Simulating Light Availability under Different Hybrid Poplar Clones in a Mixed Intensive Plantation System

Alain Paquette, Christian Messier, Pierre Périnet, and Alain Cogliastro

Abstract: Fast-growing hybrid poplars have been proposed as a means of achieving restoration objectives on former agricultural land by providing shelter for slower-growing species. Intensive two-stage scenarios of mixed plantations are also possible using valuable hardwoods interplanted among hybrid poplars. The latter would be harvested at maturity (approximately 20 years) once their protective role has been accomplished, leaving more space for the full development of the second cohort. We implemented simulations of hybrid poplar growth in the SORTIE-ND model and used it to test scenarios with clones varying in growth and crown allometry, different hardwood species, and spatial arrangements, to maximize production of both groups. Important differences in growth and allometry were manifested among clones over time, which translated into important differences in available light between rows. Sustained growth for most hardwoods appeared optimal using wider spacings of 16 m, compared with 12 m, between poplar rows. To our knowledge, this is the first attempt to integrate fast-growing hybrids and intensive silviculture scenarios into spatially explicit models. These models are necessary support tools for the efforts now being invested in intensive silviculture in the face of diminishing forest resources, increasing wood and fiber demands, and climate change. FOR. SCI. 54(5):481–489.

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THERE IS INCREASING INTEREST for multispecies plantations that can provide more ecological services and that are more resilient to future uncertainties, such as climate and market change (Erskine et al. 2006, Kelty 2006). Attention has also been directed lately to the potential for fast-growing plantations, such as hybrid poplars, to meet industry demands for increased productivity and sustained wood supplies (Messier et al. 2003, MacLean et al., in press). Moreover, high-yield tree plantations have been proposed as a means of sequestering carbon to fight global change directly or through "avoided deforestation" (Updegraff et al. 2004, Righelato and Spracklen 2007).

Fast-growing hybrid poplars can rapidly create conditions favorable for the development of a second cohort of more shade-tolerant trees growing under the poplar nurse crop (Gardiner et al. 2004). Protection from neighborhood trees, much like a shelterwood, has been recognized as beneficial in terms of protecting the young cohort from excessive evapotranspiration, wind and temperature extremes, and associated damage (Langvall and Lofvenius 2002, Agestam et al. 2003). Height growth and trunk shape could also be improved (Schütz 2001, Pommerening and Murphy 2004). Indeed, the use of crop trees to improve the value of valuable hardwood boles has long been recognized and applied in Europe (Becquey 1997, Vidal and Becquey 2008). The silvicultural model studied here is oriented toward the production of veneer quality boles and is conducted at wide spacings on former agricultural lands, as is common in agroforestry systems (Balandier and Dupraz 1999).

The proposed system, using valuable hardwoods interplanted with rows of fast-growing hybrid poplars, favors the succession of slower-growing, mid-shade to shade-tolerant hardwoods, after fast-growing shade-intolerant poplars. Interplanting, which is inspired by natural forest succession, can be used to accelerate the progression of abandoned farmland toward forested ecosystem (Gardiner et al. 2004, Updegraff et al. 2004), especially because the former is known to be resilient to tree establishment (Benjamin et al. 2005). Compared with monocultures of fast-growing hybrids, this proposed system may also be more acceptable in the public eye. With different growth rates and physiological requirements, multispecies systems may be more productive through facilitation (Brooker et al. 2008) and optimal use of ecological niches, a phenomenon known as complementarity (Scherer-Lorenzen et al. 2005, Erskine et

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al. 2006, Kelty 2006). Yet maximum yield can only be obtained as long as the choice of species and their spatial arrangement are optimized in terms of resource (especially light) partitioning. Spatially explicit forest models can be used to model the distribution of fundamental resources such as light and thus be used to test silvicultural scenarios. The objective of this study was to parameterize the light module of SORTIE-ND (Canham and Murphy 2005) using three hybrid poplar clones from contrasting families to simulate various silvicultural scenarios of mixed plantations using hybrid poplars on alternating rows with a second cohort of valuable hardwood tree species.

Methods

Parameterization of the SORTIE-ND Light Module

SORTIE-ND is a spatially explicit forest dynamics model that has been recently parameterized and adapted for the northern hardwood forests of Québec (Beaudet et al. 2002). The light module in SORTIE-ND predicts light conditions in terms of the gap light index (GLI), which specifies the percentage of incident photosynthetically active radiation that is transmitted through gaps in the forest canopy to a specific location in the understory over the course of the growing season (Canham 1988). The SORTIE-ND light module predicts GLI for any location in a forest stand based on a relatively simple representation of the forest canopy (Canham et al. 1999). For each species, the crowns of individual trees are represented in the model as cylinders, with the radius of the crown and tree height estimated as empirical functions of tree dbh (1.3 m). The base of the cylinder is estimated as a function of tree height.

To calculate the amount of light a given location gets, SORTIE-ND simulates taking a hemispheric photograph at that location to determine which parts of the sky are blocked by taller trees nearby. The amount of light received from the portion of the sky blocked by a shading neighbor is multiplied by the light transmission coefficient (LTC) for that species. The effects of multiple neighbors blocking the same patch of sky are multiplicative. Once all shading neighbors have been added to the fisheye photo, the amount of light that can still be seen from each region of the sky is totaled into a GLI (Canham and Murphy 2005). The predicted GLI is thus a function of 1) the location, dbh, and species identities of trees in the neighborhood, 2) species-specific relationships that define crown geometry as a function of dbh, 3) species-specific crown openness (LTC), and 4) the distribution of local sky brightness (i.e., incoming light hitting the canopy) (Beaudet et al. 2002, Canham and Murphy 2005).

To calibrate the equations for the model (parameterization), we obtained data from the Québec Ministry of Natural Resources (MRNFQ) from four research stations in which all or most of the clones that we tested could be found (Table 1). These clones are among those recommended by the MRNFQ for southern Québec for their growth potential and resistance to pests (Périnet et al. 2001, Riemenschneider et al. 2002) (Table 2). They are representative of the productive clones now available and come from diverse species assemblages. The sites were planted between 1981 and 1993 (Table 1). The 1981 trial was harvested at maturity in the spring of 1996 (15 years), with trees that were 40 cm at dbh and 25+ m in height. Trees on all sites were measured in the autumn over several years for total height and dbh (Table 1). These data were used for the construction of height-to-dbh equations.

During the summer of 2002, the same trees (except for St. Ours81) were measured in greater detail for crown length (total height − height of lowest living branch), crown radius (averaged from two perpendicular diameters), dbh, and total height. The trees were in their 10th to 12th year of growth at the time of those measurements. The data were used to construct crown allometry equations required by SORTIE-ND, i.e., crown radius versus dbh and crown length versus total height. These equations, together with those described above, were computed using iterative nonlinear procedures in JMP (version 6; SAS Institute, Cary, NC).

For validation we used another independent, carefully mapped site in southern Québec that contained the three clones. This mixed plantation was established in spring 2000 on agricultural land (St. Rémi) (Table 1). The 3-ha site was planted after light soil preparation (disking) of the planting rows and installation of a 1.2-m-wide plastic mulch. Rows alternated between hybrid poplars and hardwoods. The plantation is divided in two row spacing trials of

Table 1. Summary of hybrid poplars research stations used in this study

	Platon (MRNFQ)	St. Ours81 (MRNFQ)	St. Ours93 (MRNFQ)	Windsor (MRNFQ)	St. Rémi
Year planted (spring)	1991	1981	1993	1993	2000
Year harvested	—	1996 (spring)	—	—	—
No measurements	5	11	4	3	7
Clones[a]	3230; 3308	3230; 3308	3230; 3308; 3729	3230; 3308; 3729	3230; 3308; 3729
Location	46°40′N 071°51′W	45°55′N 073°10′W	45°55′N 073°10′W	45°42′N 071°58′W	45°14′N 073°40′W
Elevation (m)	60	20	20	260	60
Degree-days above 5°C	1,722	1,889	1,889	1,611	2,031.1
Soil pH	5.05 ($CaCl_2$)	5.73 ($CaCl_2$)	5.73 ($CaCl_2$)	5.62 ($CaCl_2$)	7.0 (water)
Soil texture and origin	Sandy clay loam (marine)	Deep clay loam (marine)	Deep clay loam (marine)	Loam (deep till)	Sandy clay loam (marine)

[a] Many clones were planted on the Québec Ministry of Natural Resources (MRNFQ) sites; only those used in the present study are listed.

Table 2. Hybrid poplars used in this study

Clone[a]	*Populus* hybrid type and cultivars	Origin
3230	*P. trichocarpa* Torr and A. Gray × *P. deltoides* Marsh. 'Boelare'	Belgium
3308	*P. deltoides* Marsh. × *P. nigra* L. 'Regenerata Bâtard d'Hauterive'	France
3729	*P. nigra* L. × *P. maximowiczii* A. Henry NM6	Germany

[a] From the Québec Ministry of Natural Resources list of recommended clones (Périnet et al. 2001).

12 and 16 m between poplar rows (Figure 1). Each spacing trial, in turn, was divided into four completely randomized blocks, each containing all three clones.

Cuttings (20 cm-long) of the three clones were planted every 2 m in five rows for each of the spacing trials. Black walnut (*Juglans nigra* L.) and white ash (*Fraxinus americana* L.), which perform well on agricultural soils (Cogliastro et al. 2003, Pedlar et al. 2007), were planted every 3 m in four rows midway between the poplar rows.

In block 2 of both spacing trials, the center rows of poplars (containing all three clones) were targeted for testing light modeled by SORTIE-ND against that measured in situ (Figure 1) (i.e., validation of the model). Hemispheric photographs were taken at 1 m above ground level and aligned with the planting rows (310°, later corrected with respect to true north). The photographs were taken at 1-m intervals from the center of the poplar row, in opposite directions perpendicular to the row, for up to a distance of 6 m in the 12-m spacing trial and up to 8 m in the 16-m trial. Images were later analyzed following the methods used by

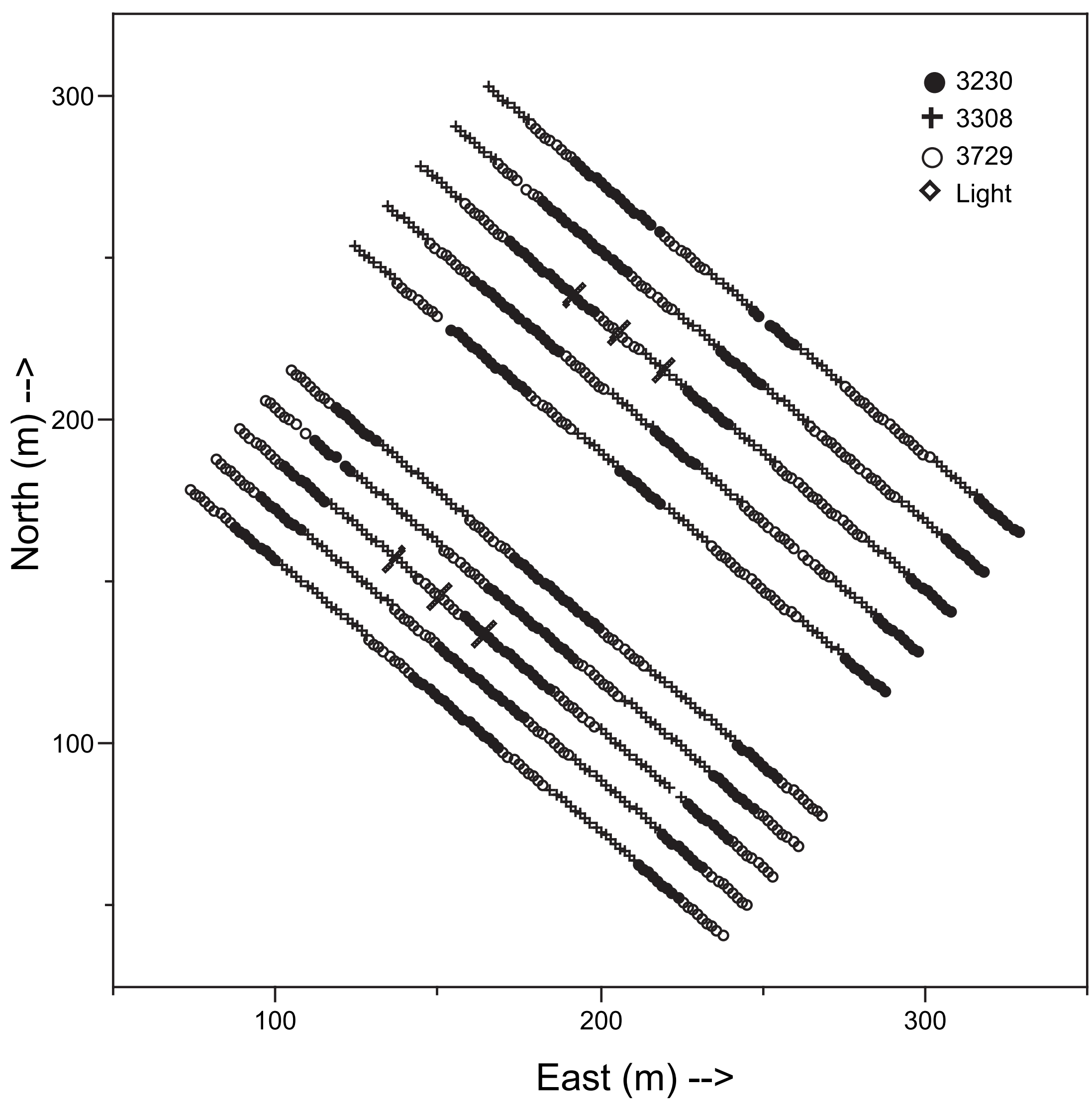


Figure 1. Schematic representation of the St. Rémi mixed plantation spacing trial, including the location of clones, target rows, and light availability measuring points. Both spacing trials are represented for simplicity but were treated separately during simulations. Rows are oriented at 310°. The rows to the southwest are those of the 12-m spacing trial, whereas those to the northeast are separated by 16 m. Hardwoods, planted in rows half way between poplar rows, are not represented for clarity. In each trial, four randomized blocks were established, each comprising the three clones. The center row (third) of the second block (from the northwest end) in each trial was chosen for the calibration of SORTIE-ND.

Beaudet et al. (2002) (growing season: June 15–September 31), to determine available light (GLI) using a gap light analyzer (Frazer et al. 2000).

Early in 2006 the hybrid poplars were thinned by removing two-thirds of the trees, thus increasing their average spacing to 6 m. This created ideal conditions for the evaluation of LTCs on isolated crowns. In SORTIE-ND, crowns of each species are assumed to have species-specific canopy openness or LTC, i.e., the fraction of sky visible through the crown (Canham et al. 1999). We took hemispheric photographs at a 3-m distance (1 m aboveground level) on both sides of the target rows for each clone in both trials and then isolated crowns in those images to measure LTC, following the procedure described by Canham et al. (1999). LTC was measured on half crowns, divided in their center following the main axis, in cases where one side of the crown could not be isolated from those of neighboring trees (6 of the 32 trees analyzed). Results from the east and west sides of a single crown were averaged.

Validation of the Light Model

We mapped both spacing trials at St. Rémi (Figure 1) using dbh and total height from the measurements of autumn 2005, before the 2006 thinning, to get the maximum effect of poplars on light. We used the referenceless X-Y coordinates of the original plantation grid to geometrically compute easting and northing coordinates for the model with reference to true north. The true position of each tree in the field could have differed slightly from these values as the trees were planted manually.

The parameters previously computed for each clone were entered into the model to be validated. We then made single runs of the SORTIE-ND light module to compute light availability (GLI) on a three-dimensional grid corresponding to the points where photographs were taken in 2005. The observed and predicted GLIs were then compared to validate the model (i.e., the specific parameters) using simple linear regression (Canham et al. 1999, Beaudet et al. 2002).

Tests of Age and Spacing Scenarios

Once the model was validated, various light profiles were simulated at three key moments in time, according to the clone and spacing used: at 7 years, after precommercial thinning that increased spacing of the poplars at 6 m in the rows; at 12 years; and at final harvest (20 years, 40–45 cm dbh). These light profiles were then used to evaluate different planting scenarios in terms of the amount of light available for the second cohort of valuable hardwoods placed midway between rows of the three hybrid poplar clones.

New maps were created, each comprising 300 trees of a different clone, spaced at 6 m on 10 equally spaced rows of 30 trees. Six maps were created for each clone, at 7, 12, and 20 years, and with 12 and 16 m between the rows. Maps were filled with trees 7, 12, or 20 years old, in which dbh was computed using equations derived from MRNFQ data for all sites, thus providing average hybrid poplars on soils of agricultural origin. Dbh values were randomly generated using the standard deviations of the regressions and PopTools (version 2.7.5; CSIRO, Canberra, Australia). GLI points were then simulated at the center of the maps, at 1-m increments along a 10-m-long line midway between poplar rows 5 and 6, and averages were computed at 1-m elevation increments aboveground from 3 to 20.

Results and Discussion

SORTIE-ND Parameters and Validation

The three clones differed in height growth relative to dbh (Table 3). Clones 3230 and 3729 clones both had similar slopes of asymptotic height growth ($B = 0.03$) and maximum heights ($H_1 = 30$–32 m), but clone 3308 had a more linear relationship with dbh throughout its development, which translates into a presumably exaggerated maximum height close to 54 m. Indeed, poplar stands 53–58 m in height have been reported (Stanturf et al. 2001), but hybrid poplars are never allowed to grow to such sizes, as they are harvested well before they attain 50 cm dbh. The largest MRNFQ trees for that particular clone were 25 m in height, with a dbh slightly over 35 cm, and were still in the linear growing phase.

Clones 3230 and 3308 both achieved a similar crown radius at higher dbh values, but 3308 crowns were smaller at lower dbh (Table 3). The 3729 crowns were the largest at higher dbh. All three clones had very similar crown length to tree height relationships (Table 3), attributable to regular pruning. Overall, crown parameters were of the same order of magnitude as those found by Pinno et al. (2001) for aspen (*Populus tremuloides* Michx.), but the plantation-grown hybrids presented here all had somewhat wider and longer crowns then naturally established aspen. Finally, crown LTCs did not differ among clones (Table 3, test not shown) and were roughly 30% on average.

GLI points that were simulated using those parameters for the 2005 St. Rémi plantation had a very high power of prediction with respect to observed GLIs that were calculated from hemispheric photographs taken at the same locations ($R^2 = 0.92$) (Figure 2), but the equation slightly underestimated available light at lower GLI values. This discrepancy can be explained mainly by three factors: some hemispheric photographs were taken very close to the poplar rows (at 1 m) and had lower branches that brought large leaves close to the lens, which is a common problem with hemispheric photographs at lower light values that cannot be appropriately accounted for by simulations (Beaudet et al. 2002); the coordinates of the poplar trees in the simulated maps were not exact, which would be especially important at close range; and the equations used for crown parameters were constructed using data collected on the MRNFQ sites in 2002. These MRNFQ trees included a wide range of sizes, but they were larger on average than the ones simulated, which were only in their 6th year of growth. The use of the MRNFQ data for older trees was justified given that we are interested both in distances further away from the rows (where valuable hardwoods would be planted) and in older poplar trees, when light availability may become a concern. Pinno et al. (2001) obtained similar results ($R^2 =$ 0.92 in mapped stands, with slight underprediction at high

Table 3. **Allometric parameters of the hybrid poplars used in this study for SORTIE-ND**

Parameter relationship[a]	Clone 3230	Clone 3308	Clone 3729
Height (m) versus dbh (cm): height $= 1.35 + (H_1 - 1.35)(1 - e^{-B\times \mathrm{dbh}})$			
N	345	256	135
H_1	32.28	53.71	30.09
B	0.02988	0.01515	0.03101
R^{2b}	0.95	0.96	0.94
Crown radius (m) versus dbh (cm): crown radius $= C_1 \times \mathrm{dbh}^a$			
N	48	40	27
C_1	0.2330	0.1676	0.1494
a	0.7364	0.8303	0.9630
R^2	0.78	0.78	0.70
Crown length (m) versus tree height (m): crown length $= C_2 \times \mathrm{height}^b$			
N	48	40	27
C_2	0.8350	0.7020	0.6761
b	0.9683	1.032	1.037
R^2	0.91	0.90	0.81
LTC (N)	0.33 (6)	0.29 (5)	0.30 (5)

[a] Sample sizes differ among classes of parameters: height-dbh relations are based on MRNFQ data over several years; crown radius and length were computed on 2002 data from the same source; light transmission coefficients were computed using hemispheric photographs taken in St. Rémi in 2006 (images were taken from both sides of the rows, then averaged; the actual number of photographs analyzed is twice the sample size). H_1, maximum tree height (m); B, slope of asymptotic height to dbh; C_1, slope of asymptotic crown radius to dbh; a, crown radius exponent; C_2, slope of asymptotic crown length to tree height; b, crown length exponent.

[b] R^2 coefficients are provided but should be interpreted with caution, as there is no well-defined equivalent for nonlinear regression.

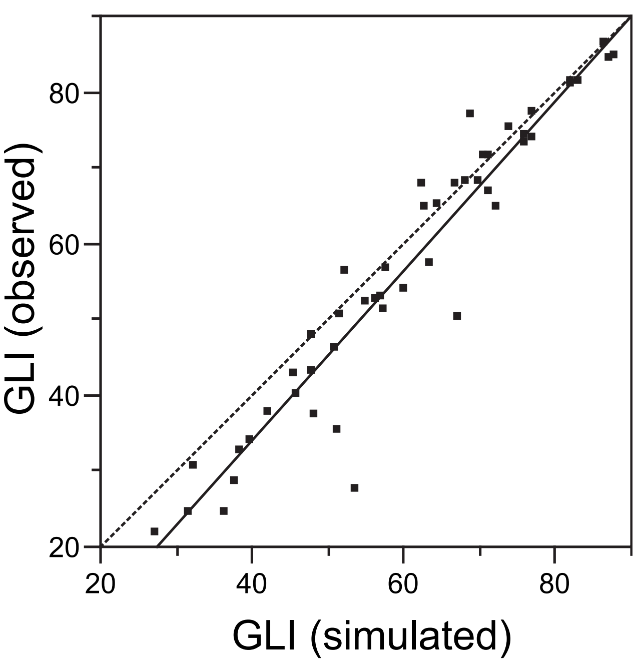


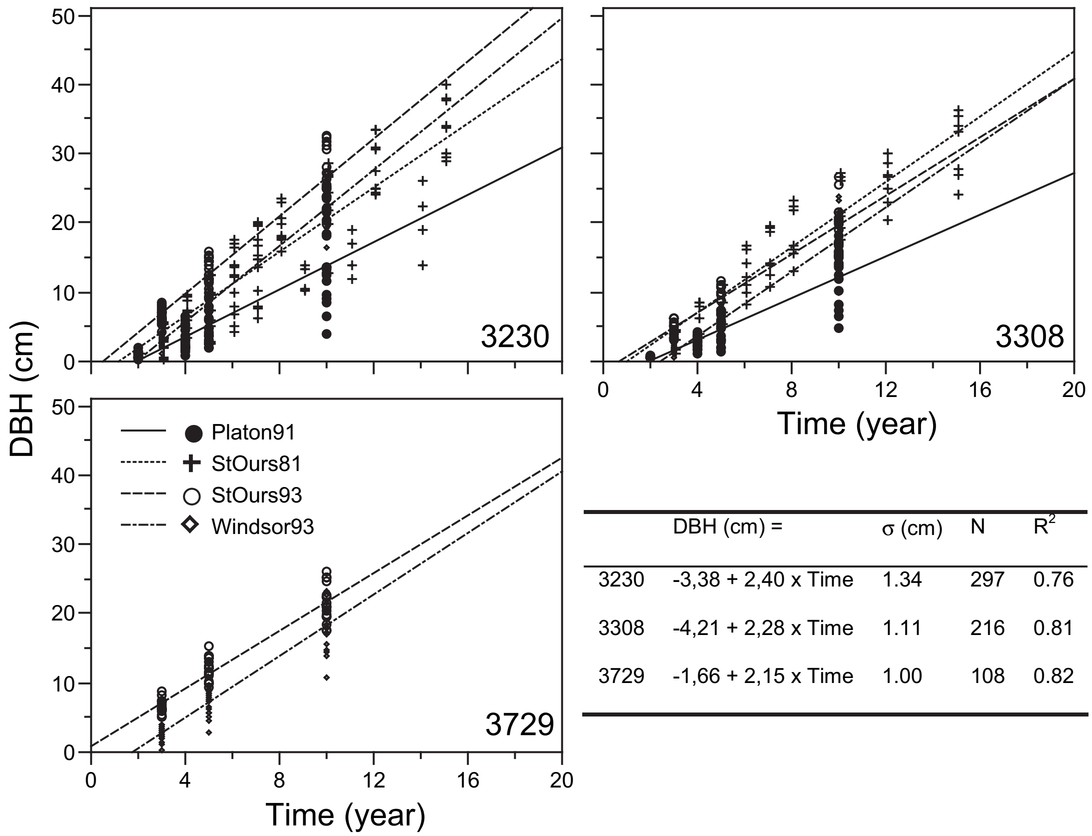
Figure 2. Simulated GLI values (SORTIE-ND) versus actual GLI (1 m above ground level) measured at the St. Rémi plantation in 2005. Regression equation is GLI (observed) = −10.8955 + 1.1204939 × GLI (simulated); $R^2 = 0.92$; $p <$ 0.0001; $n = 48$. The 1:1 relationship is represented with a dotted line for reference.

light levels and overprediction at low levels) with the parameterization of the MIXLIGHT model (Stadt and Lieffers 2000) for juvenile aspen stands.

Availability of Light during the Development of Hybrid Poplars to Harvest Age

We formulated predictive equations of dbh to construct simulated maps of hybrid poplars at different moments in time using data from the four MRNFQ sites (Table 1). All sites were agricultural in origin, but they differed in soil quality, which translates into significant differences in growth, as is shown by the regression lines (Figure 3). They thus represent reasonably well the important gradient of yield that can be expected from hybrid poplars growing under contrasting conditions, from the optimal deep clay loam of the St. Ours sites to the imperfectly drained sandy clay loam at Platon (Table 1).

The light available in the simulated stands of hybrid poplar varied as expected with respect to row spacing, age, and the clone that was used (Figure 4). At age 7, hybrid poplars were on average 12–13 cm in diameter, depending on the clone, were 23–25 cm at 12 years, and were 41–45 cm at the proposed end of rotation (20 years). At age 7, both 3230 and 3729 clones produced sensibly the same light conditions midway between rows, where hardwoods would be growing, whereas more light was available under clone 3308 trees (Figure 4). This trend was modified during the development of the trees, with clone 3729 diverging further from the other two and casting even greater shade. At the same time, clone 3230 moved from low light transmission at age 7, to moderate at age 12, and, finally, to most light being let through at age 20. This could be explained by the different allometries of the clones. Clone 3729 had the largest crown of the three, thereby casting deeper shade, but letting relatively more light through at higher elevations from the ground as it aged because of less sustained height growth (Table 3). In contrast, clone 3308 grew more slowly at early stages but continued growing in height almost linearly with dbh throughout its development (at least up to harvest size), thus casting a longer shadow. Using the GLI calculated from hemispheric photographs taken in 2005, we detected a similar strong clone effect on light availability very early in their development at the St. Rémi site ($P =$ 0.002; not shown).



	DBH (cm) =	σ (cm)	N	R^2
3230	-3,38 + 2,40 x Time	1.34	297	0.76
3308	-4,21 + 2,28 x Time	1.11	216	0.81
3729	-1,66 + 2,15 x Time	1.00	108	0.82

Figure 3. Dbh versus time relationship calculated for each clone from Québec Ministry of Natural Resources data from four sites, for the construction of simulation maps. Regressions and standard deviations in the inset are those used for the simulation (computed using all sites).

The objective of the design is to allow for the growth, on the same surface, of two intensive productions: that of hybrid poplars and that of valuable hardwoods. The planted hardwoods should receive the same care provided to the poplars, such as controlling for competition (Coll et al. 2007) and benefiting from high resource levels with protection from the poplar rows. Data from widely spaced hardwood plantations are scarce (Cabanettes et al. 1999), but we expect sustained growth that is at least equivalent to that of dense plantations on agricultural soils with competition control. We found data for such conditions for black walnut and white ash, which were the species planted in the St. Rémi test, from a 30-year-old plantation in Ontario, Canada (von Althen 1988, Pedlar et al. 2007). This plantation was densely planted and never thinned (except through natural mortality), but chemical weed control was applied on four occasions early in its development. Both species grew well on that site and are comparable to those on other similar plantations (Pedlar et al. 2007). We computed simple predictive regressions of height through time using the means presented by Pedlar et al. (2007), who measured height on six occasions from age 3 to 30 (not shown). To provide a more complete picture, we also computed regressions from a red oak (*Quercus rubra* L.) and red ash (*Fraxinus pennsylvanica* Marsh.) plantation in southern Québec (described in Paquette 2000). We only used data from this site in plots that had received weed control treatments (either plastic mulch or herbicide) and that were measured on 10 occasions from age 2 to 17 to compute predictive regressions of height. Red oak did especially well on that site, which had a sandy soil with low pH, and growth of both species was comparable with that on other younger-aged sites in the region (Cogliastro et al. 2003). From our experience, these are good examples of the yield range that can be expected from well-managed valuable hardwood plantations on soils of marginal to average agricultural value.

Much has been published about minimum light levels necessary for survival in the understory (e.g., shade tolerance literature), but the lowest light levels that are required for maximum growth in plantations have not received much attention. In a review of under-planting experiments conducted in forested stands, Paquette et al. (2006) found that an intermediate level of shelterwood, corresponding to 25–50% available light, produced the most growth in temperate deciduous species (mostly red oak). Gardiner et al. (2001) found that physiological activity of oaks interplanted beneath poplars was not adversely affected at 43% available light. As for red oak, red ash, and white ash, the information that can be found in the literature for seedlings growing under shade experiments suggests that optimal growing conditions are found under 30–45% available light (Phares 1971, Schlesinger 1990, Bartlett and Remphrey 1998). In our simulated scenario of 12-m interspacing of hybrid poplar rows, the light levels expected at harvest age (20 years) for the predicted height of the valuable hardwoods would

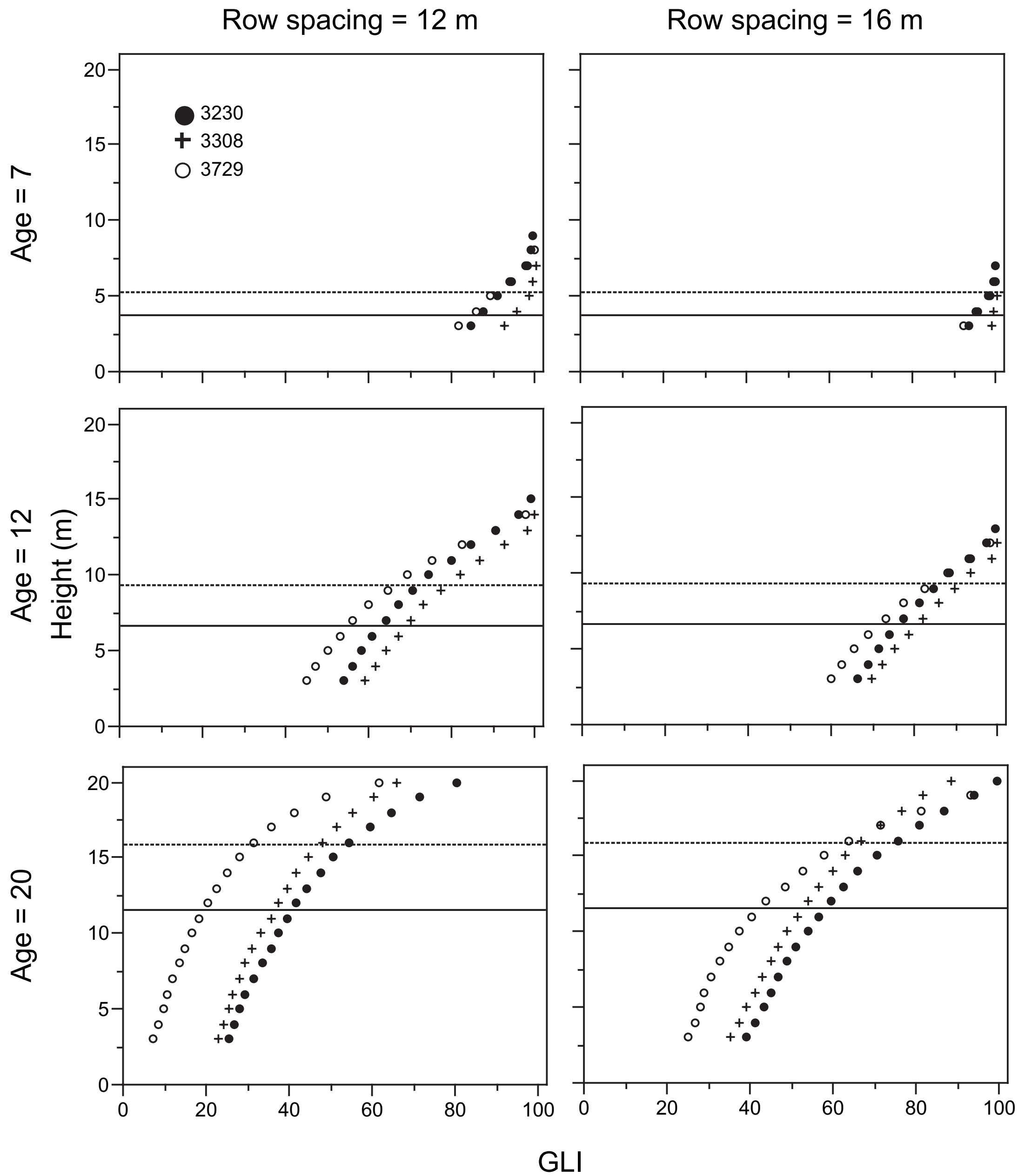


Figure 4. Available light profiles (GLI) as a function of height above the ground, age, spacing between hybrid poplar rows, and clone, as simulated using SORTIE-ND at the center of a map (10 rows × 30 trees) of a given clone. Each point is the average of 10 simulated GLI points placed every meter midway between rows five and six of 10-row maps. Trees are placed every 6 m on the rows. References for height of plantation-grown noble hardwoods are given: the solid horizontal line is average for black walnut and white ash from a 30-year-old plantation, as well as red ash from a 17-year-old site; the dotted line is red oak from the same 17-year-old site (see text for details).

be insufficient or barely sufficient to sustain optimum growth of the hardwoods, depending on clone and hardwood mixture (20–50 GLI) (Figure 4). This insufficiency would require earlier removal of the poplars. Clone 3729 produced light levels that are too low even for relatively fast-growing, taller trees such as the red oaks of the southern Québec plantation. The levels obtained with the same spacing with more open clones such as 3230 or 3308 would be sufficient only for faster-growing species or for more shade-tolerant species such as sugar maple (*Acer saccharum* Marsh.).

The 16-m spacing with the same clones, on the other hand, seemed to provide ample light conditions with all clones for faster-growing hardwoods (dotted line), even with clone 3729 because of the increased light it allows at greater heights. Slower-growing trees would receive optimal light levels with both 3308 and 3230 clones, whereas clone 3729 should only be used with more shade-tolerant species (Figure 4). Similar results, favoring spacings of 16 m between poplar rows, have been obtained recently in France from mixed-intensive plantations of hybrid poplars and walnuts, with 20-m poplars nearing the end of their rotation (Vidal and Becquey 2008).

Conclusion

Many factors must be considered when poplar clones are chosen for a given situation, such as rusticity and tolerance to pests (Riemenschneider et al. 2002) and wood properties appropriate for the intended application (Pliura et al. 2007). In the case of a two-stage-intensive model, such as that tested here, careful planning with respect to the choice of both productions must also be based on the allometric characteristics of the fastest poplar clones to ensure the optimal development of both groups of tree species.

To help in this task, we have successfully integrated and validated three hybrid poplar clones of varying origins, which are widely available for intensive silviculture, in the SORTIE-ND light module. We have also simulated a mixed-intensive silviculture scenario, using hybrid poplars as the nurse crop for interplanted valuable hardwoods. The simulation demonstrated the importance of using wide spacings and the appropriate choice of poplar clones and hardwoods for the operation to be successful for both productions.

We believe the model can now be used to accelerate the testing and implementation of finely tuned scenarios with respect to the objectives sought. For example, a three-stage scenario where poplars are planted more densely toward a first rotation of pulp-quality trees on half the rows, followed by the delayed planting of valuable hardwoods, could be even more favorable for the development of the latter as better protection would be offered by already established poplars. Mixed-intensive plantations such as the one tested here are under investigation, as are even more elaborate agroforestry systems (Gillespie et al. 2000, Thevathasan and Gordon 2004, Rivest and Olivier 2007); these efforts can greatly benefit from prior testing using simulation models to focus on optimal designs.

We believe that such intensive multistage plantations are among the most sustainable responses to the current and ever-increasing demand for wood products. They are also capable of achieving restoration objectives on former agricultural land by providing shelter for slower-growing species (Gardiner et al. 2004). Furthermore, such plantations may also prove to be very successful as carbon offsetting projects through sequestration and avoided deforestation (Righelato and Spracklen 2007), being both productive and providing high-quality lumber with expected longer carbon storage time.

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