional measurement (i.e. vertical) where orientation is not important. Tree height can be measured routinely in a plot with various devices such as a clinometer, measuring pole or laser altimeter (Clark and Clark, 2011; Larjavaara and Muller-Landau, 2013) or from airborne systems such as lidar and stereo-photogrammetry with large-scale aerial photographs (Wulder et al., 2012). The vertical elongation of the main tree axis is, however, only one of the components of primary growth. It is actually composed of the increment of each branch, with the end result being the expansion of the crown. However, *in situ* measurements of branch elongation increments or total crown expansion are rarely done on adult trees due to the inaccessibility and the inherent complexity of the branching systems. Mature trees can be destructively sampled (Heuret et al., 2002; Lintunen and Kaitaniemi, 2010; Weiskittel et al., 2007) and primary growth measured retrospectively using markers, but it is generally laborious or impossible and does not allow growth monitoring. Dynamic studies with crown growth monitoring are hard to carry out due to logistical and cost constraints; tree crown studies are thus generally limited to crown attributes at a given time (Barbeito et al., 2014; Getzin and Wiegand, 2007; Longuetaud et al., 2013). Therefore, quantifying primary growth and crown changes over time for adult trees presents a huge methodological challenge.

Aerial (ALS) and terrestrial laser scanners (TLS) provide very accurate three-dimensional (3D) point cloud representations of the spatial distribution of elements composing the forest canopy (Côté et al., 2012). These remote sensing tools enable users to obtain complex and diverse canopy metrics without destructive sampling or climbing trees. In the last decade, many authors have used ALS and TLS systems to quantify canopy structure and its diverse roles in forest dynamics (Kato et al., 2009; Seidel et al., 2012). Metrics can now be easily obtained from point clouds and allow the estimation of canopy density profiles (Ashcroft et al., 2014) or above-ground biomass (Dassot et al., 2012). Indeed, above-ground biomass estimates based on TLS data were reported to be more accurate compared to traditional allometric equations (Calders et al., 2015; Srinivasan et al., 2014). Since laser scanners are non-destructive, changes in forest structure can be obtained (Liang et al., 2012). Furthermore, crown metrics such as crown asymmetry used to estimate crown plasticity can now be much more accurately measured. The envelope of the crown allows a precise quantification of the space occupation and the surface of the crown, both of which can be precisely assessed with TLS data (Bayer et al., 2013; Martin-Ducup et al., 2016). Finally, the potential for some of these new metrics to predict tree growth or tree crown plasticity have also been highlighted (Seidel et al., 2015b, 2011). Despite these technological advances, to our knowledge, no studies have tried to quantify changes over time of individual tree crowns.

The main objective of this study was to develop a procedure to quantify canopy changes with TLS data. This was achieved by developing computationally easy indicators of growth and displacement that can be quickly extracted from TLS point clouds. More specifically, the proposed method quantifies the amount of displaced vegetation biomass and its global, horizontal and vertical changes using multi-temporal TLS data. The method can be applied to produce vertical profiles of the entire tree crown or by cardinal direction. The proposed method was applied to adult trees in order to characterise their response to canopy openings. Using the proposed method, we were able to test the hypothesis that (i) Sugar maple (*Acer saccharum* Marsh.) trees have a stronger response to canopy openings than Balsam fir (*Abies balsamea* (L.) Mill.), (ii) trees growing in pure stands show no differences compared to trees growing in mixed stands when competition for light was removed, and (iii) both species show a stronger crown response in the most sun exposed direction (south).

2. Materials and methods

2.1. Study site and species

A total of six Sugar maple and Balsam fir mixed forest sites located in eastern Quebec, Canada, were selected using the provincial eco-forest maps developed by the Quebec Ministry of Forests, Wildlife and Parks (MFFP, 2007). Each site was composed of three stand types: a pure Balsam fir stand, a pure Sugar maple stand, and a mixed stand with both species (see Martin-Ducup et al. (2016) for details on the mixed stand composition). Tree characteristics of both species in pure and mixed stands are given in Table 1. Balsam fir and Sugar maple are both very shade tolerant species (Humbert et al., 2007) which present well contrasted architectural developments. On the one hand the Balsam fir is a softwood species with a Massart architectural model (*sensu* (Hallé et al., 1978). The strong apical dominance of the main axis (the trunk) and the horizontal branches yields this species' rigid conic shape with a well-defined trunk. On the other hand the Sugar maple is a hardwood species which presents a combination of several architectural models: Leuwenberg/Koriba/Rauh. Its development changes during the ontogeny and a progressive loss of the apical dominance is observable giving to this species a sparse crown which allows a more flexible crown development (Millet, 2012).

2.2. Target-tree measurements

In August 2013, five to six healthy co-dominant trees (i.e. no evidence of damage on the stem or the main branches) per species were selected in both the pure and mixed stands for each site. The direct competitors of each Target-Tree (TT) were felled in order to release the TT from competition on all sides so as to simulate small