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Predictions of understorey light conditions in northern hardwood forests following parameterization, sensitivity analysis, and tests of the SORTIE light model

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Abstract

We parameterized the light model of SORTIE for northern hardwoods in eastern Canada, and performed a sensitivity analysis and validation tests of the model before using it to predict the effect of various types of partial cutting on understorey light conditions. The parameterization was done by characterizing the crown geometry and openness of sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britt.), and beech (*Fagus grandifolia* Ehrh.). Those results indicated that beech casts a deeper shade than sugar maple and yellow birch. The sensitivity analysis showed that the model predictions were more sensitive to variations in the crown geometry parameters, especially the crown radius parameter, than to variations in crown openness. Validation tests of the model were performed in both mapped and unmapped plots by comparing light predicted by SORTIE to light measured in the field using hemispherical photographs and sensor-based measurements. In mapped stands, the model provided reasonably accurate predictions of the overall variation in understorey light levels between 2 and 30% full sunlight, but the predictions tended to lack spatial precision. In unmapped stands, SORTIE accurately predicted stand-level mean light availability at 5 m aboveground for stands ranging in basal area from 19 to 27 m^2/ha. At heights lower than 5 m, SORTIE accurately predicted the light availability in a recent selection cut with a low density of understorey vegetation, but tended to overestimate light availability in stands with relatively dense undergrowth. Finally, a demonstration of the possible usefulness of the SORTIE light model is presented by using the model to compare the proportion of various light microsites created by a variety of selection cutting systems in use in eastern Canada (selection cutting with different harvesting intensities, group selection, and patch selection).

Keywords: Light transmission; SORTIE model; Northern hardwoods; *Acer saccharum*; *Betula alleghaniensis*; *Fagus grandifolia*

1. Introduction

The effect of partial cutting on understorey light conditions is an important factor to control to obtain the desired species composition of tree regeneration (Coates and Burton, 1997). The understorey light availability is important because at the microsite level, light is a major determinant of tree growth and survival (Bazzaz, 1979; Björkman, 1981; Pacala et al., 1994; Kobe et al., 1995; Beaudet and Messier, 1998). At the community level, variations in light conditions can affect important processes such as species succession

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(Forcier, 1975; Canham and Marks, 1985; Beaudet et al., 1999). The effect of partial cutting on understorey light conditions can be controlled, at least partially, by adjusting the size and location of canopy openings. Different harvesting options are available to forest managers such as selection cutting, group selection, and patch selection, all with possible variations in the harvesting intensity, and in the size and location of openings (Coates and Burton, 1997; Ministère des Ressources Naturelles du Québec, 1998; Lessard et al., 1999).

Determining which silvicultural system will produce the optimal distribution of light levels at the stand-level is not necessarily easily accomplished with field studies. Field-based comparisons of various silvicultural systems require harvesting the trees according to the different silvicultural prescriptions while controlling for the confounding effects of variation among stands in factors such as species composition, diameter distribution, stem density, abundance of understorey vegetation, soil conditions, and topography. Exhaustive light measurements are then required to capture the temporal and spatial variations in light availability. Of course, a well-planned experimental design and sampling protocol will enable successful and useful field-based investigations. However, an alternative approach could be to use simulations obtained from a forest light model. Numerous forest light models have been developed in the recent years (e.g., Koop and Sterck, 1994; Cescatti, 1997a; Stadt and Lieffers, 1998). However, the utility of a forest light model in exploring different harvesting options in a wide range of stands is often limited by the large data requirements of the model. For instance, it is not uncommon among existing forest light models that the measurement of the crown dimensions and precise location of each individual tree present in a stand is required to obtain predictions of understorey light levels. Compared to most existing forest light models, the amount of input data required by the SORTIE light model is remarkably small (Pacala et al., 1993).

SORTIE is a spatially explicit forest dynamics model which was originally developed for the transition oak–northern hardwood forests of northeastern North America (Pacala et al., 1993, 1996). Recently, the model has been parameterized and adapted for forests of British Columbia (Canham et al., 1999). The light model in SORTIE predicts light conditions in terms of the gap light index (GLI), which specifies the percentage of incident photosynthetically active radiation (PAR) that is transmitted through gaps in the forest canopy to a specific location in the understorey over the course of the growing season (Canham, 1988). The SORTIE light model predicts GLI for any location in a forest stand based on a relatively simple representation of the forest canopy. The predicted GLI is a function of (i) the location, DBH (diameter at breast height), and species identities of trees in the vicinity, (ii) species-specific relationships that define crown geometry as a function of DBH, (iii) species-specific crown openness, and (iv) local sky brightness distribution (Canham et al., 1999).

We had four objectives in this study. (i) The first was to parameterize the light model of SORTIE for northern hardwoods in Quebec through a characterization of crown geometry and openness for sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britt.), and beech (*Fagus grandifolia* Ehrh.). (ii) The second objective was to evaluate the sensitivity of SORTIE light predictions to variations in the values of the crown geometry and openness parameters. (iii) The third objective was to test the predictions of the SORTIE light model in stands that differed in basal area, cutting history, and density of understorey vegetation. Two tests of the model were performed. First, we compared GLI predicted by SORTIE to observed GLI in four mapped stands. However, if the model is to be used to predict the effects of different harvesting systems on understorey light conditions, we cannot assume that SORTIE will always be provided with a detailed map of the stands. It is more likely that only standard forest inventory data will be available (Stadt and Lieffers, 1998). This is why a second test of the model was performed in which individual trees were randomly positioned by SORTIE based on stand basal area and species-specific DBH distributions. (iv) Finally, the fourth objective was to use the SORTIE light model to compare the effects of various harvesting scenarios on stand-level patterns of light availability in northern hardwood stands. The silvicultural systems that we compared were selection cutting with two different harvesting intensities, group selection, and patch selection (Ministère des Ressources Naturelles du Québec, 1998).

2. Methods

2.1. Parameterization of the SORTIE light model for yellow birch, sugar maple, and beech

2.1.1. Crown geometry

The SORTIE light model requires three functions that describe crown geometry for each species: (i) tree height as a function of DBH, (ii) crown depth as a function of tree height, and (iii) crown radius as a function of DBH (Canham et al., 1999). We measured saplings and mature trees of yellow birch, sugar maple, and beech from two stands (DUC89 and DUT89, Table 1) at the Duchesnay Forest Station (46°56′N, 71°40′W), approximately 40 km northwest of Quebec City. Approximately 15 trees ($\mathrm{DBH} > 10\,\mathrm{cm}$) of each species were selected in each stand. The base of the crown was defined as the lowest point where foliage was found on non-epicormic branches. Crown depth was calculated as the distance between the top of the tree and the base of the crown. Crown radius was measured in the four cardinal directions, and the mean crown radius was calculated for each tree. For saplings, we used individuals with $\mathrm{DBH} > 1\,\mathrm{cm}$ and height $> 1.5\,\mathrm{m}$ from the data set of Beaudet and Messier (1998), supplemented with data collected on saplings in the two study sites at Duchesnay. Total sample size (saplings and adult trees) was 53, 43, and 52 for yellow birch, sugar maple, and beech, respectively. The DBH of sampled trees ranged from 1 to 50 cm, and height ranged from 1.5 to 30 m.

Nonlinear least-squares regression was used to predict tree height as a function of DBH using the equation

$$\mathrm{Height} = \mathrm{MaxHeight}[1 - \mathrm{e}^{-(\mathrm{DBH} \times h/\mathrm{MaxHeight})}] \qquad (1)$$

The equation produces a curve with an exponential approach to an asymptotic maximum height (MaxHeight) with the steepness of the curve controlled by the exponential decay parameter h (Canham et al., 1999). A value of 30 m was arbitrarily given to MaxHeight for the three species because our samples did not contain large enough trees to independently estimate maximum tree height. Least-squares regression was used to express crown depth as a linear

Table 1
Characteristics of the four stands where validation test 1 was performed (BA: basal area)

	St-Gilles (STG)	DUT89	DUC92-1	DUC89
Location	St-Gilles	Duchesnay	Duchesnay	Duchesnay
Cutting history	Clear-cut in the 1930s	Highgrading prior to 1950	Selection cut in 1992 (24% of BA)	Selection cut in 1989 (30% of BA)
Basal area[a] (m^2/ha)	29.8	28.2	20.8	19.5
Density[a] (n/ha)	496	398	510	349
Tree species composition (% BA)[a]				
Sugar maple	79.2	50.4	80.1	63.5
Yellow birch	0.7	12.0	16.3	22.7
Beech	16.4	36.4	2.5	13.8
Other[b]	3.7	1.2	1.1	0
Density of understorey vegetation (n/ha, $1\,\mathrm{cm} < \mathrm{DBH} < 10\,\mathrm{cm}$)				
All species	367	1822	289	267
Sugar maple	356	178	167	89
Yellow birch	0	289	56	78
Beech	0	1289	33	0
Other[c]	11	66	33	100

[a] Of trees with $\mathrm{DBH} > 10\,\mathrm{cm}$.
[b] Other tree species included: *Abies balsamea*, *A. rubrum*, *Ostrya virginiana*, *Populus tremuloides* (in STG); *A. balsamea*, *Picea rubens* (in DUT89); *A. balsamea*, *Fraxinus americana* (in DUC92).
[c] Other species included: *O. virginiana* (in STG); *P. rubens*, *Sambucus pubens*, *V. alnifolium* (in DUT89); *A. spicatum*, *S. pubens* (in DUC92); *Prunus pensylvanica* (in DUC89).

function of height (crown depth $= d \times$ height, where both crown depth and tree height are in meters), and mean crown radius as a linear function of DBH (crown radius $= c \times$ DBH, where the radius is in meters and DBH is in centimeters).

2.1.2. Crown openness

The method we used to determine species-specific mean crown openness is similar to that described in Canham et al. (1999). It is based on image analysis of tree crown photographs. A 35 mm Canon camera equipped with a Canon 50 mm 1:1.8 lens was used with Kodak MAX 400 ASA color film. Photographs of individual tree crowns were taken with the lens pointing at the crown at an angle between 45° and the zenith. This range of angles corresponds to the range of angles taken into account in SORTIE. Photographs were taken under overcast conditions to minimize glare from direct sunlight and to improve contrast between sky and foliage. Sample size (number of trees) was 12 for yellow birch, 21 for sugar maple, and 20 for beech. After processing, the photographs were scanned and analyzed using PhotoShop 5.0. A threshold level was selected for each photograph and the color image was transformed into a black and white image. The area occupied by the crown on each image was selected (using the Marquee tool of PhotoShop 5.0) and the percent crown openness of each tree was calculated as the percentage of white pixels for that portion of the image (obtained using the Histogram tool of PhotoShop 5.0). Mean crown openness was calculated for each species. After verifying that the normality and homoscedasticity conditions were met, mean crown openness was compared among species with a one-way analysis of variance (ANOVA) and a post-hoc Tukey multiple comparisons test.

2.2. Sensitivity analysis

We tested the sensitivity of the model predictions to variation in the values of the crown geometry and openness parameters. The sensitivity analysis was run on a hypothetical stand with an initial basal area of 29 m^2/ha, an inverse J-shaped DBH distribution, a maximum DBH of 60 cm, and comprising only one hypothetical species. The base values assigned to the four parameters were $h = 1.2$ for the tree height–DBH function, $d = 0.45$ for the crown depth–tree height function, $c = 0.1$ for the crown radius–DBH function, and 20% for crown openness. Each of the four parameters was subsequently individually decreased and increased to 25, 50, 150, and 200% of its base value. The base values of the parameters were selected to insure that the range of variation that would be tested would be, as much as possible, within the range of values previously observed for those parameters (Canham et al., 1994, 1999). In the hypothetical stand, we created a 400 m^2 gap (reducing basal area slightly). We then used SORTIE to predict the GLI at three locations in the stand: at one point under the closed canopy, and at the southern and northern borders of the gap. The model calculated GLI at 1, 2, and 5 m above the ground. Since results obtained at 2 and 5 m were similar to those at 1 m, only the latter are presented. The sensitivity of the model predictions to variation in the parameter values was assessed graphically.

2.3. Validation test 1: prediction of understorey GLI in mapped stands

For the first validation test, we compared GLI predicted by the model to understorey light availability measured in four mapped stands that comprised an even-aged closed canopy stand, an uneven-aged stand that had not been cut recently, and two uneven-aged selection cuts (Table 1). In each stand, a 70 m $\times$ 70 m plot was established, and each plot was subdivided in 49 subplots (10 m $\times$ 10 m). The validation plots were physically separate from the sites where parameterization data were collected.

In each validation plot, hemispherical photographs were taken at the center of each of the nine central subplots. Photographs were taken at 1 m aboveground in all stands except DUC89 where they were taken at 5 m because of the presence of a dense understorey vegetation. A Canon 35 mm camera equipped with a Canon 7.5 mm f/5.6 fisheye lens was used with Kodak TMAX 400 ASA black and white film. The camera was mounted on a tripod, carefully leveled, with the top to the north. In stand DUC89, the camera was mounted on a monopod equipped with a leveling device. Photographs were generally taken under overcast conditions to minimize glare from direct sunlight and to optimize contrast between sky and tree crowns. After processing, the photographs were scanned and the GLI (Canham, 1988) was calculated using the GLI/C software (Canham, 1995). GLI was calculated for a growing season starting on 1 May and ending on 15 September. Beam fraction was set to 0.5, clear sky transmission to 0.65, and the number of altitude and azimuth grids to 18 and 36, respectively (see Canham, 1995).

Trees and saplings were mapped in each validation plot. Since only crowns located within 45° of the zenith were taken into account in SORTIE, we did not map small trees at the periphery of the plot because they should not affect light prediction by SORTIE in the central subplots. In the nine central subplots, all vegetation greater than 1.5 m in height was mapped (species, DBH, and *x–y* coordinates were recorded). In the 16 subplots surrounding the nine core subplots, all trees taller than 5 m were mapped, while in the 24 outermost subplots only trees taller than 15 m were mapped.

The SORTIE model was initialized with our tree map data (i.e., the *x–y* coordinates, DBH, and species identity of each tree) for each of the four validation plots. A parameter file was created for each plot that specified the crown geometry and crown openness parameters for each species, as well as the parameters specific to each plot location (e.g., latitude, longitude). For sugar maple, yellow birch, and beech, we used our own crown geometry and openness parameters. A few other tree species were present as well, but since they never accounted for more than 4% of the plot basal area (Table 1), we decided not to characterize their crown geometry and openness. Instead, all those species were given the same set of parameters, the values of which were arbitrarily selected within the range of parameter values observed in this study ($h = 1.45$, $d = 0.5$, $c = 0.11$, and openness $= 10\%$). The stem map file and parameter file were then used with SORTIE to predict GLI values for the nine locations in each of the four validation plots. Least-squares regression was used to describe the relationship between GLI values predicted by SORTIE (GLI_{pre}), and measured GLI (GLI_{obs}).

2.4. Validation test 2: prediction of mean stand-level GLI in unmapped stands

For a second validation test, we compared model GLI predictions to measured understorey light conditions in four 1 ha plots that had not been mapped, but for which we knew the density distribution of trees by DBH class, and by species. The plots were located in stands that ranged in basal area from 19 to 27 m^2/ha (Table 2). Two types of comparison were done between measured and predicted light conditions. First, we compared GLI values obtained from hemispherical photographs taken at 5 m aboveground to GLI values predicted by SORTIE. This comparison was done for conditions prevailing at a height of 5 m above the ground in order to focus on how light conditions are determined by the location, crown geometry, and openness of overstorey trees. A second comparison was performed to determine whether

Table 2
Characteristics of the four stands where validation test 2 was performed

	DUC92-2	DUT92	SVC83	SVT83
Location	Duchesnay	Duchesnay	Ste-Véronique	Ste-Véronique
Cutting history	Selection cut in 1992 (24% of BA)	Highgrading prior to 1950	Selection cut in 1983 (38% of BA)	Highgrading prior to 1950
Basal area[a] (m^2/ha)	19	24	22	27
Tree species composition (% BA)[a]				
Sugar maple	52	38	82	94
Yellow birch	41	37	4	2
Beech	0	4	12	4
Other	7	21	2	0
Density of understorey vegetation (n/ha, 1 cm $<$ DBH $<$ 10 cm)				
All species	555	655	5500	2100

[a] Of trees with DBH $>$ 10 cm.

SORTIE can accurately predict the attenuation of light availability with decreasing height in the understorey. To do so, GLI values predicted by SORTIE at 0.2, 1, 2, and 5 m were compared to light conditions measured at those same heights. For this validation test, predicted GLI values were compared to observed %PPFD (photosynthetic photon flux density) values because we did not have hemispherical photos for heights lower than 5 m. Previous results have shown that the relationship between GLI and %PPFD was not different from a 1:1 relationship (Gendron et al., 1998).

In each of the four validation stands, the light conditions were sampled at 20 different points located at the intersections of a 20 m $\times$ 20 m grid that covered an area of approximately 1 ha in each stand. At each point, an hemispherical photograph was taken at 5 m aboveground with the camera mounted on a monopod equipped with a leveling device. The photographs were taken and analyzed using the methods described for validation test 1. These analyses yielded a total of 80 observed GLI values (GLI_{obs}). PPFD was measured at 0.2, 1, 2, and 5 m aboveground at each sampling point using a quantum sensor (LI-190SA, LI-COR, Lincoln, NE) installed on a telescopic pole. A second sensor was installed in an open area near the study sites, and was linked to a datalogger (LI-1000, LI-COR, Lincoln, NE) programmed to record 1 min averages of readings taken every 5 s ($PPFD_0$). The time of each measurement was recorded and %PPFD for each sampled point was calculated as $(PPFD_x/PPFD_0) \times 100$, where $PPFD_x$ and $PPFD_0$ were values recorded at the same time ($\pm$1 min). All PPFD measurements were made under overcast conditions following the method described in Parent and Messier (1996).

When the precise location of individual trees in a stand is not known, the SORTIE model can be initialized using data on tree density per DBH class. In such a case, the model assigns random coordinates to each tree. We used tree density and DBH distribution data obtained from Z. Majcen (pers. comm.) for stands DUC92-2 and DUT92, and from Majcen (1995) for stands SVCJ83M and SVT83. For each stand, we used SORTIE to generate five different stem map files. The model was then used to predict GLI at 20 points located at the intersections of a 20 m $\times$ 20 m grid located in the core 1 ha area of the simulated plot. For each point, SORTIE predicted GLI at four heights above the ground (0.2, 1, 2, and 5 m).

We compared observed and predicted GLI values at 5 m aboveground for each of the four validation stands using one-way ANOVA. In order to meet the normality and homoscedasticity conditions, GLI values were log-transformed ($\log[x+1]$). We also compared the vertical profiles of observed %PPFD and predicted GLI. For each stand and height aboveground, we performed a one-way ANOVA on log-transformed data to determine whether there was a difference among the six data sets (one set of observed PPFD data and five sets of predicted GLI). When a significant difference was found, we used a post-hoc Dunnett multiple comparisons test to test the presence of a difference among all possible pairs of observed and predicted data.

2.5. Simulation of light conditions under alternative harvesting scenarios

Since the validation tests indicated that the GLI predictions obtained with SORTIE were accurate soon after cutting and when the understorey vegetation is not very abundant (see Section 3), we used the SORTIE light model to predict understorey GLI under four different partial harvesting scenarios (Table 3). The 30% selection, group selection, and patch selection scenarios were designed to meet the requirements specified by the Ministère des Ressources Naturelles du Québec (1998). The group selection and the selection cut with clear-cut patches are recommended to favor the regeneration of species with lower shade tolerance (Ministère des Ressources Naturelles du Québec, 1998).

First, a tree map file was created for a 9 ha stand with the pre-harvest conditions described in Table 3. The total basal area, species composition, tree density by DBH class, and density of saplings (1–10 cm in DBH) were specified to SORTIE, but the position of each tree was randomly determined by the model. The base tree map file was then modified according to the four harvesting scenarios described in Table 3. The output requested from SORTIE was a list of predicted GLI values at 0.2 m aboveground along a 5 m $\times$ 5 m grid covering the entire 9 ha. The frequency distributions of predicted GLI were calculated for the pre-harvest and the four different post-harvest stands.

Table 3
Description of the pre-harvest conditions and of the four harvesting scenarios for which understorey light conditions were predicted using the SORTIE light model

Treatment	Description	Trees DBH > 10 cm		Saplings DBH 1–10 cm at density (n/ha)
		BA (m^2/ha)	Density (n/ha)	
Pre-harvest conditions	Inverse J-shaped DBH distribution Maximum DBH of 60 cm Species composition: 70% sugar maple, 20% yellow birch, and 10% beech (% of BA for stems > 10 cm in DBH, and % density for saplings)	27.0	373	750
Selection cut 20%	Harvest of 20% of BA (DBH > 10 cm) Assumed that one-third of the saplings were destroyed by the logging operations Maintained same species proportions as in pre-harvest stand	21.9	299	500
Selection cut 30%	Harvest of 30% of BA (DBH > 10 cm) Assumed that one-third of the saplings were destroyed by the logging operations Maintained same species proportions as in pre-harvest stand	19.0	265	500
Group selection	Creation of 900 m^2 gaps in which all stems are harvested and all saplings destroyed The 900 m^2 gaps covered 9% of the total stand area In the areas between and around the 900 m^2 gaps, a selection cut (20% of BA) was performed and we assumed that one-third of the saplings were destroyed by the logging operations Maintained same species proportions as in pre-harvest stand	19.9	273	460
Patch cutting	Creation of patches 1.44 ha in area in which all stems are harvested, and all saplings destroyed The clear-cut patches covered 16% of the total stand area In the areas between and around the clear-cut patches, a selection cut (20% of BA) was performed and we assumed that one-third of the saplings were destroyed by the logging operations Maintained same species proportions as in pre-harvest stand	18.3	251	423

The frequency distribution of GLI was also calculated specifically for a 900 m^2 gap from the group selection cut and for a 1.44 ha patch from the patch selection cut. All simulations were performed with SORTIE version 4.1, and statistical analyses were performed with Systat 7.0 and SPSS 8.0. Probability values <0.05 were considered significant.

3. Results and discussion

3.1. Crown geometry and openness

The crown geometry parameters (Table 4) obtained in this study were in the same range as values previously reported by Canham et al. (1994) for the same species. For parameters d and c, the rank of the parameter values among species were the same as observed by Canham et al. (1994) (d: YB < SM < AB; c: SM < YB < AB). It should be noted that in the version of the SORTIE model used in this study, the crown radius parameter (c) is the slope of a linear function between crown radius and DBH. However, scatterplots of our crown radius–DBH data suggest that a nonlinear function would better describe the relationship between crown radius and DBH by better taking into account the fact that saplings generally have a wider crown per unit DBH than larger trees.

The mean crown openness was $4.9 \pm 0.4\%$ (mean ± S.E.) for beech, $9.7 \pm 0.6\%$ for yellow birch, and

Table 4
Values of the three crown geometry parameters determined for yellow birch ($n = 53$), sugar maple ($n = 43$), and beech ($n = 52$)

Species	Parameter value	S.E.[a]	R^2
Parameter h (see Eq. (1) for the tree height–DBH relationship)			
Yellow birch	1.413	0.043	0.975
Sugar maple	1.565	0.074	0.950
Beech	1.483	0.073	0.925
Parameter d (crown depth $= d \times$ tree height)			
Yellow birch	0.509	0.018	0.940
Sugar maple	0.538	0.018	0.956
Beech	0.544	0.021	0.931
Parameter c (crown radius $= c \times$ DBH)			
Yellow birch	0.109	0.005	0.890
Sugar maple	0.100	0.004	0.927
Beech	0.124	0.005	0.920

[a] The asymptotic standard error of the parameter estimates. Sampled trees ranged in DBH from 1 to 50 cm.

$10.8 \pm 0.5\%$ for sugar maple. A one-way ANOVA indicated a difference of crown openness among species ($F = 50.2$, d.f. $= 2$, $P < 0.001$). A post-hoc Tukey multiple comparisons test indicated that beech had a lower crown openness value than the other two species ($P < 0.001$ in both cases), which did not differ from each other ($P = 0.292$). Canham et al. (1994) also found that beech trees cast a deeper shade than other deciduous species, including yellow birch and sugar maple. Canham et al. (1994) reported higher openness values for these three species (from 8.5 to 41.5%), but used a different methodology. A more recent paper in which crown openness was evaluated for nine species of British Columbia using a method similar to the one used in this study yielded openness values that were closer to the ones observed in this study, since they ranged from approximately 5 to 20% (Canham et al., 1999).

3.2. Sensitivity analysis

As expected, predicted GLI decreased with increases in the h, d, and c parameters, and increased with increasing crown openness (Fig. 1). The sensitivity of the GLI predictions to variations in the parameter values differed somewhat among microsites (i.e., northern versus southern border of a gap, versus closed canopy, Fig. 1). In all microsites, GLI predictions were most responsive to variation in the crown radius parameter (c), and generally more responsive to a decrease than to an increase in c. The sensitivity of the GLI predictions to variations in the tree height parameter (h) was greater at the northern border of the simulated gap (Fig. 1A) than at its southern border (Fig. 1B) or under a closed canopy (Fig. 1C). In general, GLI predictions were not very responsive to variation in the crown depth parameter (d) (Fig. 1). The little impact that d had on predicted GLI probably has to do with the fact that the light model in SORTIE uses a "number of hits" algorithm,

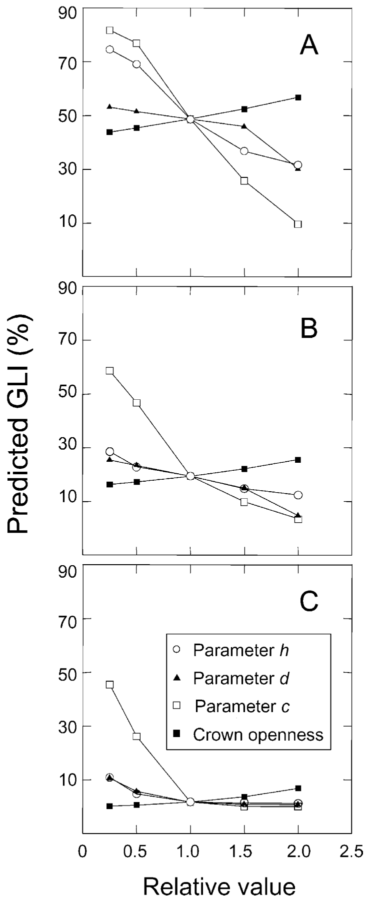

Fig. 1. Sensitivity of GLI predicted by SORTIE to variation in four parameters: h (which defines the relation between tree height and DBH), d (defining crown depth as a function of tree height), c (defining crown radius as a function of DBH), and crown openness. The sensitivity of the GLI predictions was assessed at a height of 1 m at three different locations in a stand: (A) north of a 400 m^2 gap; (B) south of a 400 m^2 gap; (C) under a closed canopy.

rather than a "path length" algorithm (see Canham et al., 1994 for details on the two alternative algorithms), and focuses on the portion of the hemisphere between 45° and the zenith. Surprisingly, variation in crown openness did not have a major impact on GLI predictions (Fig. 1). For instance, dividing the base openness value by 4 yielded GLI predictions that were lower than the base GLI by only 1–5% (in absolute terms), depending on location (Fig. 1). Obviously, when such a decrease in GLI is expressed as a proportion of the base GLI value, the relative impact is greater in the closed canopy location than in the more open locations. The results of the sensitivity analysis are in agreement with Brunner (1998) who reported that the tRAYci light model was less responsive to variations in the model parameter responsible for light attenuation in the crown than to variation in parameters describing crown geometry. However, although variations in crown geometry had a much stronger effect on predictions of understorey light levels than variations in canopy openness, it should be noted that larger differences were observed among species in terms of canopy openness than in terms of crown geometry (see values of parameters *h*, *d*, and *c* in Table 4, and values of openness in text).

3.3. Validation test 1: prediction of understorey GLI in mapped stands

For this test, GLI was predicted by SORTIE for nine microsites in each of four stands (Table 1) based on a map of saplings and trees in each stand. We found a significant linear relationship between predicted GLI (GLI_{pre}) and observed GLI (GLI_{obs}), with an R^2 of 0.634, a slope not different from 1 ($P = 0.474$), and an intercept not different from 0 ($P = 0.476$) (Fig. 2). However, many points in Fig. 2 did not lie close to the 1:1 relation, and the linear relation between predicted and observed GLI was heavily dependent on a few values from the DUC89 site. In fact, the R^2 drops to 0.270 when we only consider GLI_{obs} values <20%. A poor fit between observed and predicted light availability occurs with other light models as well under relatively shaded light conditions (i.e., <20%) (Koop and Sterck, 1994; Cescatti, 1997b; Brunner, 1998). The problem is probably unavoidable given the simplified representation of tree crowns used in SORTIE. Under closed canopies, fine-scale variations in light levels are probably influenced by small-scale disturbances (e.g., branch breakages) that cannot be predicted by SORTIE from the maps of tree DBH.

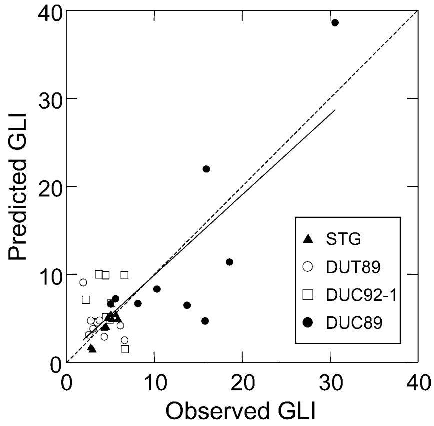

Fig. 2. Scatterplot and fitted regression line of GLI predicted by SORTIE as a function of observed GLI calculated from hemispherical photographs taken at 36 locations in four validation plots (STG, DUT89, DUC92-1, DUC89; $n = 9$ per plot). The linear regression is $y = 0.91x + 0.75$, $P < 0.001$, $R^2 = 0.634$. The dashed line represents the 1:1 relationship.

3.4. Validation test 2: prediction of mean stand-level GLI in unmapped stands

The four stands in which this validation test was performed ranged in basal area from 19 to 27 m^2/ha (Table 2). For each stand, five simulations of understorey light conditions were generated with SORTIE, yielding five different sets of GLI_{pre} values that differed somewhat from one simulation to another because the spatial distribution of trees was randomly determined by SORTIE for each simulation. The results obtained from this validation test indicated that SORTIE accurately predicted mean stand-level GLI at 5 m aboveground in the four stands, as well as how it varied among stands as a function of stand basal area. For each of the four validation stands, we did not find any significant difference between the observed and predicted sets of GLI (DUC92-2 : $F = 0.746$, d.f. = 5, $P = 0.591$; DUT92 : $F = 1.083$, d.f. = 5, $P = 0.374$; SVC83 : $F = 0.359$, d.f. = 5, $P = 0.875$; SVT83 : $F = 0.399$, d.f. = 5, $P = 0.849$). Mean stand-level GLI decreased with increasing stand basal area (Fig. 3) and the relationship between GLI and stand basal area was the same for GLI_{obs} as for GLI_{pre} (an ANCOVA

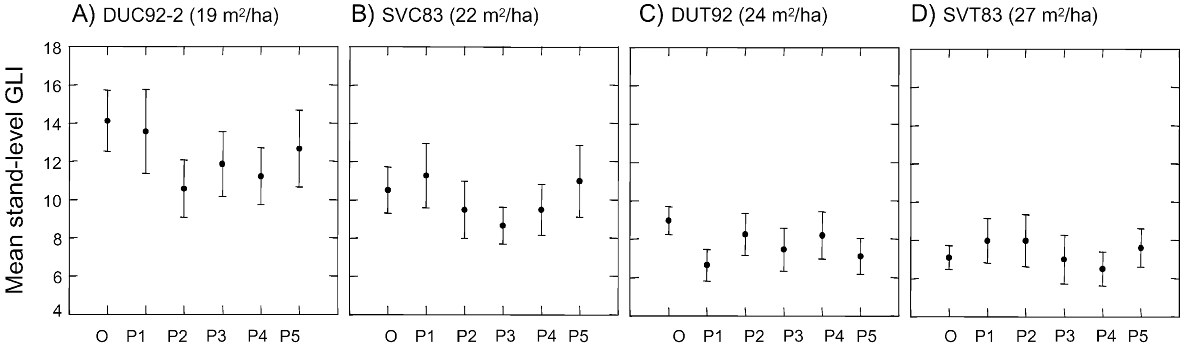

Fig. 3. Mean (±S.E.) stand-level GLI at 5 m aboveground in each of four stands that ranged in basal area from 19 to 27 m^2/ha. Six sets of GLI values are presented for each stand. First, the mean observed value (O) calculated from hemispherical photographs taken at 20 different locations in each stand, and then the results obtained from five different simulations with SORTIE (P1–P5) in which GLI was predicted at 20 locations in the virtual stand.

performed on the GLI data pooled from the four stands showed no interaction between data set—observed versus predicted—and basal area, Table 5).

The vertical profiles of GLI predicted by SORTIE were then compared to vertical profiles of observed %PPFD. At 5 m, we did not find any difference between observed %PPFD and GLI_{pre} in any of the four stands (Fig. 4). This is in agreement with the above-mentioned results that showed that GLI_{pre} did not differ from GLI_{obs} at 5 m. At heights lower than 5 m, we did not observe any difference between GLI_{pre} and observed %PPFD in the DUC92-2 stand (Fig. 4A). That stand had been logged 4 years before measurement of the light conditions, and the understorey vegetation was not very dense. In the other three stands, however, differences were observed between observed %PPFD and GLI_{pre} at 0.2 and 1 m (in all three stands), and at 2 m (in DUT92) (Fig. 4B–D).

Table 5
Analysis of covariance to test for the presence of a difference between observed GLI values and five sets of predicted GLI values in validation stands that range in basal area from 19 to 27 m^2/ha[a]

Source	d.f.	Mean-square	F-ratio	P
Data set[b]	5	0.034	0.564	0.728
Basal area	1	2.493	41.585	<0.001
Data set × basal area	5	0.028	0.464	0.803
Error	468	0.060		

[a] The analysis was performed on log-transformed data.

[b] Data set refers to the six groups of GLI values: one observed and five sets of predicted values.

Those three stands in which GLI_{pre} were higher than observed %PPFD near the forest floor had either not been cut in the recent years (DUT92 and SVT83), or had been subjected to a selection cut ∼15 years before the study (SVC83). In these stands in general, and especially in SVC83, there was a denser understorey vegetation (Table 2) and a steeper gradient of light attenuation (SVC83: Fig. 4C) than in DUC92-2 (Fig. 4A). Under such conditions, SORTIE was found to underestimate the light attenuation, and overestimated light availability near the ground.

Possible reasons for the underestimation of light attenuation by SORTIE in the understorey of stands with denser undergrowth include the underestimation of sapling crown radius due to the use of a linear function to describe the relationship between DBH and crown radius (see above). Another possible reason is that the model has not yet been parameterized for subcanopy tree and shrub species. In our study sites, yellow birch, sugar maple, and beech accounted for a large proportion of the overstorey trees (Table 2), but other species were also present in the understorey (e.g., *A. pensylvanicum*, *A. spicatum*, and *Viburnum alnifolium*, pers. obs.). Subcanopy tree species and shrubs are likely to differ from tree species in terms of crown geometry and openness because of their different growth form which can be multistem and exhibit a more planophyle leaf display (Lei and Lechowicz, 1990). So far, parameterization has not been performed for understorey species in the other sites where SORTIE was parameterized and validated (Canham et al., 1994, 1999). Light attenuation by

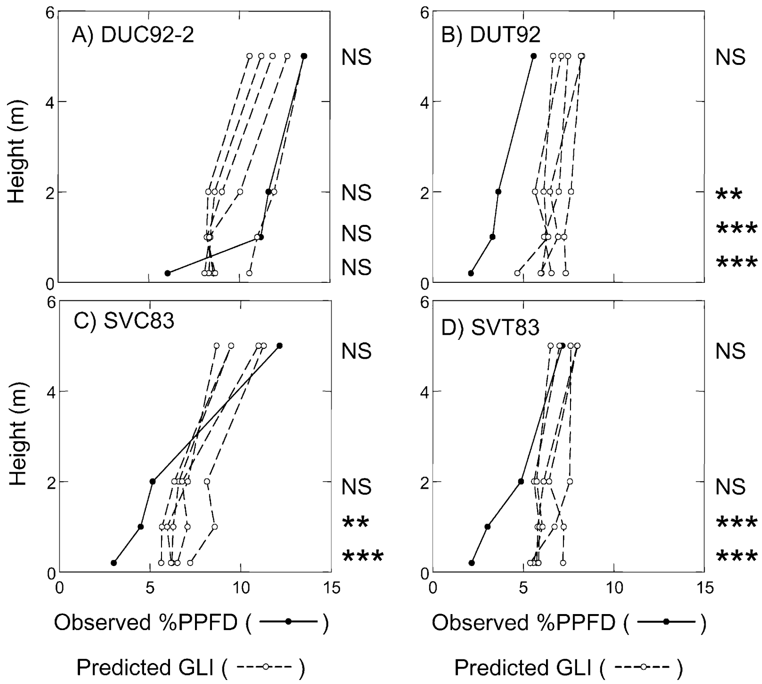

Fig. 4. Vertical profiles of observed %PPFD and predicted GLI in each of four stands. Each point represents the mean for 20 locations. Error bars were omitted for clarity. For each stand and at each height (0.2, 1, 2, and 5 m), an ANOVA was performed on log-transformed data to determine if a difference was present among the six data sets (one observed and five predicted). The results are presented along the right-hand side of each graph (NS: $P \geq 0.05$; $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$).

understorey vegetation was not a primary concern in those forests because understorey vegetation density was low and there was little variation in the understorey light profile (Canham et al., 1994, 1999). In such forests, the understorey light availability was primarily determined by overstorey trees rather than by adjacent understorey vegetation. However, a number of recent studies have underscored the important role that understorey vegetation can play in the determination of understorey light conditions (Messier et al., 1998; Lieffers et al., 1999; Aubin et al., 2000). Further studies should aim at obtaining a better representation of the understorey component in SORTIE by characterizing the crown geometry and openness of subcanopy species.

3.5. Simulation of light conditions under alternative harvesting scenarios

The SORTIE light model was used to predict the effect of different harvesting scenarios on understorey light conditions. Because SORTIE was found to underestimate light attenuation through the understorey vegetation, the predictions obtained from the model are taken as being only representative of the light conditions prevailing immediately after cutting, and assuming that most of the pre-established understorey vegetation was destroyed in the gaps created by logging. The latter condition is especially realistic for the group selection and patch selection since for those two silvicultural options, it is recommended to scarify the forest floor in the openings, hence eliminating most advance regeneration (Ministère des Ressources Naturelles du Québec, 1998).

Under the pre-harvest conditions (Fig. 5A), light availability was very low near the forest floor: 11% of the microsites had GLI $< 2\%$, 93% had GLI $< 10\%$, and none of the microsites had GLI $> 26\%$. Even the lowest intensity selection cutting (20% of BA) modified noticeably the understorey light conditions compared to the pre-harvest conditions (Fig. 5B): 6% of the microsites had GLI $< 2\%$, 79% had

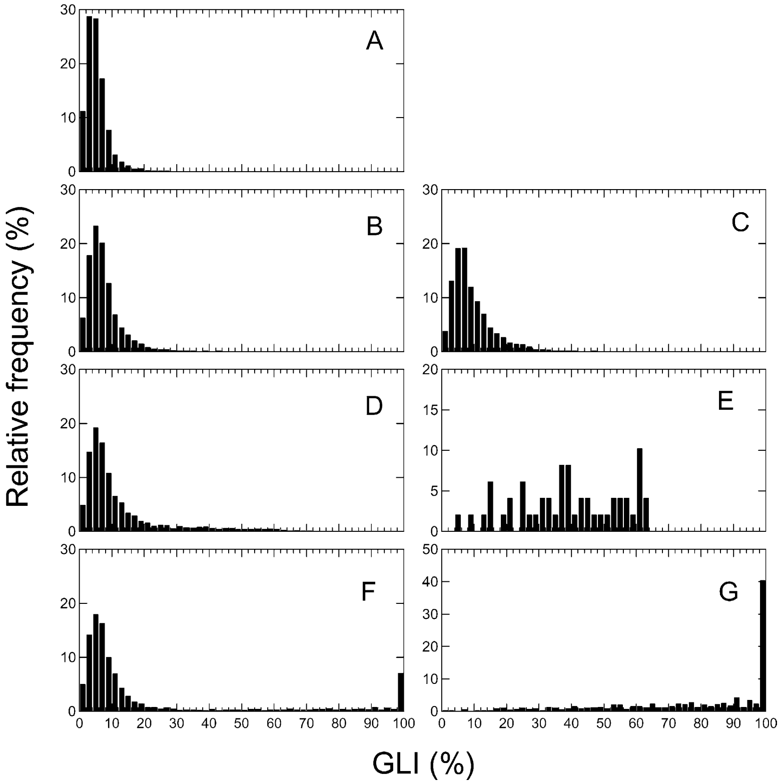

Fig. 5. Comparison of the effects of different silvicultural systems on the frequency distribution of GLI values at 0.2 m above the forest floor, as predicted by the SORTIE light model (see Table 3 for a detailed description of the treatments): (A) pre-harvest conditions; (B) 20% selection cut; (C) 30% selection cut; (D) group selection (with 900 m^2 gaps and low intensity selection cut between and around gaps); (E) in a 900 m^2 gap of the group selection treatment; (F) patch selection (with 1.44 ha clear-cut patches and low intensity selection cutting between and around patches); (G) in a 1.44 ha clear-cut patch of the patch selection treatment.

GLI $< 10\%$, and the maximum GLI was 42%. The selection cut with a 30% harvesting intensity did not increase appreciably the maximum GLI (46%) compared to the lower intensity selection cut, but provided the highest percentage (27%), among all harvesting scenarios, of microsites with GLI between 10 and 20%, a range of light conditions that might be biologically important for the species found in sugar maple-dominated forests. For the group selection and patch selection, we calculated the frequency distribution of microsites for the whole 9 ha stand (Fig. 5D and F), as well as for just one 900 m^2 gap in the group selection (Fig. 5E), and for one 1.44 ha clear-cut patch in the patch selection (Fig. 5G). The frequency distribution of GLI was obviously markedly different whether we examined the light conditions in the openings only, or in the whole 9 ha stand. For the group selection, when the whole 9 ha area was considered (Fig. 5D), the difference of light conditions compared to the 30% selection was not very important, except for an increase in the maximum GLI to 70%. The percentage of microsites with GLI $< 10\%$ was approximately the same as in the 30% selection cut (66 versus 67% of the microsites). In the 900 m^2 gap of the group selection (Fig. 5E), the light conditions were fairly well distributed among the GLI classes between 4 and 64% GLI. In the 9 ha plot treated with the patch selection (Fig. 5F), the most obvious difference compared to the other harvesting scenarios was that a noticeable proportion (9%) of the microsites were in full sun. In the clear-cut patch itself (Fig. 5G), 40% of the microsites were in full sun.

For a given stand, the choice of a silvicultural treatment will depend on the management objectives (e.g., regeneration of high value species with low shade tolerance), and will be influenced by a number of potential constraints (e.g., stem quality in the stand). Once the management objectives are defined and the constraints are known, the forest manager will need to know the potential effects of the various harvesting options on the availability of appropriate microsites for tree regeneration. The simulation results presented in this paper indicate that the SORTIE light model could be a very useful tool to evaluate, quantitatively, the potential effects of different silvicultural treatments on the proportion of various light microsites.

4. Conclusion

Desirable characteristics of a light model include: (i) a satisfactory degree of precision and accuracy in the predictions in a wide range of situations, and (ii) reasonable data requirements. Validation of the SORTIE light model in mapped stands showed that the model can provide reasonable predictions of spatial variation in understorey light levels, particularly for intermediate light levels. The light model appears to be best suited to predict spatial patterns of light when the type of light variation that is of interest results from variation in tree sizes and spacing, and are of relatively large magnitude, such as after partial cuts. Predictions of GLI under closed canopies remain accurate, but lack spatial precision, presumably because much of the variation in light levels in relatively dark understoreys is caused by factors which are not taken into account in SORTIE, such as small gaps within tree crowns due to branch damage. We argue that it would be unrealistic to expect a high level of spatial precision under such conditions, given the degree of simplification that is used in SORTIE for crown representation. At the stand-level, SORTIE accurately predicted variations of GLI at 5 m above the forest floor among stands ranging from 19 to 27 m^2/ha in basal area. The fact that a tree map was not provided to SORTIE did not seem to affect the accuracy of the stand-level GLI predictions at 5 m. A comparison of the vertical profile of GLI predicted by SORTIE to observed %PPFD revealed an underestimation by SORTIE of light attenuation at heights ≤ 2 m in forest sites where understorey vegetation was relatively abundant. Future work should aim at obtaining a better crown representation of understorey vegetation in SORTIE in order to improve the predictions of the model in forest locations with dense undergrowth.

The amount of input data required by the SORTIE light model is remarkably small compared to most existing forest light models. In SORTIE, crown geometry is modeled for each tree based on the species identity of the tree and its DBH. Tree height, crown depth, and crown radius of individual trees are then predicted as species-specific functions of DBH. This is an important difference between SORTIE and many other forest light models which require the measurement of crown dimensions for each individual tree present in the stand (Koop and Sterck, 1994; Cescatti, 1997a; Stadt and Lieffers, 1998). The other parameter that is needed by SORTIE for crown representation is the species-specific crown openness. The method described in Canham et al. (1999) for characterization of crown openness is much less time consuming than the method previously described in Canham et al. (1994). This new method enabled the detection of interspecific differences in crown openness among nine species from British Columbia (Canham et al., 1999) and among three deciduous species in northern hardwood stands (this study). Since SORTIE is a spatially explicit model, previous work with the model has been done in mapped forest stands. An alternative approach examined in this study was to obtain stand-level predictions of GLI from SORTIE for stands for which tree maps were not available. Our results indicate that the light model can accurately predict mean stand-level GLI without providing a tree map to SORTIE, at least in sites where there is not a very dense understorey vegetation. This second test of the model was critical, since the need for precisely mapped forest stands would limit the utility of the model in exploring alternative harvesting options in a wide range of stands.

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