A fast and reliable method for the delineation of tree crown outlines for the computation of crown openness values and other crown parameters

Frédéric Boivin, Alain Paquette, Pierre Racine, and Christian Messier

Abstract: Numerous crown parameters (e.g., leaf area index, diameter, height, volume) can be obtained via the analysis of tree crown photographs. In all cases, parameter values are functions of the position of the crown outline. However, no standardized method to delineate crowns exists. To explore the effect of different outlines on tree crown descriptors, in this case crown openness (CO), and facilitate the adoption of a standard method free of user bias, we developed the program Crown Delineator that automatically delineates any outline around tree crowns following predetermined sensibility settings. We used different outlines to analyze tree CO in contrasting settings: using saplings from four species in young boreal mixedwood forests and medium-sized hybrid poplar trees from a low-density plantation. In both cases, the estimated CO increases when calculated from a looser outline, which had a strong influence on understory available light simulations using a forest simulator. These results demonstrate that the method used to trace crown outlines is an important step in the determination of CO values. We provide a much-needed computer-assisted solution to help standardize this procedure, which can also be used in many other situations in which the delineation of tree crowns is needed (e.g., competition and crown shyness).

Résumé : Plusieurs paramètres de la cime, comme l'indice de surface foliaire, le diamètre, la hauteur et le volume, peuvent être obtenus par l'analyse de photographies de la cime des arbres. Dans tous les cas, la valeur des paramètres est fonction de la position du contour de la cime. Cependant, il n'existe pas de méthode standard pour délimiter la cime. Afin d'explorer l'effet de différents contours sur les descripteurs de la cime des arbres, l'ouverture de la cime dans ce cas-ci, et de faciliter l'adoption d'une méthode standard exempte de biais introduit par l'utilisateur, nous avons développé un programme, le délinéateur de cime, qui délimite automatiquement n'importe quel contour de la cime des arbres selon des paramètres de sensibilité prédéterminés. Nous avons utilisé différents contours pour analyser l'ouverture de la cime en fonction de différents paramètres en ayant recours à des gaules de quatre espèces dans de jeunes forêts boréales mélangées et à des tiges de peuplier hybride de dimension intermédiaire provenant d'une plantation à faible densité. Dans les deux cas, l'ouverture de la cime estimée augmente lorsqu'elle est calculée à partir d'un contour plus approximatif, ce qui avait une forte influence sur les simulations de disponibilité de la lumière en sous-étage effectuées à l'aide d'un simulateur de forêt. Ces résultats démontrent que la méthode utilisée pour tracer le contour des cimes est une étape importante dans la détermination de la valeur d'ouverture des cimes. Nous offrons une solution fort utile et assistée par ordinateur pour aider à standardiser cette procédure qui peut aussi être utilisée dans plusieurs autres situations où la délimitation de la cime des arbres est nécessaire comme c'est le cas avec la compétition et l'ouverture du couvert.

[Traduit par la Rédaction]

Introduction

Estimation of tree crown characteristics (e.g., width and leaf area index (LAI)) is important for multiple purposes in forestry and agroforestry systems. Because the last decade brought widespread availability of digital cameras, these characteristics are often estimated using photographs of tree crowns taken in the field rather than by direct onsite measurements. The crown characteristics derived from photographs include crown openness (CO) (Brown et al. 2000; Manson et al. 2006) and the much-used LAI (Macfarlane et al. 2007), as well as more simple crown dimensional parameters (Brown et al. 2000). These all require the crown profile outline (hereafter "crown outline") to be delineated. However, no standardized method to do so has been proposed so far. On the contrary, actual descriptions found in the literature of how outlines were traced are usually imprecise and leave a great deal to interpretation. Methods range from hand tracing (Canham et al. 1999) to the use of regular shapes from image-processing software (Beaudet et al. 2002; Macfarlane et al. 2007) and sometimes are not described at all (Astrup and Larson 2006; Manson et al. 2006). Although these methods

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were likely consistent within each study, the lack of a standardized method renders the comparison of estimated parameters among studies difficult, as acknowledged by Lefrançois et al. (2008).

One of the main reasons for determining crown characteristics is to include them in simulators to predict light filtering through canopies (e.g., Claveau et al. 2002; Friday and Fownes 2002; Kobe 2006). Many light models have been proposed over the years (e.g., Canham et al. 1994; Koop and Sterck 1994; Van Noordwijk and Lusiana 1998), with the simplest of them representing tree canopies as homogeneous monolayers characterized by random foliage distributions below which light attenuates exponentially with depth, not requiring individual crown parameters (Monsi and Saeki 1953; Sonohat et al. 2004). These models are adequate for dense monospecific and even-aged stands devoid of gaps, but are often inappropriate for natural and managed forests and agroforestry systems characterized by irregular, widely spaced canopy structures. In these cases, spatially explicit light models that simulate the annual run of the sun and then estimate the percentage of incident radiation intercepted by individual tree crowns are more suitable (Brunner 1998; Pacala et al. 1993).

Light interception by tree crowns depends on leaf orientation, density, and clumping (reviewed in Brunner 1998) and on crown architecture (Horn 1971). This can be modeled by the calculation of light ray interception or estimation of light attenuation as a function of the distance travelled through a three-dimensional crown (Brunner 1998; Leroy et al. 2009; Stadt and Lieffers 2000). A simpler yet effective method consists of representing crowns as two-dimensional objects that reduce the amount of light by a given amount, an attenuation factor, for each crown encountered (i.e., hit model) (Canham et al. 1994; Groot 2004). Hit models have the advantage of being simpler to parameterize and faster to run (Canham et al. 1999). The attenuation factor attributed to each crown hit can be determined mathematically (e.g., CORONA; Groot 2004) or empirically by measuring crown openness (CO) from hemispherical photographs with forest simulators such as SORTIE-ND (Canham et al. 2005) or SeXI-FS (Manson et al. 2006).

CO has been found to differ among species, tree size, and site characteristics (Astrup and Larson 2006; Lefrançois et al. 2008). Yet, the larger source of variation might lie in the method used to delineate crowns and determine its area, prior to computing CO itself. CO is measured as the ratio of the sky visible through the crown over the total crown surface of an individual tree (Canham et al. 1999) (for examples of tree crown outlines, see Fig. 1). This is not to be confounded with canopy openness as measured from a densiometer or hemispherical photographs, which can be considered the end results, at the stand level, of multiple layers of individual crowns. CO values, as well as a number of other crown descriptors computed from photographs, are therefore dependent on the determination of the crown outline.

The objectives of this paper were twofold. First, we present and test the new program Crown Delineator that automatically produces crown outlines using any of three mathematical algorithms and preset sensitivity levels. The outlines can then be used, for example, to calculate specific CO values. Second, we assessed the relative importance that different outlines can have on the outcome of forest dynamic simulations. The program was used to analyze the CO of saplings of four boreal mixedwood species and three hybrid poplar clones from a plantation, using seven different outlines varying from a loose rectangle to a very tight fit around the crown outline. Using SORTIE-ND (Canham et al. 2005), we performed light simulations with the seven CO values and a CO = 0 representing a completely opaque crown (eight simulations in total) and compared the results with observed values from both regenerating mixedwood boreal stands and a hybrid poplar plantation. As SORTIE-ND is a “hit model”, where the amount of light emitted from a section of the sky is altered by the number of crown hits on its path, we also analyzed how the average number of crown “hits” influenced simulation results to detect when variations in CO (and therefore in crown outline position) are more likely to cause light simulation variation.

Materials and methods

Data collection

Saplings from a young boreal mixedwood forest

The first part of the data collection for this study was conducted in the vicinity of La Tuque, Quebec, Canada (47°27′N, 72°47′W), within the balsam fir – yellow birch bioclimatic domain that is part of the boreal mixedwood forest zone (Saucier et al. 2009). We sampled 20 sites in the summers of 2007 and 2008 containing individuals of the four most abundant species, pin cherry (*Prunus pensylvanica* L.f.), aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* Marsh.), and balsam fir (*Abies balsamea* [L.] Mill.), as well as black spruce (*Picea mariana* [Mill.] BSP). Stands were naturally regenerating forests 9 to 14 years following clearcutting, with tree densities varying between 8 000 and 40 000 trees per hectare and stand heights between 3 and 6 m. On each site, all shrubs and trees (hereafter trees) with diameter at breast height (DBH) ≥ 5 cm were identified and mapped in a 12 m radius (species, DBH, azimuth, and distance from plot center). The same measurements were done for trees with DBH ≥ 3 cm within a 9 m radius and for trees with DBH ≥ 1 cm within a 7 m radius. A thorough description of the sampling method can be found in Boivin et al. (2010).

On each site, up to 20 individuals of each of the above five species were selected for allometric measurements. For each of these trees, we measured tree height, crown width (CW), and crown depth (CD). CW was defined as the average length of two measures: the widest crown diameter and its orthogonal projection to the ground. CD was the distance from the first leaf located on a nonepicormic branch to the top of the live crown. In all, 259 pin cherry, 283 paper birch, 333 aspen, 257 balsam fir, and 54 black spruce were sampled using that protocol. Using these data, crown geometry equations for these species were determined using least squares linear and nonlinear regression (Supplementary material *a*)[1] (Canham et al. 1999) and later were used to simulate understory light.

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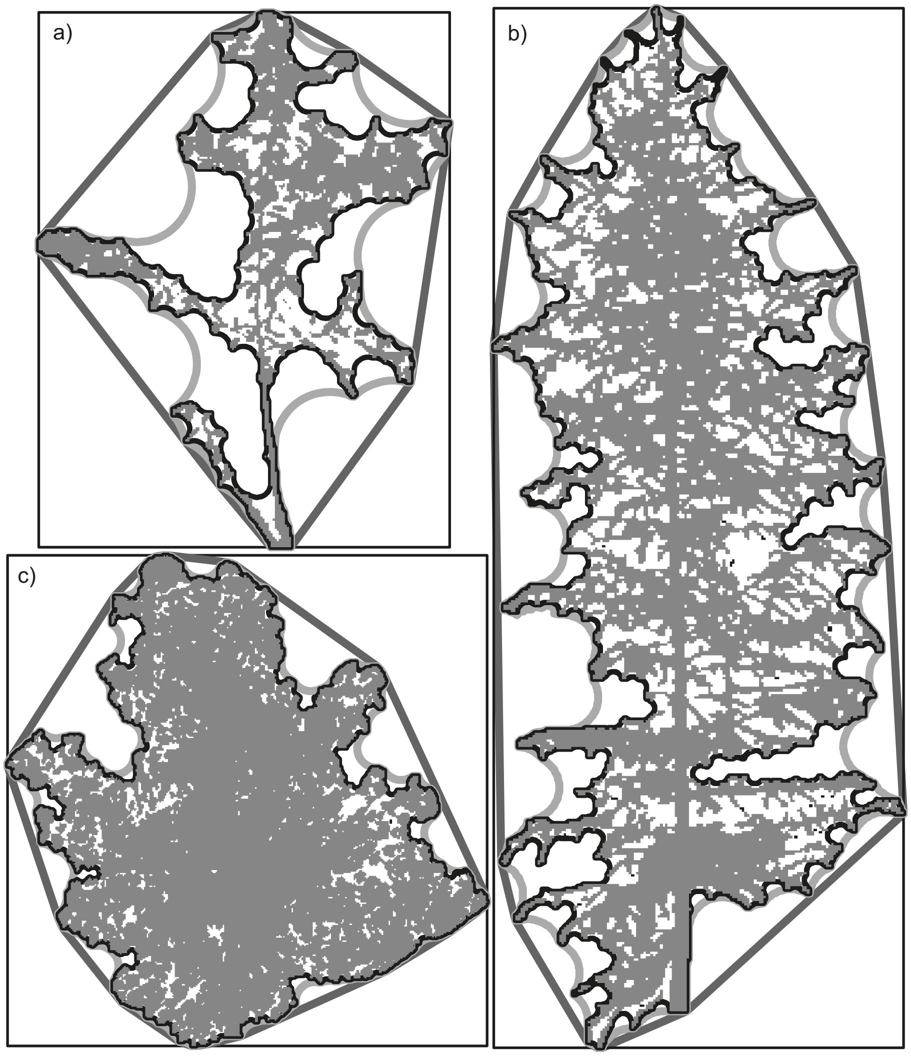
[1] Supplementary materials are available with this article on the journal Web site (http://nrcresearchpress.com/cjfr).

Fig. 1. Examples of four of the seven crown outlines delineated in Crown Delineator for three contrasting tree species and sizes: (*a*) a 3.5 m pin cherry and (*b*) a 7.1 m balsam fir, both from young mixedwood stands, and (*c*) a 12.2 m hybrid poplar from a plantation (Paquette et al. 2008). Digital photographs were first converted to black and white binary images (see text). The rectangle outline (black line surrounding the entire crown and comprising the letter) is the smallest rectangle perpendicular to the ground that includes the entire crown. The convex hull outline (dark gray) is the smallest convex polygon comprising the entire crown. The remaining two outlines are based on geometrical buffers for which the outline corresponds to the trace that would leave the edge of a "moving" disc of a certain radius circling the crown. The disc cannot pass through black pixels (crown foliage or branch). The radii of the discs (in pixels) for the two outlines are 160 (light gray) and 40 (black line tightly following the edge of the crown). A color image with the seven outlines is available online (Supplementary material *b*).[1]



On nine sites, up to five trees per species among the four most abundant (pin cherry, aspen, paper birch, and balsam fir) were systematically picked for CO analysis (one of every four selected trees turning clockwise and starting from North). Black spruce was not used because not enough of them were available to be representative. Each tree was cut and moved to a nearby clearing to facilitate the taking of a hemispherical photograph of its crown. Photographs were taken using a Nikon Coolpix 990 digital camera equipped with a FC-E8 Fisheye Converter (Nikon Corporation, Tokyo, Japan) at a resolution of 2048 × 1536 pixels. It is important to note, however, that the method does not require the tree to be cut. In our case, trees needed to be cut to determine their age and growth rate using growth ring analysis as required for a companion study on competition (Boivin et al. 2010). This type of measurement is usually performed on trees in closed-canopy forests without having to cut them by moving around the tree to find an orientation where the crown is isolated from neighbours (Canham et al. 1999; Lefrançois et al. 2008). Consequently, orientation and angle of crown photographs relative to a horizontal plan are usually not held constant (Beaudet et al. 2002; Canham et al. 1999). In our case, photographs were centered on the crown at an angle of 20° to 40° relative to the horizon and at various orientations, depending on the space available to take the photograph. Based on previous studies that found no (Astrup and Larson 2006) or small (Lefrançois et al. 2008) influence of angle of photographs on crown openness, we assume that these variations in angle and orientation can be safely ignored at least for the focus of this study, i.e., the development and testing of an automated crown delineation method. A total of 151 crown photographs were taken (40 paper birch, 41 pin cherry, 38 aspen, and 32 balsam fir).

Trees from a hybrid poplar plantation

To analyze the influence of crown delineation on medium-sized trees, we reanalyzed the CO values of three hybrid poplar clones (average DBH = 10 cm) from a plantation that was part of an agroforestry system established in 2000 near St-Rémi, southern Quebec, Canada (45°14′N, 073°40′W). More details than those summarized here can be found in Paquette et al. (2008) and Rivest et al. (2009). The plantation was established in a 3 ha field divided in two spacing trials (12 m and 16 m between poplar rows), each separated into four randomized blocks containing all three hybrid clones. Trees were planted at 2 m intervals in five rows in each trial. The three hybrid poplar clones were among those available for reforestation in Quebec and came from contrasting lineage: clone 3230 ($n = 6$, *Populus trichocarpa* × *P. deltoides*), clone 3308 ($n = 5$, *P. deltoides* × *P. nigra*), and clone 3729 ($n = 5$, *P. nigra* × *P. maximowiczii*). Hemispherical photographs of the crowns of the standing hybrid poplar clones were taken in the plantation in 2006 at 3 m from the trees on both sides of the rows. In this case, hemispherical photographs were taken upwards and not centered on tree crown. This caused the crowns to be off-center in the photographs and the angles relative to the horizon and tree crown to vary. The fact that the photographs were not centered on tree crown diverges from the method used for the saplings of the mixedwood forest, which limits our capacity to draw comparison between results from both data sets. However, this allows us to test the effect of crown delineation on different data, which was our main objective.

Analyses of CO by Crown Delineator

The procedure used to determine CO is based on the technique described in Canham et al. (1999). For each crown photograph, pixels of leaves, branches, and the main trunk within the live crown were converted to black and pixels of the sky and of the trunk and branches below the live crown were converted to white. Seven outlines were automatically traced for each crown using Crown Delineator (Fig. 1). The first outline tested was defined as the smallest rectangle perpendicular to the ground that included the entire crown. The second outline used the convex hull algorithm and created the smallest convex polygon comprising the entire crown, that is, the smallest closed surface that can be created using straight lines and no angles superior to 180°. The remaining five outlines were based on geometrical buffers for which the outline corresponds to the trace that would leave the edge of a “rolling disc” circling the edge of the crown. The radii of the discs for the five geometrical buffer outlines were 320, 160, 80, 40, and 20 pixels, with smaller buffer radii corresponding to finer crown delineations (Fig. 1). For each of the outlines, a different CO value was then calculated as the ratio of white pixels to the total number of pixels within the crown. CO_{rect}, CO_{CH}, CO_{320}, CO_{160}, CO_{80}, CO_{40}, and CO_{20} correspond to the CO as measured using the number of crown pixels within the rectangle, the convex hull, and the five geometrical buffer outlines, respectively. Crown Delineator is available as a free online supplement to this article. Two versions of Crown Delineator exist to make it easier for researchers to use. The first was written in Python (Python Software Foundation, http://www.python.org/psf/) and requires ArcGIS 9.3 (ESRI, Redlands, California, http://www.esri.com/) to run (Supplementary material *c*).[1] The second was written in R (R Foundation for Statistical Computing, Vienna, Austria, http://r-project.org) using the spgrass6 package for GRASS GIS (Howeth and Leibold 2010) (Supplementary material *c*).[1]

Observed vs. predicted understory light using different CO

To assess light conditions in the boreal mixedwood stands, eight hemispherical photographs were taken at each site (hereafter “site hemispherical photographs”) using the same camera and settings as for the crown photograph. The camera was mounted on a leveled tripod. Photographs were taken at every half-cardinal direction 3 m from the center of the plot at a height of 1.4 m from the ground. Two photographs were taken at each location, and the one with the least sun glaze was kept for further analysis. Hemispherical photographs are routinely used to characterize forest understory light climates (Gendron et al. 1998; Paquette et al. 2007).

We explored the effect of varying crown outline positioning to estimate CO on light simulation using SORTIE-ND (Canham et al. 2005) and compared the result of the simulations with observed light measurement. Observed light measurements (gap light index (GLI)) were estimated by analyzing the site hemispherical photographs with Gap Light Analyzer v.2.0 (GLA; Frazer et al. 2000). We discarded photographs in which leaves were present near the camera lens as these cause an underestimation of GLI (Paquette et al. 2007). Overall, 103 photographs from 18 sites (from the 20 sites where the trees were sampled, 2 of the 20 sites did not have photographs taken due to camera problems) covering light conditions from 0.067 to 0.687 fraction of above-canopy light (average 0.233) were used as validation points.

We used the SORTIE-ND (Canham et al. 2005) light model to simulate light conditions at the validation points using the mapped stand data, the crown geometry equations, and CO values of the studied species. SORTIE-ND predicts available light (GLI) as the fraction of the light emitted by the sky reaching the focal point in the same fashion as GLA by producing and analyzing hemispherical images of the modeled canopy, making our observed and simulated values perfectly compatible (Canham et al. 1994). The simulations were performed eight times using each CO value drawn from the seven outlines and an additional time assigning a CO of 0 to all species (opaque crowns). A CO of 0 is sometimes used to speed up analyses (Canham et al. 2004; Stadt et al. 2007). All other parameters were kept constant. Only the light emitted above 45° from the horizon was included in the calculations (Canham et al. 2004). The four modeled species represented 87% of the trees in our sites, and we assigned CO and allometric equations of similar species to those species for which real values were unknown (Hartmann et al. 2009), except for black spruce allometry for which we had specific equations. For example, paper birch crown geometry and CO values were assigned to yellow birch (*Betula alleghaniensis* Britton). We used least squares linear and log-log regressions to compare the light predictions of SORTIE-

ND with observed light measurements for each simulation. Regression slope and intercept were used to evaluate the effect of outline delineation on simulation results. All analyses were made in JMP 7.0 (SAS Institute Inc., Cary, North Carolina).

In addition, we reproduced the SORTIE-ND light simulation for the 48 validation points of the original study of Paquette et al. (2008) using the same crown geometry equations and parameters, except for CO values for which we used the seven outputs from Crown Delineator and CO = 0, as well as the original hemispherical photographs taken at 1 m from the ground in 2005. The crown geometry and parameters are available in Paquette et al. (2008). Validation points where the hemispherical photographs were taken were located every 1 m from the center of the poplar row in opposite directions perpendicular to the center row up to a distance of 6 m in the 12 m spacing trial and to a distance of 8 m in the 16 m trial. The tree map was simply drawn from the original design.

Analyses of crown hits

The SORTIE-ND light model is a "hit" model in which the energy of each light ray is multiplied by the CO values of each crown encountered between the sky and the focal point where light is simulated. We explored the influence of the average number of crown hits by light rays on light predictions by determining the average number of hits for the 103 validation points of the young mixedwood stands and for the 48 validation points of the hybrid poplar plantation using GLI Ray Analyzer (L. Canham and C. Murphy, Cary Institute of Ecosystem Studies, Millbrook, New York (available online at http://www.sortie-nd.org/other_downloads/index.html). For each point, the number of hits was calculated in 16 directions (every 22.5°) at three angles (45°, 60°, and 75°), which represents a 8% sampling rate of the 36 × 16 rays (576) used in light simulations. The number of crown hits was averaged across all light rays for each validation point. The relation between the predicted light for the different CO values and the average number of crown hits was determined with least-squares exponential regression in JMP. We also performed the ray interception analysis for the 48 validation points of the plantation.

Results

Crown openness (CO) as calculated with different crown delineation

As expected, for all saplings of the mixedwood species and the medium-sized hybrid poplar trees, there was a clear trend of increasing CO with increasingly looser outlines (Fig. 2). The increase was more progressive for the saplings of the mixedwood species than for the medium-sized hybrid poplar clones. The difference in CO between the loosest (CO_{rect}) and tightest (CO_{20}) outline was important (at least halved in all cases) and in the same range for all species and clones ($\Delta CO = CO_{rect} - CO_{20}$, minimum $\Delta CO = 0.38$, maximum $\Delta CO = 0.42$).

Effects of varying CO on predicted understory light using SORTIE-ND

We used SORTIE-ND to predict light eight times for each of the 103 validation points of the young mixedwood stands, changing only species CO between simulations using the seven CO estimated based on the outline traced by Crown Delineator and CO = 0 (opaque crown). The regression of predicted to observed light was highly significant for all simulations ($p < 0.0001$) but differed among each other (Fig. 3*a*). Intercepts of the linear regressions were similar for all simulations ranging from –0.06 to –0.03 except for the simulation using CO_{rect}, which had an intercept of 0.04 (Fig. 3*a*). Slopes were more variable and ranged from 0.16 when CO = 0 to 0.83 when CO_{rect} was used (Fig. 3*a*). The fit of the linear regressions were similar (R^2 between 0.46 and 0.52) except for CO = 0. That simulation produced 92 zero values out of 103 simulations and accordingly had the worst fit ($R^2 = 0.28$). The least biased simulations were obtained using CO_{rect} (slope = 0.832, $R^2 = 0.51$), although simulations using CO_{160}, CO_{320}, and CO_{CH} were slightly more precise ($R^2 = 0.52$). We presented the above linear regressions because they are easier to interpret graphically and enable the direct comparison of CO results based on slopes and intercepts. However, the fitness of the boreal mixedwood regressions were biased due to an expected heteroscedasticity of the error (with more variance and fewer data at higher light levels) (Fig. 3*a*, insert), suggesting that log-log regressions should be used. As expected, the fitness of the regressions was thus reduced to between 0.36 and 0.42 (except for CO = 0; 0.019), but the ranking and interpretation did not change: CO_{rect} still was the best, least biased simulation.

It should be noted also that we did not account for spatial autocorrelation in computing fitness values (to account for the fact that within-site observation points were spatially related). Accounting for it would indeed increase the fit of a model by including a spatial component (ANCOVA with site as a covariable and a nested effect); however, it would also make it nearly impossible to compare the overall slopes and intercepts of the general relationships. Because our focus was on the comparison of simulated and observed values, we used several sites to increase the range of light climate on which to test that relation and therefore did not account for the spatial autocorrelation of validation points.

For the poplar plantation, the relation between predicted and observed light ($p < 0.0001$ in all cases; Fig. 3*b*) also varied with CO used. The intercept of the linear regressions varied more in the plantation than in the mixedwood stands, ranging from –0.01 to 0.43. Regression slopes also varied (0.55 to 0.95), although less than for the mixedwood stands. Precision was similar among all simulations ($R^2 \sim 0.90$). Contrary to simulations in the mixedwood stands, the least biased predictions came from simulations using CO = 0, with a slope of 0.95. Nonetheless, over the sampled light range, simulations using CO_{20} were closer to the real light values, even if the slope of the regression diverged further from unity (0.91; Fig. 3*b*).

Effects of crown hits

The average number of crown hits by light rays for each of the 103 validation points of the mixedwood stands varied between 1.3 and 11.8. The light predicted by SORTIE-ND at the validation points declined exponentially, with an increased number of hit for all simulations ($R^2 \geq 0.90$), except when light was predicted using CO = 0. For simulations using CO_{20}, most validation points had predicted GLI < 0.05

Fig. 2. Mean crown openness (CO) measured from seven crown outlines (Fig. 1) for (*a*) saplings of pin cherry (▬, *n* = 41), aspen (◆, *n* = 38), paper birch (●, *n* = 40), and balsam fir (★, *n* = 32), and (*b*) three clones of hybrid poplar (Paquette et al. 2008): 3230 (▬, *n* = 6), 3308 (●, *n* = 5), and 3729 (★, *n* = 5). Error bars are one standard deviation.

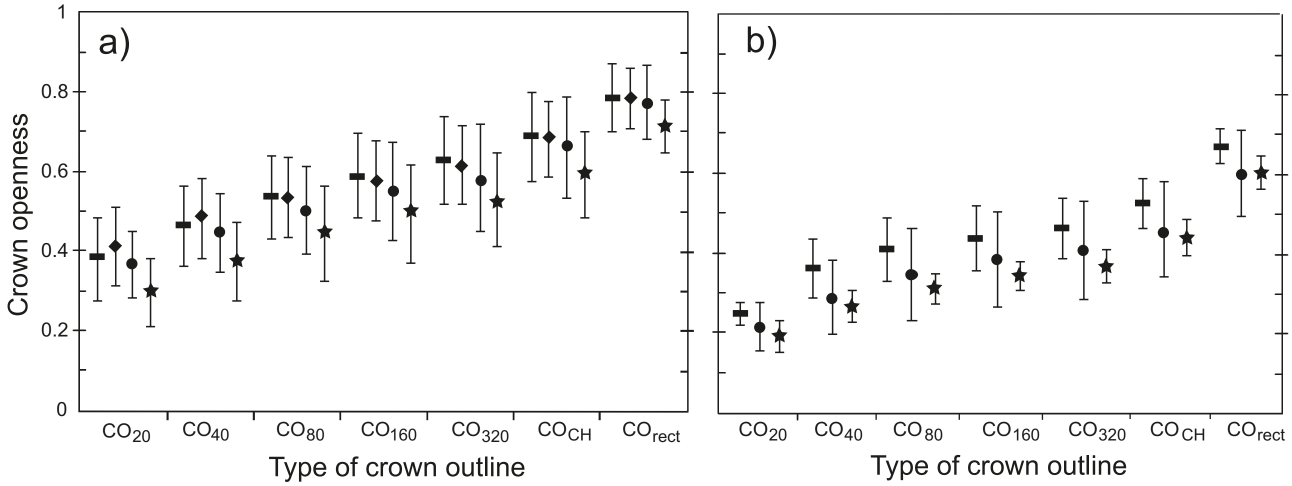
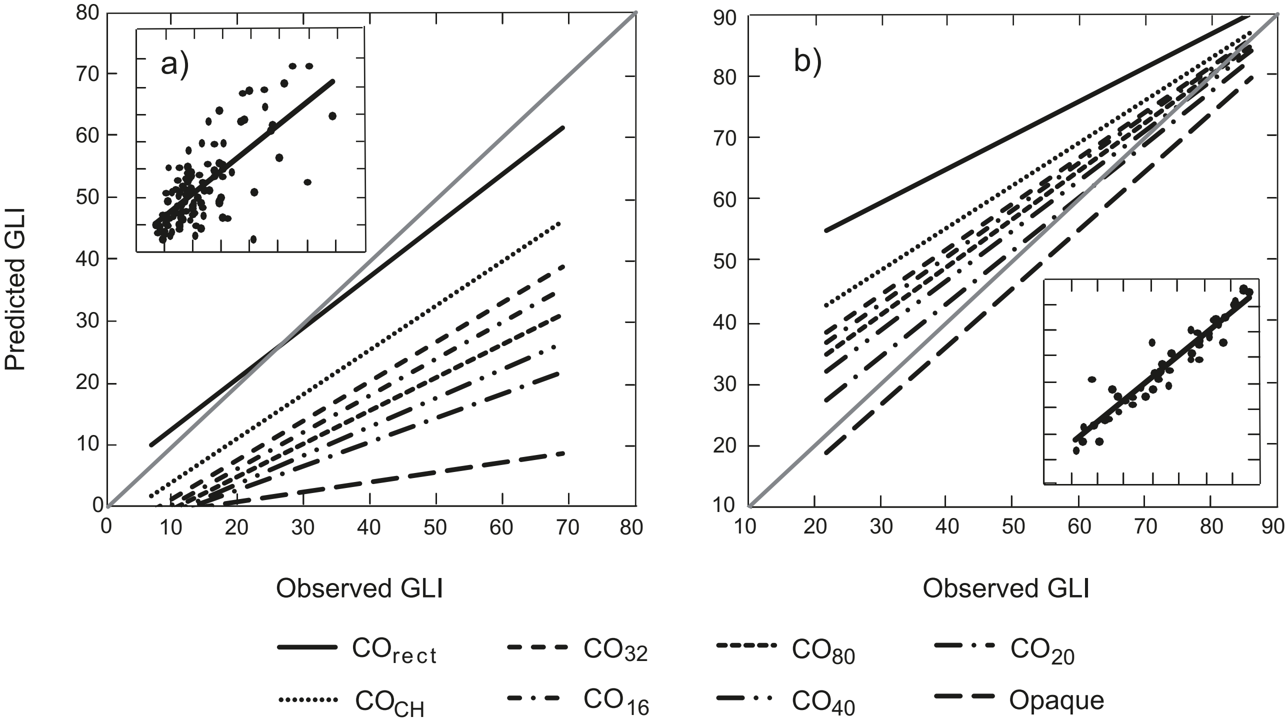
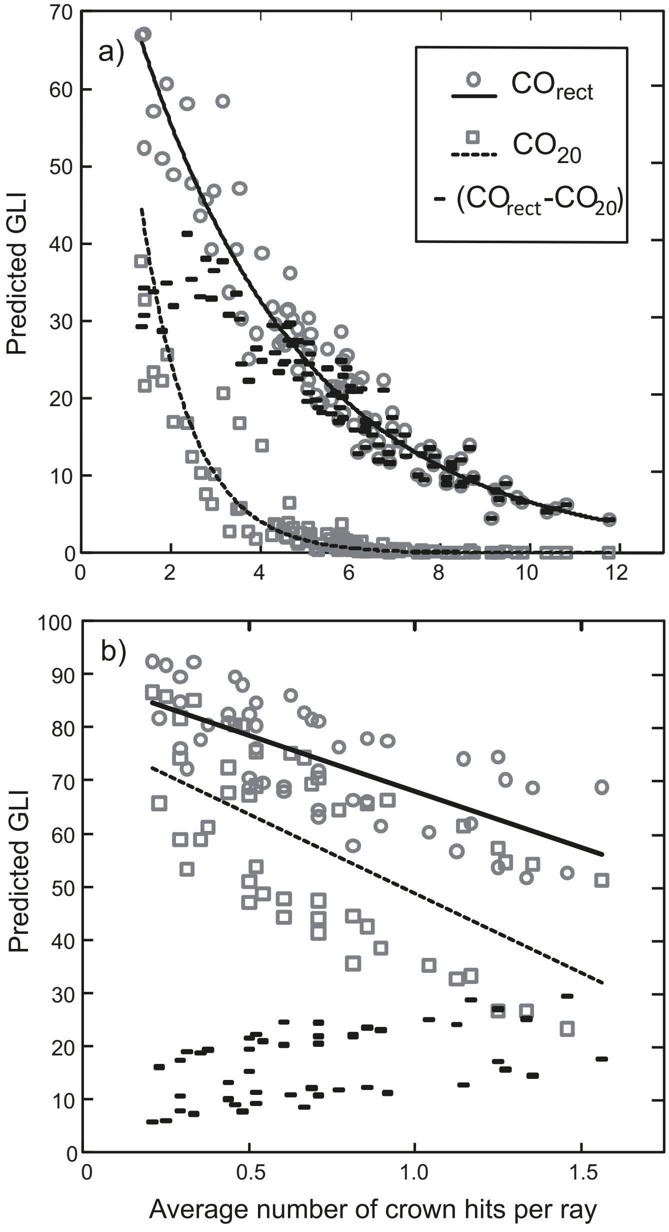


Fig. 3. Linear regression lines of gap light index (GLI) predicted by SORTIE-ND using different crown openness (CO) values calculated from seven crown outlines and an opaque crown (CO = 0) as a function of observed GLI obtained by the analysis of hemispherical photographs using Gap Light Analyzer (GLA; Frazer et al. 2000) for (*a*) 103 validation points from 18 boreal mixedwood stands and (*b*) 48 validation points from a hybrid poplar plantation (Paquette et al. 2008). Diagonal lines are 1:1 relationships. All regressions were highly significant ($p <$ 0.0001). Slopes of the eight linear regression lines varied in (*a*) from 0.16 to 0.83 and in (*b*) from 0.55 to 0.95; and the intercepts varied from –0.06 to 0.04 and from –0.02 to 0.43, respectively. Inserts show predicted GLI as a function of observed GLI and linear regression lines of the respective best simulation: CO_{rect} in (*a*) ($y = 0.043 + 0.83x$, $R^2 = 0.51$) and CO_{20} in (*b*) ($y = 0.086 + 0.86x$, $R^2 = 0.91$). Because the error variances from the boreal mixedwoods were heteroscedastic (as shown in the insert), they were also analyzed using log-log regressions, again with CO_{rect} providing the best relationship ($\ln(y) = -0.32 + 0.83\ln(x)$, $R^2 = 0.42$).



when the average number of hits reached four or more (Fig. 4*a*). With an average of four hits, the simulation using a more open crown (CO_{rect}) still had a predicted GLI of ~0.3. Moreover, predicted GLI using CO_{rect} was still ~0.05 when the average number of hits reached 12. The maximum absolute difference in predicted GLI between the CO_{20} and CO_{rect} simulations occurred around an average of two to three hits per ray and declined with an increasing number of hits (Fig. 4*a*). The same pattern was observed between all others simulations.

Fig. 4. GLI predicted by SORTIE-ND as a function of the average number of crown hits by 48 light rays emitted from angles of 45°, 60°, and 75° at every 22.5° of azimuth for (*a*) 103 validation points in 18 boreal mixedwood stands and (*b*) 48 validation points from a hybrid poplar plantation. In both cases, results are from two different light simulations of the same validation points using either CO_{rect} or CO_{20}. Only these two cases are shown for clarity. Solid lines are regressions of the predicted GLI for CO_{rect} (*a*) exponential regression $y = 0.94e^{-0.265x}$, $R^2 = 0.93$, and (*b*) linear regression $y = 0.89 - 0.21x$, $R^2 = 0.49$; dotted lines are regressions for CO_{20} (*a*) exponential regression $y = 1.46e^{-0.895x}$, $R^2 = 0.90$, and (*b*) linear regression $y = 0.79 - 0.30x$, $R^2 = 0.40$. Black dashes are the differences between predicted light by both simulations.



The ray analysis was also performed for the validation points of the hybrid poplar plantation, and results differed markedly from the mixedwood stands. First, as expected, the average number of hits was much lower, ranging from 0.2 to 1.6, with an average of 0.7 (Fig. 4*b*). The light predicted by SORTIE-ND in relation to the number of hits was better explained by a linear relationship ($R^2 = 0.4$ to 0.49). Maximum differences in light predictions between CO_{rect} and CO_{20}, both in absolute and relative terms, occurred at low light when the number of hits averaged 1.6 per ray.

Discussion

Variations in CO values based on different outlines

CO as estimated from the seven outlines traced by Crown Delineator varied by a factor of two in all cases between the tightest and loosest outlines. The difference was more gradual for the naturally growing saplings of the mixedwood species than for the medium-sized trees of the hybrid poplar plantation. This was probably due to the smaller and more irregular crowns of the saplings relative to the plantation-grown hybrid poplars and the consequent greater relative effect of moving the outline over a small and irregular surface (see Fig. 1*a*). This could also be due, in part, to the fact that crown photographs of the hybrid poplars were not centered on the hemispherical photographs, which may have caused some distortion to occur. The fact that crown delineation influenced CO for both types of photographs and for very different types of trees (small saplings from dense forest versus open-grown hybrid poplar) concurs with our general argument that location of outlines matters when estimating crown characteristics from photographs.

Interaction between CO, number of hits, and light simulations

A large effect of CO variation on light predictions in young mixedwood stands was observed when the average number of crown hits per light ray was between one and four, with the peak located between two and three (Fig. 4*a*). This is explained by the structure of the model, which multiplies the "energy" of light rays by the CO of each crown it hits. This structure implies that the relative difference in energy of two light rays will increase after each passage through crowns with different CO. On the other hand, the absolute difference in energy between rays peaks after two or three hits and declines steadily with subsequent hits. This decrease in absolute difference causes the GLI estimates of light simulations to converge after about three hits and reduces the importance of CO variations in denser stands. Therefore, the sensitivity of the light model to CO variations depends on stand structure.

The maximum difference in predicted GLI among simulations for both types of stand occurred at opposite ends of the light range (Fig. 3). This is a consequence of the number of crown hits being nearly equal (~1.5) for both type of stands at these opposing ends of the light gradient (GLI ~ 0.7 for the mixedwood stands and GLI ~ 0.2 for the plantation). The objective of most forest light models is ultimately to predict understory tree growth as of function of light, which usually follows an exponential increase at low light before reaching a maximum (Pacala et al. 1994). Therefore, differences caused by the variation in CO values that can be caused by crown delineation will likely be more important for stand development predictions when they occur at the lower light range as in the hybrid poplar plantation.

It is yet not clear which outline is best to choose in different situations as CO_{rect} and CO_{20} gave the best simulation results in the mixedwood forests and the hybrid poplar plantation, respectively. It is quite possible that no single outline will be best in all cases, as illustrated here using the ray hit model. It is also possible that the differences found between our two settings stems from differences in how photographs were taken. To decide which type of crown outline produced by Crown Delineator is best for CO estimations, we recommend that more tests be carried out on other tree species in other settings with a standardized photograph technique. This next step is already taking place in Spain and in Panama, where other researchers are using the program (L. Coll and J. Sapijanskas, personal communications). The most important outcome of the development of Crown Delineator was to provide a tool to standardize crown outline tracing.

Other possible uses for Crown Delineator

Crown Delineator could serve in other types of light analyses such as the study of light harvest of scattered trees in open agroforestry systems (Montero et al. 2008) or for studying crown shyness (Meng et al. 2006; Rudnicki et al. 2001). For example, Rudnicki et al. (2001) used a GIS program to study crown collisions caused by wind. The shape files of crowns created by Crown Delineator could be incorporated in a GIS program to perform this type of analysis using actual crown shapes photographed in the stand. GIS programs could also be used to measure mean distances between crowns as a function of species, tree bole size, etc. Shape file output could also be used to quickly measure individual crown dimensional parameters (Brown et al. 2000) such as perimeter, surface ratio, and volume, and more importantly, results could be directly compared between studies. The evaluation of crown LAI from photographs (Macfarlane et al. 2007) also requires the prior delineation of crown perimeters, which could be standardized using Crown Delineator. The design and study of windbreak porosity in agricultural systems would also benefit from a reproducible, reliable method of crown delineation.

Conclusions

We have proposed and tested a new program that automatically and reliably traces tree crown outlines free of user bias. Crown Delineator can be used to evaluate CO or other crown characteristics from any photograph, including the reanalysis of older images from previous studies (such as what was done here with hybrid poplars). Analysis of the program output showed that this step is especially important for CO estimations of small naturally growing trees such as saplings, whereas medium-sized, more regular trees were more robust to CO evaluation. These variations had important effects on the outcome of light simulations and likewise should be important for any forest dynamic simulation that models growth as a function of light. Indeed, the best simulations in young mixedwood stands and the hybrid poplar plantation were obtained using CO values drawn from the tightest and the largest outline, respectively. It is not yet possible to determine the cause of such a difference, although variation in the method used to take crown photographs may explain part of the difference. Ongoing research in other laboratories might shed light on this soon. However, this result also highlights the necessity of standardizing the way in which outlines are traced in future studies. For these reasons, we feel that Crown Delineator is a useful tool that should help researchers obtain better, replicable estimates of tree crown openness. We also feel that the influence of crown delineation on other tree crown parameter estimation from photographs (e.g., LAI, volume) should be explored.

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