Evaluation of a tree classification system in relation to mortality risk in Québec northern hardwoods

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ABSTRACT

A tree classification system was developed in the 1980s as part of a guide for tree-marking in the rehabilitation of uneven-aged northern hardwood stands in Québec. It differentiates trees that are at high and low risk of mortality, trees with sawlog potential and cull trees. The risk class was assessed based on the presence of major crown and bole defects. The main objective of the present study was to evaluate this system with respect to its capacity to predict the probability of tree mortality. The variables used to classify the trees were observed in 88 experimental plots (0.5 ha) established between 1983 and 1999. Tree-level mortality probabilities were modelled for sugar maple (*Acer saccharum* Marsh.), American beech (*Fagus grandifolia* Ehrh.) and yellow birch (*Betula alleghaniensis* Britt.) to test the significance of the classification variables. The presence of decay, fungus or canker, wounds, uprooting, the death of at least 30% of the crown or of the roots, and the product class had significant ($p < 0.05$) effects on mortality probabilities for at least one of the 3 species studied. In the main, the results supported the tree classification system. However, this system could be modified to differentiate not only trees with a high or low mortality risk, but also to identify some very high-risk trees.

Key words: northern hardwood, mortality, defect, quality, classification, selection cutting, partial cut, sugar maple, American beech, yellow birch, uneven-aged, tree-marking

RÉSUMÉ

Un système de classement des arbres a été conçu, durant les années 1980, afin d'orienter le marquage des arbres lors de la réhabilitation des forêts de feuillus nobles de structure inéquienne au Québec. Il sépare les arbres d'un degré de risque de mortalité élevé ou faible, de même ceux propices ou non à produire du bois d'œuvre. Le degré de risque a été évalué selon la présence de défauts majeurs sur la cime ou le tronc. L'objectif premier de l'étude est d'évaluer la capacité de ce système de prévoir la probabilité de mortalité des arbres. Les variables de classement des arbres ont été notées dans 88 placettes expérimentales (0,5 ha chacune) établies de 1983 à 1999. La probabilité de mortalité des tiges a été modélisée afin de tester le niveau de signification des variables de classement de l'érable à sucre (*Acer saccharum* Marsh.), du hêtre à grandes feuilles (*Fagus grandifolia* Ehrh.) et du bouleau jaune (*Betula alleghaniensis* Britt.) La présence d'un champignon ou chancre, d'une blessure, de pourriture, de déracinement, de la mort d'au moins 30 % de la cime ou des racines, ainsi que la classe de produit ont eu des effets significatifs ($p < 0,05$) sur la probabilité de mortalité d'au moins une des 3 essences étudiées. Ces résultats viennent appuyer, en grande partie, le système de classement des arbres conçu durant les années 1980. Cependant, quelques modifications pourraient être apportées à ce système afin de différencier non seulement les arbres d'un degré de risque de mortalité élevé ou faible, et aussi afin d'identifier ceux d'un degré de risque de mortalité très élevé.

Mots clés : feuillus nobles, mortalité, défaut, qualité, classification, coupe de jardinage, coupe partielle, érable à sucre, hêtre à grandes feuilles, bouleau jaune, inéquienne, marquage

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Introduction

Northern hardwood forests cover the southern part of eastern Canada and the northern part of east-central United States. Earlier studies have shown that these old-growth stands, dominated by sugar maple, are uneven-aged (Gates and Nichols 1930, Tubbs 1977, Leak 1985, Majcen *et al*. 1985, Kenefic and Nyland 1999). In general, until the 1980s in Québec these forests were logged using diameter-limit cutting, which frequently resulted in high-grading but maintained an uneven-aged structure.

Given the reduced proportion of high-quality trees in the large-diameter classes in these forests, selection cutting was proposed to rehabilitate stands still having the potential of producing high-quality timber. This selection cutting in Québec began in 1983. A network of 43 experimental blocks had been established in northern hardwood stands by 1999. Five-year to 15-year growth results from the network have already been published, and have demonstrated a significant increase in net growth in treated plots as compared to control plots (Majcen and Richard 1992, 1995; Majcen 1995, 1997; Bédard and Majcen 2001, 2003; Majcen *et al*. 2005). This gain in net growth, when observed over a 15-year period, was solely attributed to the reduction of mortality from 0.28 m^2/ha/yr in control plots to 0.14 m^2/ha/yr in treated plots (Majcen *et al*. 2005). The removal of most defective trees explained this reduction in mortality (Majcen *et al*. 2005), as Eyre and Longwood (1951) also reported in Michigan.

At the time the experiment began, some tree-marking guidelines had already been published in the United States, mostly for second-growth stands (Arbogast 1957, Trimble *et al*. 1974, Leak *et al*. 1987). They stipulated that trees with the highest future value, or potentially yielding the highest financial rate of return or a higher rate than the owner's objectives, were to be left for future cuts. Harvesting priority is given to the trees having the poorest silvicultural and economic characteristics, such as culls, near-culls and trees with significant rot in the main stem. Leak *et al*. (1987) pointed out the importance of recognizing valuable high-risk trees; those trees likely to die or to lose merchantable volume or quality before the next harvest.

Some adaptations of these guidelines were required, mainly to simplify or clarify their application in the Québec rehabilitation context. Indeed, among high-priority issues in Québec is the need to retain the better-quality trees among the many low-quality stems and to be able to do so using an efficient working method using many newly trained tree markers.

The 4-class system applied in the experimental blocks (Majcen *et al*. 1990) is actually the combination of 2 binary classifications: one for the risk of mortality and one for the stem product. Therefore, it differentiates trees that are at high and low risk of mortality from trees with a sawlog potential as well as cull trees. The risk class was assessed based simply on the presence of major crown and bole defects.

Although this classification has recently been proven highly significant in explaining the mortality probabilities at the tree level (Fortin *et al*. 2008), the effect of the individual defects on mortality probabilities is still unclear. In other words, this classification and the ones published earlier were all designed with a *priori* assumptions that some stem and crown defects had similar effects on mortality probabilities and, consequently, that they could be grouped. However, without a *posteriori* analyses, there is no certainty that the grouping is optimal.

The main objective of this study was to evaluate in more detail the classification of Majcen *et al*. (1990) with regard to its capacity to differentiate trees having different levels of mortality risk. This evaluation was performed through a quantification of the effect of major stem defects on the mortality probabilities of 3 northern hardwood species. The analysis offered an opportunity to calibrate and validate species-specific mortality models for individual trees in northern hardwood uneven-aged stands in southern Québec.

Study sites

Ecological features

From 1983 to 1999, the Direction de la recherche forestière of the Ministère des Ressources naturelles et de la Faune du Québec carried out many experimental trials of selection cutting in uneven-aged northern hardwood stands. The experiments reported here are confined to 18 study sites distributed throughout the temperate forest zone (Fig. 1). This zone roughly consists of a belt running east-west across the province between 45° 30′ N and 48° 00′ N.

Except for the St. Lawrence Plain, the soil deposits in this zone are mostly glacial tills. The topography is usually a succession of rolling hills, interspaced with more or less flat lands (Robitaille and Saucier 1998). The estimated mean annual temperature and precipitation for the study sites ranges from 1.8 to 4.0°C and from 920 to 1420 mm, respectively (Régnière *et al*. 1995). In addition to local elevation gradients, the regional climatic variables follow a geographical gradient from the southwest to the northeast. The southwestern parts of the province are warmer and dryer than are the northeastern parts.

Despite the variability of the ecological conditions, Québec's temperate forest zone is mostly dominated by mixed stands of hardwood species. Sugar maple (*Acer saccharum* Marsh.) is usually the most abundant species in these stands, which develops on imperfectly to well-drained sites located on mid- and upper slopes. Yellow birch (*Betula alleghaniensis* Britt.) and American beech (*Fagus grandifolia* Ehrh.) are the most common associated species. These 3 species comprise at least 2/3 of the basal area of the selected sites, and sugar maple is always present.

Treatments

A mix of single-tree and small-group selection cuttings was conducted on an experimental basis at each site. The main objectives of the treatment were to decrease mortality losses, improve stand quality and maintain an uneven-aged structure in the residual stand (Majcen *et al*. 1990). Marking was carried out so that trees thought to be at high risk of mortality were ranked high in priority for harvesting. About 30% of the merchantable basal area, i.e., the total basal area of all trees with a diameter at breast height (DBH, 1.3 m) equal to or greater than 9.1 cm, was harvested. Selection cutting was done in one or several stands within each site and, in a few stands, 2 or 3 plots were established in the harvested part in order to test different residual basal areas.

A part of each treated stand was left unmanaged as a control. Several decades ago, all studied stands were logged at least once, generally in the form of a high-grading diameter-limit cut.

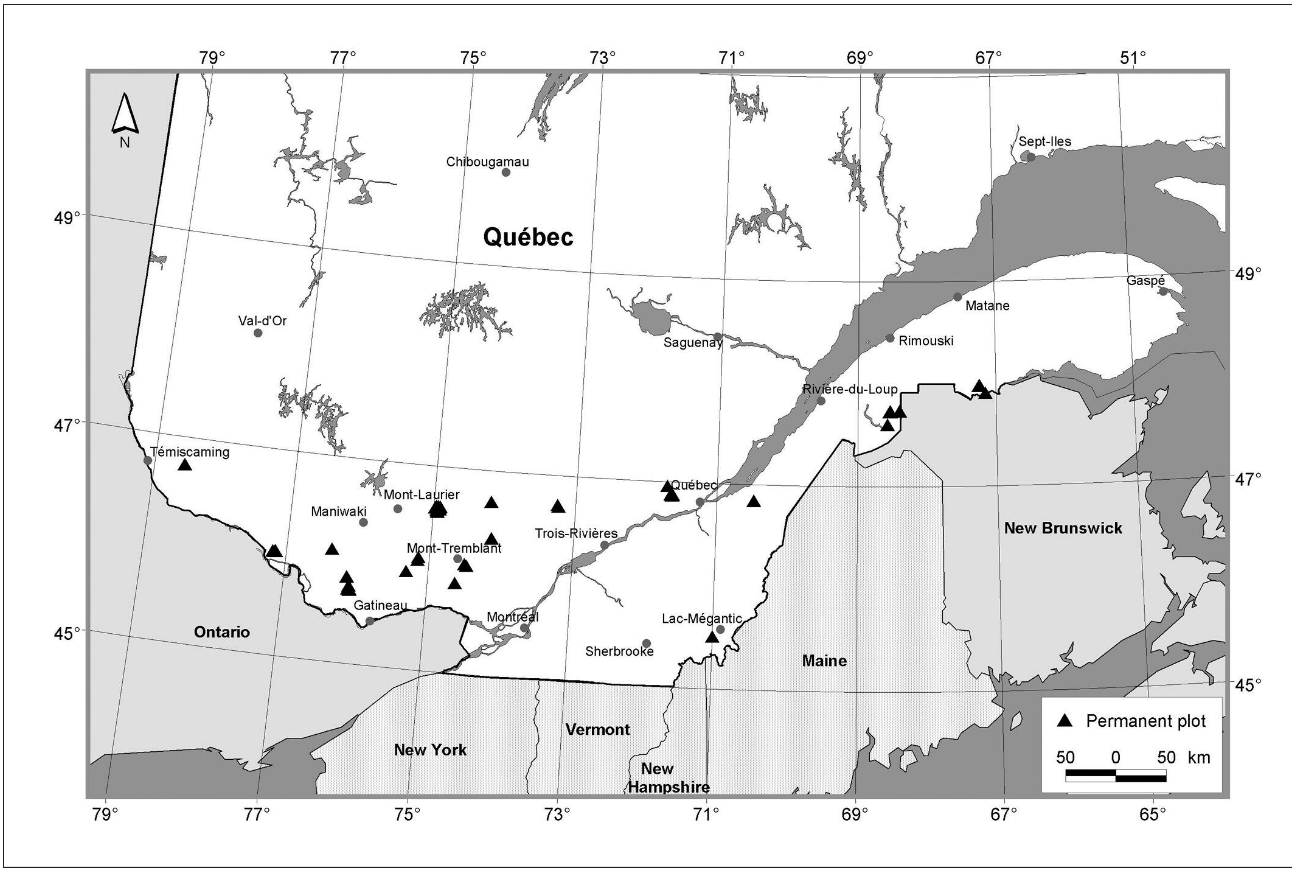

Fig. 1. Location of the study sites (a triangle represents at least 2 plots).

Experimental design and database

Permanent sample plots of 0.5 ha were established in both the untreated (control) and the harvested (treated) parts of every stand. Within plots, all trees with a DBH ≥ 91 mm were numbered during plot establishment, after harvesting. The tree species was recorded and DBH was measured to the nearest millimetre using a diameter tape. In each case, both the risk class and tree quality were assessed according to a 2-class system, which resulted in a 4-class system (Majcen *et al.* 1990). The risk class was assessed based on the presence of major crown and bole defects, as defined in Table 1, and the presence of these defects was recorded. Hardwoods were also classified either as a cull or as having a sawlog potential depending on the straightness of the bole and the external defects. The minimum requirement for a potential product was the presence of one face with a clear cutting of 1.82 m (6 feet) at any location on the bole, with no deduction for rotten cull applicable to this grading zone. The absence of a minimum diameter in the definition permitted it to be applied to pole-size stems (DBH from 9.1 to 23.0 cm), in addition to sawlog-size stems (DBH ≥ 23.0 cm). However, high-risk poles were not classified as having a sawlog potential. After the post-harvest measurement, measurements were conducted on a 5-year basis, on average, to record tree death or survival.

On the whole, 48 treated and 40 control plots were available for modelling mortality probabilities. Plot basal area averaged 25.6 m^2/ha in control plots and 18.4 m^2/ha in treated plots at the time of their establishment (Table 2). The database contained 17 875 trees (n) of 20 commercial species. Analyses were performed only for the 3 most abundant species, which are sugar maple (n = 12 134), American beech (n = 2119) and yellow birch (n = 1976, Table 3).

Method

Statistical approach

For individual trees, death or survival can be represented as a binary outcome. Consequently, the assumption of normally distributed error terms does not apply, and traditional statistical methods based on least squares are irrelevant. A common strategy for such binary data consists in using a generalized linear model (GLM) (McCullagh and Nelder 1989). A GLM requires the specification of a distribution (binary in this case study) and a link function that makes it possible to express the model in a linear fashion. Most studies on mortality use a logit link function (Yao *et al.* 2001, Jutras *et al.* 2003) or a complementary log-log (CLL) link function (e.g., Rose *et al.* 2006, Fortin *et al.* 2008). In this case study, we preferred the CLL link function because of its better mathematical tractability (Fortin *et al.* 2008). Using matrix notation, the model with the CLL link function can be expressed as follows:

$$[1] \quad 1n(-1n(1-y_i)) = x_i\beta \text{ for } i = (1,2,\dots,n)$$

where y_i is the response variable that takes the value of 1 if the tree dies or 0 if it survives, x_i is a vector of explanatory variables, β is a vector of unknown parameters and i is the observation index.

Table 1. Definitions of defects, corresponding recorded data and associated risk level according to the tree classification system of Majcen et al. (1990).

Defect	Definition and data recorded	Risk level
Wound of a mechanical origin (WMO)[a]	Any part of the bole where the bark has been removed by a mechanical process. The sapwood is exposed and is affected or not by significant decay. The most likely causes are another tree falling onto the bole or logging equipment from the current selection cut or a previous cut. The height and width (cm) of every wound was recorded.	High when >50 cm^2 (DBH 10–28 cm), >150 cm^2 (DBH 20–28 cm), and >300 cm^2, (DBH ≥ 30 cm)
Wound of a biological origin (WBO)[a]	Any part of the bole where the bark has been removed and the sapwood exposed as a result of bird-pecking (generally a strip of holes of about 6 mm each), sugar maple borer (*Glycobius speciosus* Say), beaver (*Castor canadensis* Kuhl) or the common porcupine (*Erethizon dorsatum* Linnaeus). The height and width (cm) of every wound was recorded.	Same as WMO
Decay	Presence of significant decay in a knot, crack, seam or wound.	High
Proportion of dead crown (PDC)	The proportion of crown (%) dead due to dieback or lost due to crown breakage. The death of lower branches due to natural pruning of the bole is not included.	High when >30%
Lean	3 categories: ≤10°, >10° and ≤45°, and >45°.	High when >45°
Roots cut	The presence of roots having been cut by logging equipment.	High when >30% of the roots were cut
Uprooting	Living tree uprooted due either to windthrow or logging.	High
Fungus or canker (FC)	The presence of a fungus or canker on the bole. Although the species wasn't recorded, the most common fungi in such stands are known to be: *Armillaria spp*., *Phellinus cinereus* (Niemelä) Fr., *Phellinus igniarius* (L.: Fr.) Quel., *Oxyporus populinus* (Sokum.: Fr.) Donk, *Kretzschmaria deusta* (Hoff.: Fr.) Martin, *Inonotus glomeratus* (Pk.) Murr. and *Inonotus obliquus* (Pers.: Fr.) Pilat. The most common cankers are *Eutypella parasitica* (Davidson and Lorenz) and *Neonectria galligena* (Bres.) Rossman and Samuels. Note that symptoms of canker rot (often caused by *I. glomeratus*) and beech bark disease, *Nectria coccinea* (Pers.: Fr.) var. *faginata* (Lohm., Wats. and Ay.) were not recorded.	High

[a]In the original system of Majcen *et al.* (1990), trees having white face wounds were not considered as high risk. This interpretation of the risk was introduced through the operational implementation of the system to asses for logging damages.

Table 2. Minimum, mean and maximum plot basal areas (m^2/ha) per treatment and species group.

	Control plot			Treated plot		
Species group	**Minimum**	**Mean**	**Maximum**	**Minimum**	**Mean**	**Maximum**
Sugar maple	4.3	16.4	29.2	1.3	12.7	20.3
American beech	0.0	3.0	13.8	0.0	2.0	9.0
Yellow birch	0.0	4.2	20.0	0.0	2.5	13.6
Other species	0.0	2.0	8.5	0.0	1.2	4.9
Total	**20.3**	**25.6**	**31.9**	**12.9**	**18.4**	**24.5**

The CLL link function facilitates the inclusion of a time factor in the model. Actually, if the logarithm of time in years ($1n(\Delta t)$) is specified as offset, the model works under the assumption of an exponential survival rate, i.e., the model provides a probability of survival on an annual basis and time acts as a composite interest rate over this probability (Fortin *et al.* 2008). The assumption can be test by specifying $1n(\Delta t)$ as a fixed effect. If the parameter estimate is not significantly different from 1, the assumption holds and eq. [1] can be rewritten as follows:

$$[2] \quad 1n(-1n(1 - y_i)) = x_i\beta + 1n(\Delta t_i) \text{ for } i = (1,2,\ldots,n)$$

The parameters, i.e., the element of β, are usually estimated through the maximum likelihood method or its derivatives. However, these methods rely on the assumption of independ-

Table 3. Number of observations of defects per species

Species	Any	Cull	WMO	WBO	Decay	Dead crown	Lean 10–45°	Lean >45°	Roots cut	Up.	FC
Sugar maple	12 134	5 287	1 591	878	1 829	1 433	2 538	178	71	89	1 179
American beech	2 119	1 360	391	178	408	294	328	21	15	15	176
Yellow birch	1 976	653	203	52	275	173	446	16	8	7	104

WMO: wound of a mechanical origin, WBO: wound of a biological origin, Up.: uprooted, FC: fungus or canker class.

ent error terms. Considering the data structure, this assumption is unlikely to be true, as the trees within the same plot are not spatially independent from each other. Furthermore, the mortality probabilities for trees observed during the same interval for a particular plot are likely to be correlated as well.

These correlations can be taken into account by specifying random effects in the model. A GLM with random effects becomes a generalized linear mixed model (GLMM). The mathematical developments behind the estimation of the parameters for a GLMM are tedious, and we will not describe them extensively. For further information, the reader is referred to Wolfinger and O'Connell (1993) or to the documentation of the GLIMMIX procedure (SAS Institute 2006).

Model calibration

Although they are not necessarily direct contributing factors (Vanclay 1994), many variables may explain the mortality of individual trees. Hamilton (1986) classified potential explanatory variables into 4 groups of measurements: tree size, stand density, individual tree competition and growth rate (vigour). The DBH was the only available trait to represent tree size, and it is an important and reliable trait (Monserud and Sterba 1999). To account for several possible relationships between DBH and mortality rate (e.g., Monserud and Sterba 1999, Eid and Tuhus 2001), DBH, DBH^{-1}, DBH^2 and DBH^3 were tested. The cubic transformation of DBH is not common, but we hypothesised that it could bring more flexibility to account for changing trends with different explanatory variables. Stand density was described directly with the basal area (m^2/ha) and indirectly with the variable treatment (2 levels). The basal-area-in-larger-trees, BAL (Monserud and Sterba 1999), was tested as a competition index. The BAL (m^2/ha) of a subject tree is the summarized basal area of every other tree within the plot having a DBH equal or greater than the subject tree. The proportion of dead crown (%) was preferred to growth rate as an indicator of tree vigour and mortality risk, because it is much easier and faster to observe during tree-marking or surveys. Several other risk variables were tested in the models for the purpose of this study: product class (2 levels), wound area (cm^2), ratio of maximum wound width to tree circumference at breast height (WR) and the presence or absence (2 levels) of every defect described in Table 1 (8 variables). To account for regional differences, mean annual temperature (°C) and precipitation (mm) were also tested. These climatic data were not monitored on sites, but were estimated using Biosim (Régnière *et al.* 1995). Finally, the duration of the time interval in year (Δt), expressed in logarithmic form ($1n(\Delta t)$), was also an explanatory variable.

In regard to the random effects, 4 hierarchical levels were identified in this case study—the measurements nested in the plots, which were nested in the stands, which were in turn nested in the study sites. All these random effects were specified on the model intercept.

Specific models were developed for each species. It was first considered to develop one integrating model, with the species (3 levels) as an explanatory variable. However, after some preliminary trials it was obvious that this variable was in interaction with most other tree-level covariates. This approach would have led to the development of an unnecessarily complex model and, therefore, was rejected.

Although repeated measurements were available for 82 out of the 88 plots, only one measurement per tree was randomly selected for model calibration and validation. The use of all repeated measurements was first considered, specifying this effect with the GLIMMIX procedure, but this approach resulted in major difficulties to have the models converge.

Several regressions were performed to test the significance of the fixed effects in the models and check Pearson residuals. The significance of the effects was tested at a level (α) of 5%. A t-test was performed on preliminary estimates of the parameters associated with ($1n(\Delta t)$). The models were reduced by specifying $1n(\Delta t)$ as an offset variable when this parameter was not significantly different from 1 at the 5% level.

Goodness of fit

The Hosmer–Lemeshow goodness of fit test (Hosmer and Lemeshow 2000) with 8 degrees of freedom was used to evaluate the model fit. The test was applied to the predicted mortality probabilities obtained from both the calibration and the leave-one-out cross-validation. In the latter case, the predicted mortality probability for stems within a given plot was obtained from the calibration of the model with all the data, except those of that particular plot. Since the model is not strictly linear, the population-averaged predicted mortality probabilities were calculated by integrating the marginal probability over the distribution of the random effect. This integral was computed numerically through Monte Carlo simulation.

Results

For the 3 models, the plot random effect was the only significant random effect at $\alpha = 5\%$. Consequently, only this random effect was kept in the models. Moreover, the preliminary estimate for the parameter associated with $1n(\Delta t)$ was not significantly different from 1 at $\alpha = 5\%$ for every model. The models were then reduced by specifying $1n(\Delta t)$ as an offset variable. The final parameter estimates are shown in Table 4.

Predicted mortality probabilities are presented for each species in the following sections and in Figs. 2, 4 and 5. Note that these predicted probabilities are dependent on the char-

Table 4. Results of model calibration and estimates of parameters

		Sugar maple		American beech		Yellow birch	
Fixed effects	**Class**	**Estimate**	**Std Err**	**Estimate**	**Std Err**	**Estimate**	**Std Err**
Intercept	–	-3.22090***	0.508100	-4.82120***	0.911600	-2.42900**	0.707300
Mean annual temperature	–	0.38860**	0.100800	0.51160*	0.222500	–	–
DBH	–	-0.14890***	0.031320	0.05169***	0.006849	–	–
DBH^2	–	0.00440***	0.001014	–	–	–	–
DBH^3	–	-0.00004**	9.70E-06	–	–	–	–
BAL	–	–	–	–	–	0.02656*	0.012930
Product	Cull	1.09460***	0.091030	0.82240**	0.220400	0.38640*	0.174700
	Sawlog pot.	0	–	0	–	0	–
Decay	Without	-0.24960**	0.084100	-0.51030**	0.172600	–	–
	With	0	–	0	–	–	–
FC	Without	-0.46470***	0.087360	-0.67970**	0.19730	-1.56230***	0.223200
	With	0	–	0	–	0	–
Roots cut	Without	-1.47300***	0.214900	–	–	–	–
	With	0	–	–	–	–	–
Uprooting	Without	–	–	-2.65980***	0.50490	-1.54440*	0.640400
	With	–	–	0	–	0	–
WBO	Without	-0.33340**	0.107900	–	–	–	–
	With	0	–	–	–	–	–
WR	–	1.7393***	0.390900	–	–	2.49700**	0.952000
PDC	–	–	–	0.03072***	0.003153	0.03575***	0.003301
PDC × treat.	Partial cut	0.03532***	0.006391	–	–	–	–
	Untreated	0.06588***	0.005483	–	–	–	–
PDC^2 × treat.	Partial cut	-0.00011	0.000075	–	–	–	–
	Untreated	-0.00034***	0.000067	–	–	–	–
Random effect							
Variance of the plot random effect	–	0.16040**	0.046500	0.37680**	0.159900	0.19100*	0.101900

Std Err: standard error; DBH: diameter at breast height (1.3 m); BAL: basal-area-in-larger-trees; FC: fungus or canker; WBO: wound of a biological origin; WR: ratio of the maximum mechanical wound width to tree circumference at breast height; PDC: proportion of dead crown (%).
*P < 0.05, **P < 0.01, ***P < 0.0001

acteristics of the group of reference trees. As the model is not strictly linear because of the link function, these differences might change slightly in proportion with other reference characteristics. The mean predicted probabilities of mortality are illustrated only to help with sizing the magnitude of the differences.

Sugar maple

The significant explanatory variables for the sugar maple model were mean annual temperature, DBH^3, product class, presence of decay, presence of fungus or canker, presence of a wound having a biological origin, roots cut, proportion of dead crown in interaction with the treatment, and ratio of maximum mechanical wound width to tree circumference at breast height (Table 4; Fig. 2). The model with random effects did not converge when fixed effects were specified as a lean of more than 45°, a partial uprooting or an area of wound of mechanical origin. The same occurred in cross-validation when the mean annual precipitation was set as an explanatory variable. These last 4 variables, therefore, were not retained in the final model.

The predicted mortality probabilities were significantly higher on warmer sites than on cooler sites (Fig. 2a). For instance, the predicted 15-year mortality probabilities for a 40-cm tree with sawlog potential and no major defect on a warmer site (4.0°C) is 5.1%. It is a little more than twice the predicted values (2.2%) for the cooler site (1.8°C).

The DBH significantly affected the mean mortality probabilities in a cubic fashion (Fig. 2b). The predicted mortality probabilities decreased from 10 to 30 cm in DBH, and then followed a near plateau until attaining a DBH of about 56 cm for trees with sawlog potential and no significant defect. The 15-year difference in predicted mortality probabilities between the DBH peak at 10 cm and the hollow at 26 cm was only 1.8% for stems with sawlog potential and without significant defect. Beyond a DBH of 56 cm, predicted mortality probabilities decline rapidly. Actually, none of the sugar maple stems having a DBH ranging from 56 to 80 cm (n = 46), sawlog potential and no major defect died during the study period. Within this DBH range, mortality was concentrated within the more numerous defective trees (n = 103), for which the observed 15-year mortality rate was 33%.

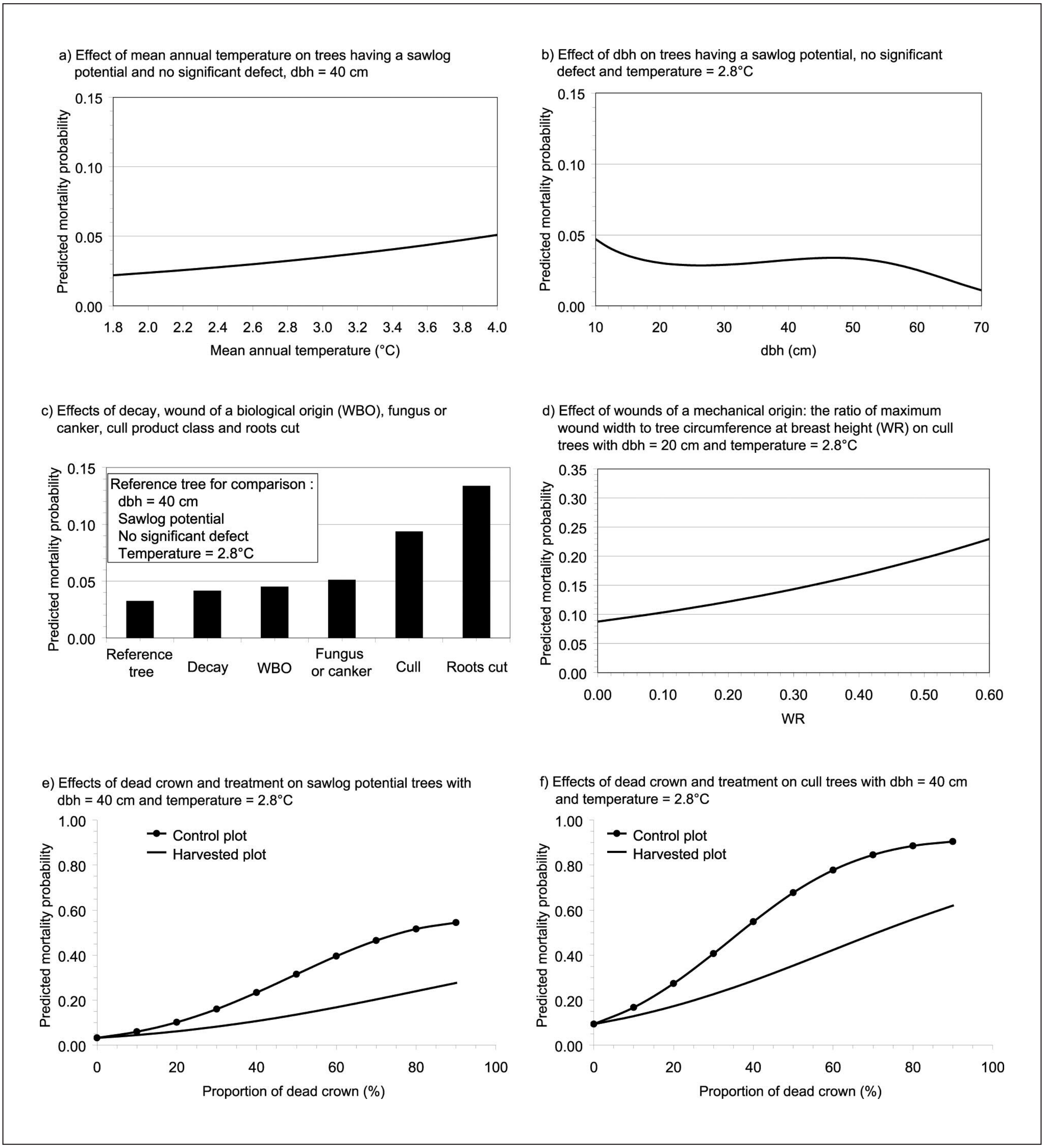

Fig. 2. Effects of the explanatory variables on the mean predicted probabilities of mortality for an upcoming 15-year interval for sugar maple (other covariates are kept constant).

The mean mortality probabilities were significantly different between trees with sawlog potential and cull trees, with the 15-year risk being 6% higher for a 40-cm cull tree (Fig. 2c). When compared to the reference tree, the occurrence of decay on the bole increases the mean mortality probability by 1% (Fig. 2c). The increase is about double when fungus or canker is present. It is notable that there is an absence of interaction between the product class, the presence of decay and the observation of fungus or of a canker. These effects appeared to be somewhat additive in relation to the mortality probabilities, although the model is not strictly linear because of the link function.

The effect of wounds of biological origin was not related to their area or width in relation to the DBH, but only to their presence on the stems (Fig. 2c). The effect was more important on smaller poles because of the combined effects of DBH

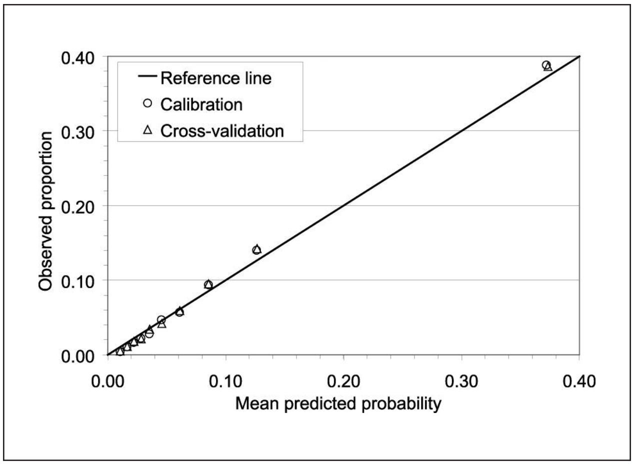

Fig. 3. Goodness of fit between the observed proportions of dead sugar maples and the mean predicted probabilities of mortality for each partition and group of probabilities (the reference line indicates a perfect fit)

and end product (Fig. 2b, c). Indeed, most poles with a wound of biological origin were classified as cull because the wound size exceeded the maximum area allowed in the sawlog potential product class. The predicted mortality probabilities reached 18% for these smaller poles.

The presence of roots cut from logging had a significant and important effect in the model (Fig. 2c). Most stems classified with this defect were cull stems of pole size, and their 15-year predicted mortality probabilities ranged from 32 to 47%. Moreover, half of them had a certain proportion of dead crown, which increases the probability for mortality. Overall, observations in the database indicated that 65% (n = 66) of sugar maples whose roots were cut died during the study period.

Although partial uprooting and trees leaning more than 45° could not be included in the model due to non convergence of the function, observations in the database indicated they have serious effects. In fact, in the case of partial uprooting, 58 of the 70 trees observed over the 15-year period died (83%). Likewise, 46 out of the 95 trees (48%) trees leaning more than 45° (without uprooting) died over the 15-year period.

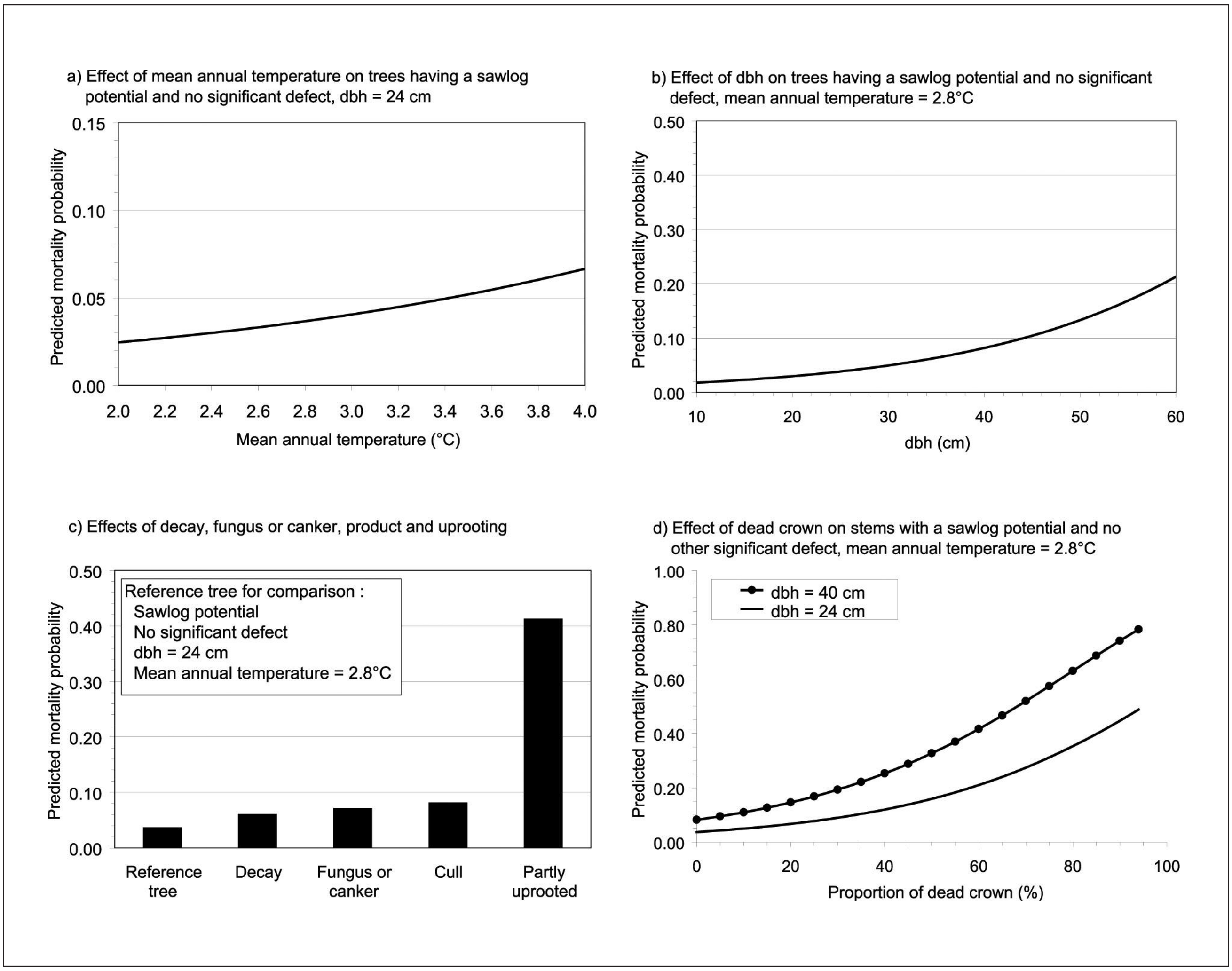

Fig. 4. Effects of the explanatory variables on the mean predicted probabilities of mortality for an upcoming 15-year interval for American beech (other covariates are kept constant).

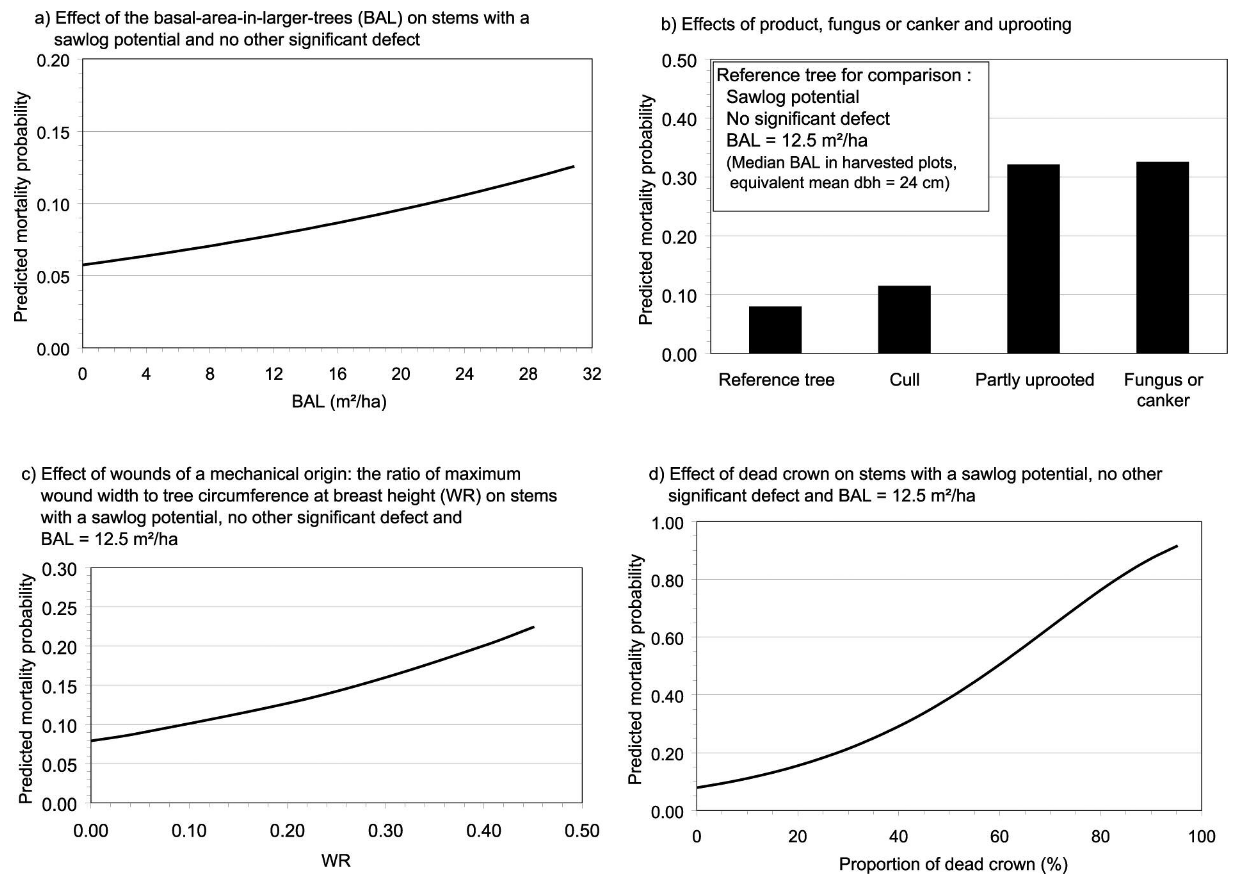

Fig. 5. Effects of the explanatory variables on the mean predicted probabilities of mortality for an upcoming 15-year interval for yellow birch (other covariates are kept constant)

In the case of wounds with a mechanical origin, the indicator of the ratio of the maximum wound width to tree circumference at breast height was a significant cause of mortality (Fig. 2d). In addition to these results, some small wounds had indirect effects, because they forced pole-size stems to be classified as cull rather than as having sawlog potential. This was the case for wounds larger than 50 cm^2 and 150 cm^2 for small and large (DBH from 19.1 cm to 23.0 cm) poles, respectively (Table 1). Observations in the database indicated that these thresholds are somewhat conservative but appropriate overall. For instance, the observed 15-year mortality rate for sugar maple poles having a sawlog potential and no other defect, but with a wound that is a little smaller than the product class thresholds, was 14% (n = 21). This is much more than the rate predicted on similar poles without wounds (2.9 to 4.7%, Fig. 2b), and is quite similar to the rate predicted for pole-size cull trees without other defects (8.5% to 13.4%).

The significant effect of the proportion of dead crown interacted with the treatment (Fig. 2e, f). Trees with the same proportion of dead crown were more likely to survive in partial cuts than in control plots. For example, a 40-cm sugar maple with sawlog potential and 30% of dead crown had a predicted mortality probability at 15 years of 16% in a control plot versus 8% in a treated plot. When these stems had no sawlog potential the probabilities are 41% and 23%, respectively (Fig. 2f).

The Hosmer–Lemeshow goodness of fit test produced χ^2 statistics of 17.2 and 13.7 for the calibration and the cross-validation data sets, respectively. The probabilities ($Pr > \chi^2$) associated with these statistics were 0.0281 and 0.0910, respectively. Although the test indicated a significant probability for the calibration data set, there was no major departure between the observed and predicted values (Fig. 3). The main divergences between the observed and predicted values were due to a relatively small overestimation (<0.7%) and underestimation (<1.6%) of the mortality probabilities in the groups of stems having the lowest and highest mortality probabilities, respectively. Moreover, for the validation period, the model predicted 940 deaths and 951 death trees were actually observed (98.8%).

American beech

Explanatory variables retained in this model were mean annual temperature, DBH, product class, presence of decay, presence of a fungus or canker, presence of partial uprooting, and the proportion of dead crown (Table 4 and Fig. 4). The model of random effects did not converge when mean annual precipitation, BAL, tree lean of more then 45° or roots cut were specified as fixed effects, so these variables were not retained in the final model.

Like sugar maple, the mortality probabilities were significantly higher on warmer sites than on cooler sites (Fig. 4a). The 15-year mortality probabilities for a 24-cm tree with sawlog potential and no major defect ranged from 2.4% to 6.7% along the mean annual temperature gradient from 2.0°C to 4.0°C.

The DBH significantly affected the mean predicted mortality probabilities in a somewhat linear fashion (Fig. 4b). For a reference tree with sawlog potential and no major defect, the predicted 15-year mortality probabilities varied from 1.8% to 21.3% over a DBH range of 10 cm to 60 cm. These probabilities nearly doubled when the product class was cull rather than sawlog potential (Fig. 4c).

The observation of decay, fungus or canker had similar and significant effects on the mean mortality probabilities (Fig. 4c). As was the case for sugar maple, no interaction occurred between the product class, the presence of decay and the observation of fungus or canker in the American beech model. These effects appeared to be somewhat additive in relation to the mortality probabilities, although the model is not strictly linear because of the link function.

Partial uprooting had significant and major effects on the predicted mortality probabilities (Fig. 4c), especially for pole-size and small sawtimber-size stems, where they were mostly observed. Most stems affected by this defect were cull stems of pole size; their 15-year predicted mortality probabilities ranged from 45% to 67%.

Although roots cut by machinery and trees leaning more than 45° could not be included in the model due to non-convergence of the function, observations in the database indicated they may have important effects. Indeed, over 15 years of observation 4 of the 11 trees whose roots were cut (36%) died. Similarly for trees leaning more than 45° (without uprooting), out of the 10 trees observed there were 3 deaths (30%).

The proportion of dead crown was a significant indicator of increased mortality probability (Fig. 4d). Along with uprooting, it is one of the most important variables explaining very high mortality rates.

The Hosmer–Lemeshow goodness of fit test produced χ^2 statistics of 12.7 and 9.3 for the calibration and the cross-validation data sets, respectively. The probabilities (Pr $>\chi^2$) associated with these statistics were 0.1230 and 0.3185, respectively. The test gave non-significant probabilities, indicating that there was no evidence of major departure between the predicted probabilities and the observed mortality proportions.

Yellow birch

The explanatory variables that were significant at $\alpha = 5\%$ in the yellow birch model were basal-area-in-larger-trees (BAL), product class, presence of fungus or canker, partial uprooting, the ratio of the maximum wound width to tree circumference at breast height and the proportion of dead crown (Table 4 and Fig. 5). Contrary to the 2 previous models, no variable was excluded from the yellow birch model because of the function not converging.

BAL significantly affected the predicted mortality probabilities of yellow birch (Fig. 5a). In light of the fact that this competition index integrates some effects of plot basal area and DBH, higher BAL were observed on smaller trees and on trees from the denser control plots. The predicted mortality probabilities for the smallest yellow birch in the denser plots (BAL = 30.8 m^2/ha) were about twice those predicted for the largest yellow birch trees (BAL = 0 m^2/ha). In fact, the largest yellow birch trees had the lowest predicted mortality probabilities. Indeed, none of the yellow birch with a sawlog potential and no major defect in the DBH range from 50 cm to 88 cm (n = 42) died during the study period. Within this DBH range, mortality was concentrated within the defective trees (n = 50) for which the observed 15-year mortality rate was 28%. The inclusion of BAL in the model does not explain by itself the absence of effects of plot basal area and DBH. Indeed, even when subtracting BAL from the model, plot basal area and DBH had no significant effect on predicted mortality probabilities.

The predicted mortality probabilities of yellow birch stems were significantly higher for cull trees than for trees having a sawlog potential; they were increased by 3.5% for the reference tree (Fig. 5b). The observation of fungus, canker or partial uprooting on yellow birch brought about a 4-fold increase in mean mortality probabilities when compared to the reference tree. Roots cut and trees leaning more than 45° had no significant effect on the model, simply because they were rare events (n = 10 and n = 16, respectively) and frequently correlated with uprooting. Nonetheless, more than 1/3 of these stems died over the 15-year study period.

In the case of wounds with a mechanical origin, the WR had a significant effect on mortality (Fig. 2c). In addition to the WR effect, in the model wounds had another indirect effect on poles through the effect of the product class. Indeed, small and large poles were not allowed to be classified as having a sawlog potential if wounds were larger than 50 and 150 cm^2, respectively (Table 1).

The proportion of dead crown significantly increased mortality probability (Fig. 5d). The 15-year predicted mortality probability for a reference stem having 30% dead crown (21%) is almost 3 times greater than for a stem without dead crown (8%).

The Hosmer–Lemeshow goodness of fit test produced χ^2 statistics of 5.7 and 5.5 for the calibration and the cross-validation data sets, respectively. The probabilities (Pr $>\chi^2$) associated with these statistics were 0.6830 and 0.7037, respectively. The test gave non-significant probabilities, indicating that there was no evidence of significant differences between the predicted probabilities and the observed mortality proportions.

Discussion

This study provides direct relationships between mortality risk and some plot and stem features, including major bole defects. Although many tree-marking guides are available for northern hardwoods (e.g., Arbogast 1957, Trimble *et al.* 1974, Leak *et al.* 1987, Majcen *et al.* 1990, OMNR 2004, SWDNR 2007), mention of the relationship between major defects and mortality was found only in the recent publication of Majcen *et al.* (2005). The other authors' analyses addressed stand-level relationships, but not stem mortality probabilities as in the present study. This study was actually designed to validate some guidelines by Majcen *et al.* (1990) and more deeply analyze the effect of major defects in comparison to Majcen *et al.* (2005).

The relationships between mortality risk and stem features are useful in developing tree-marking guidelines aimed at reducing risk of trees. Moreover, these relationships can be used to prepare a silvicultural prescription or to forecast the mortality rate of stands for management purposes. In fact, the models demonstrated an acceptable forecasting capability. The Hosmer–Lemeshow goodness of fit test gave non-significant probabilities for the American beech and yellow birch models. It indicated that there was no evidence of a significant difference between the predicted probabilities and the proportion of observed mortality. Although the goodness of fit test gave a significant probability for the sugar maple model, the main difference between observed and predicted mortality rates were small and do not affect management implications. Moreover, the model with the validation dataset predicted a number of dead trees (940) that was close to the number observed (951). The very high number of observations for the sugar maple model (n = 12 134) made the Hosmer–Lemeshow test very powerful, to such a degree that it can detect any differences.

Formal tests of differences between the 3 specific models were not presented, but the results in Fig. 2, 4 and 5 show that the different species tend to have different behaviours in mortality terms.

Tree level

The effect of DBH at the tree level was different for each of the 3 studied species. The relationship of sugar maple to DBH was cubic, with a general decreasing trend and a small peak, or almost a plateau, from 30 cm to 56 cm for stems with sawlog potential and no significant defect (Fig. 2b). The highest peak in the mortality rate was observed with the smallest maples (DBH of 10 cm), mostly belonging to the suppressed and intermediate crown positions. In the mid-size DBH classes (around 20 to 30 cm), most sugar maples have reached a codominant position in the canopy and the mortality rate is lower. This is consistent with other observations reported at the stand level in northern hardwoods (e.g., Lorimer *et al.* 2001). The model indicates that sugar maples could have been facing another more difficult survival stage at a DBH near 50 cm, where the near plateau is slightly peaking. According to our data, it is correlated to a stage where most maples are transferring from the codominant to the dominant crown position. Thereafter, the larger sugar maples with sawlog potential and no major defect had very low mortality probabilities, and most of them belong to the dominant crown position. This was not the case for American beech. Its mortality probabilities increased with DBH (Fig. 4b). The smallest merchantable American beech stems exhibited one of the lowest predicted mortality rates among the 3 species. This result is thought to be related to the high shade tolerance of this species. As for the largest beech stems, they exhibited the highest mortality rates. Since the beginning of the study, beech bark disease has spread through most study sites (Morin *et al.* 2007) and may have increased the mortality rates, especially for larger stems. However, this disease is not yet a big issue in Québec. Also, these study plots are located at the extreme northerly boundary of the native range of American beech, and can therefore have higher risks of experiencing temporal damaging or killing events, such as late spring frosts (Tubbs and Houston 1990). The presence of cracks or seams could occur more frequently at this latitude, and they could increase the occurrence of decay. Most large beech stems were culls or had major defects. Moreover, they rarely reached the dominant crown position.

As regards yellow birch, DBH had no direct significant effect. However, the effect of basal-area-in-larger-trees (Fig. 5a) indicates some DBH trends—smaller birch stems are more likely to die than are larger ones, and this effect is related to plot basal area. These results are thought to be related to the shade tolerance of yellow birch, which is lower than that of sugar maple, the dominant species in these stands. Smaller birch trees may suffer from competition for light, while larger ones may have gained adequate space under full light conditions.

The effect of the product class was relatively similar for the 3 species, and it was among the important variables explaining mortality probabilities, also reported in Fortin *et al.* (2008). The predicted mortality probabilities for sugar maple and American beech were more than twice that for cull trees than for a tree with a sawlog potential (Fig. 2c and Fig. 4c), and it was a little less than twice that of yellow birch (Fig. 5b). This effect was expected from rotten cull trees. However, even apparently sound cull trees had significantly higher mortality rates. Indeed, the product effect is independent of the presence of major defects associated with the presence of external evidence of decay. Sound cull trees are characterized by an abundance of living or dead limbs, frequent surface bumps, and the presence of crook or sweep. Consequently, they may have less mechanical resistance. Moreover, the relative abundance of natural pruning bumps may also indicate a tree's difficulty to overcome these because of a slow growth rate. Slow-growing trees are generally known as being less vigorous and having a higher mortality probability (Hamilton 1986). Because of the magnitude of the product effect, it would be interesting to test for model improvement through the use of the cull proportion in the model, but these data were not recorded in our plots. The cull proportion is already used in some marking guides to classify the quality of the growing stock (Arbogast 1957) or its vigour (SWDNR 2007), defined as the measure of the growth potential of an individual tree.

The effect of decay, fungus or canker on mortality probabilities differed among the 3 species, and was less on sugar maple (Fig. 2c). In this case, the 15-year mortality probability for a tree with sawlog potential increased by only 1% in the presence of decay, and by about 2% in presence of a fungus or canker. Consequently, these results suggest that decay or fungus generally pose a higher risk of a loss in quality (Shigo 1966) rather than a direct risk of mortality over a 15-year period. However, as the bole decays, the product class may eventually shift from sawlog potential to cull, and then the mortality risk increases substantially. This process could have been faster for American beech, where the presence of decay, fungus or canker was associated with increased mortality rates of about 3% to 6% (Fig. 4c). The greatest effect of fungus or canker on the mortality probabilities was for yellow birch, with an increase of about 25% for a sawlog potential tree (Fig. 5b). An unexpected and unexplained result for yellow birch was the clearly non-significant ($p = 0.4043$) effect of the presence of decay.

The various effects of fungus and canker among species may also be caused by differences in the pathogens involved. The most frequently observed pathogens on sugar maple in our study plots (unpublished data) are *Oxyporus populinus* (Sokum.: Fr.) Donk, *Phellinus igniarius* (L.: Fr.) Quel., I*nonotus glomeratus* (Pk.) Murr., *Kretzschmaria deusta* (Hoff.: Fr.) Martin and *Eutypella parasitica* (Davidson and Lorenz). These are either absent or rarer on yellow birch, for which the most frequent pathogens are *Phellinus cinereus* (Niemelä) Fr., *Inonotus obliquus* (Pers.: Fr.) Pilat. and *Neonectria galligena* (Bres.) Rossman and Samuels. American beech seems to be mainly affected by pathogens among those observed on the other 2 species, except for *Inonotus obliquus* (Pers.: Fr.) Pilat. and *Eutypella parasitica* (Davidson and Lorenz).

The ratio of the maximum wound width to tree circumference at breast height significantly affected mortality rates in sugar maple and yellow birch for wounds having a mechanical origin (Table 4; Fig. 2d and Fig. 5c). From the observations of Shigo (1966) on variables associated with the volume of decay in wounded trees, it was expected for sugar maple that total wound area would better explain the variation in mortality than WR. However, the model did not converge with this variable. Even though Shigo (1966) reported that wound size was weakly associated with the volume of decay on yellow birch, it was associated with the volume of discolouration, which also causes a loss in the volume of higher-quality wood.

The effect of wounds from a biological origin was associated with their presence on sugar maple, independent of their area or width. The relatively low frequency of occurrence of such wounds having a large area may explain the absence of a significant effect of the wound area. At least half of these wounds on sugar maple were caused by the sugar maple borer (*Glycobius speciosus* Say); the remainder attributed to bird-pecking or the common porcupine (*Erethizon dorsatum* Linnaeus). The occurrence of damage caused by the sugar maple borer may not only be a cause of increased mortality risk, but also an indicator of slowly growing trees under stress (Newton and Allen 1982).

As expected, trees that were uprooted, leaning more than 45° or whose roots were cut had a higher probability of mortality. These effects were included in the models when convergence was possible and observations were numerous enough (Tables 3 and 4; Fig 2c, 4c and 5b). These effects were mostly observed on poles and small sawlog-size stems. A lean of more than 10 degrees is considered as a moderate defect in Ontario (OMNR 2004). However, the 10° to 45° tree-leaning class in this study had no significant influence on mortality rates.

The proportion of dead crown was highly related to the mortality probabilities of the 3 species (Fig. 2ef, 4d and 5d). It is worth noting that most study sites were not seriously affected by maple decline, severe insect defoliation or severe storm damage (ice, snow or wind) at the time of plot establishment. Consequently, observations of dead crown reported in this study could mainly be attributed to tree-level or stand-level factors, such as an isolated ice, snow or wind event, a fallen tree or the senescence of a defective tree. For sugar maple, there were enough observations to detect differences in the effect of dead crowns, depending on the treatment. Such trees located in treated plots have smaller predicted mortality probabilities than in control plots. This observation supports the hypothesis that releasing trees with some dead crown caused by crowding may reduce their mortality probabilities. This is consistent with observations that higher inter-tree competition may predispose stands to more decline (Bauce and Allen 1992) or may increase the mortality of overstorey trees affected by insect defoliation (Wink and Allen 2007). The predicted increases in mortality probabilities were small when the proportion of dead crown was below about 75% for trees with sawlog potential (Fig. 2e). This is similar to what was observed in a study on sugar maple decline (Roy *et al.* 2006) and in most preliminary or short-term observations reported following the major ice storm that occurred in 1998 in northeastern North America (Boulet *et al.* 2000; Nielsen 2000; Bédard and Majcen, unpublished results). For American beech and yellow birch, there was no significant interaction between the proportion of dead crown and any other covariate. If some effects similar to the ones observed on sugar maple existed, there were too few observations to detect it.

Stand level

The mean annual temperature had a significant effect on both sugar maple and American beech. The predicted mortality is higher for plots located on warmer sites, which are mainly located in the southwestern parts of the province or at lower elevations. The effect of increased mortality with higher mean annual temperature could be due to an increased water deficit during the growing season, though the sugar maple and American beech models did not converge when mean annual precipitation was specified as a fixed effect. The absence of a significant effect of temperature and precipitation on the yellow birch model is likely to be related to the distribution of this species among the plots. Indeed, yellow birch was rare or absent from plots located on the dryer or warmer sites. The species is known to prefer cool areas with abundant precipitation (Erdmann 1990).

The plot basal area had no direct significant effects on predicted mortality probabilities for the 3 species. However, it had some indirect effects for sugar maple through the treatment variable with a dead crown proportion and through the basal-area-in-larger-trees variable for yellow birch (Table 4). From these results on basal area and treatment, it is thought that the usually higher mortality rates observed at the stand level in denser plots would be due to a higher abundance of defective trees. As the plot basal area increases, competition could induce a stress, which in turn could increase the probabilities of a stem becoming defective. Afterwards, the mortality probabilities are increased.

Data and models

The defects (Table 1) were useful indicators of a tree's mortality probability, although some were recorded and analyzed in broad categories. It was the case for crown dieback and crown breakage, which were recorded in one class, though they may have distinct origins. Fungi and cankers could have been differentiated, since they have different effects on lumber quality, with those of fungi being more diffuse and cankers more localised. Moreover, sound cankers could have been differentiated from rotten ones. Wounds of a biological origin could have been differentiated between bird-pecking, sugar maple borer, beaver (*Castor canadensis* Kuhl) or the common porcupine. The location of decay in a knot, crack, seam or wound was also not recorded. Shakes and cracks were not included in the analysis because they were recorded in the same category as large bumps and bumps with decay.

However, distinctions within each of these broad categories were recorded in plots established since 1989, and will allow for a more detailed analysis in future, as remeasurements are done. There were not yet enough observations to develop more detailed models, with only the 52 plots established from 1989 to 1999. Indeed, the dataset contains about half the total number of observations, and we would have wanted to include in the models more than twice the number of explanatory variables.

Nevertheless, preliminary analyses were performed with this more detailed database to detect possible bias from the grouping of some defects. They indicated no evidence that having differentiated any of the broader defect categories would have led to markedly different results or implications for management. Future measurements in this network should allow for more precise analysis and model improvement.

The unbalanced character of this kind of experiment could be one important explanation of the difficulties encountered in properly fitting the models and reaching convergence with some variables in the presence of random effects. Some rare defects were not observed in every plot, or were concentrated within a few plots or within small DBH classes. Moreover, the number of observations and their extent through time varied among plots. Some plots were remeasured only once, while others were remeasured 2 or 3 times. Correlation between some independent variables, such as tree leaning more than 45° and uprooting for instance, was also a cause of difficulties in fitting models and reaching convergence.

Implications

Based on the results of the present study, we can state that the tree classification system of Majcen *et al.* (1990) is generally appropriate to classify the risk of stem mortality. First, almost every defect considered as major (Table 1) did have a significant effect on the observed mortality rates. The presence of decay on yellow birch was an exception, since it did not significantly increase mortality probabilities. The effect of the wound area remains unclear in relation to the classification by Majcen *et al.* (1990), because the sugar maple model did not converge with wounding area and it had no significant effect on American beech and yellow birch models. However, the ratio of maximum wound width to tree circumference at breast height had a significant effect on sugar maple and yellow birch models. Second, the distinction made for the 2 product classes was highly significant in terms of expected mortality rates, in addition to quality considerations. Third, observed mean mortality rates were clearly different among most classes (Table 5). Only low-risk culls and high-risk stems with sawlog potential had relatively close mortality rates. Fourth, 15-year growth results in experimental plots have already demonstrated a significant increase in net growth in selection plots marked using this system, when compared to control plots (Majcen and Richard 1992, 1995; Majcen 1995, 1997; Bédard and Majcen 2001, 2003; Majcen *et al.* 2005).

However, this system could be modified for application in a rehabilitation context to better differentiate trees based on their level of mortality risk. For instance, a class of non-growing stock, which is a class of very high-risk trees, could be created. Non-growing stock could be defined as the group of trees having a predicted mortality rate similar to or higher than survivors' growth rate. This group of trees would not be contributing to the growth of the stand, but rather to its decline. Moreover, both cull classes could be merged into one because they both represent higher mortality risk, but with no risk of losing good-quality volume.

Before adding new variables or classes to such a system, it is important to keep in mind the context in which it will be applied. Tree-marking during the first cutting cycles in a rehabilitation context should be concerned almost entirely with very defective trees. Indeed, it is rarely possible during the first cutting cycle to both harvest every defective stem and maintain an acceptable residual basal area for wood quality production. As a result, tree markers must be given the tools to classify defective trees along a risk gradient so as to select the worst for harvesting and the best for future growth. Tree-marking should also be a relatively quick activity with low cost, because of the low revenue expected the first time, which comprises mostly cull trees. At this stage there is generally no need to compare quality stems for selection, as there are so few of them, although it is sometimes important.

The results also have implications for the study of long-term forest dynamics. For instance, observation of a U-shaped mortality function for sugar maple and yellow birch could be associated with a higher frequency of defective trees in larger DBH classes. While descending monotonic size–mortality trends could be associated with higher levels of acceptable growing stock in these larger DBH classes, the same might not be true for American beech. It may be useful to note the major defects and the degree of stem quality while monitoring, and to separate the species when performing analyses, to help understand forest dynamics.

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Table 5. Relative abundance in control plots and observed 15-year mortality rates per tree class using the system of Majcen *et al.* (1990) applied to the 3 studied species

Variable	Low risk Sawlog potential	Low risk Cull (sound)	High risk Sawlog potential	High risk Cull
Relative abundance (% basal area)	47	13	13	27
Observed 15-year mortality rate (% basal area)	5	13	16	39

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