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Visual assessment of tree vigour in Canadian northern hardwood forests: The need for a simplified system

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ABSTRACT

Northern hardwood forests include many degraded stands dominated by trees of low vigour due to past management. To facilitate the implementation of stand improvement, several classification systems have been developed to help tree markers visually assess tree vigour at time of harvest based on the presence of individual defects. Because very few studies have tried to empirically validate such systems, it remains uncertain whether many of these defects should be used to guide the tree marking process. In this study, we assess tree vigour using repeated measurements collected as part of long-term silvicultural trials conducted in 615 permanent plots throughout the northern hardwood forest of Quebec, Canada. We aimed to determine whether the defects that are commonly used for classification have a significant effect on both growth and survival over three decades, using 9,338 sugar maple and 1,316 yellow birch trees. We also conducted a retrospective analysis to quantify the rate at which vigorous trees develop defects. Our results confirmed that crown dieback is by far the best indicator of vigour for both sugar maple and yellow birch trees. Conversely, our results revealed that stem defects did not contribute much to explaining the variation in vigour, except for the presence of cankers and fungi, which had modest effects. Consequently, stem defects should not be used as the main indicators of tree vigour, and existing classification systems should be simplified by reducing the number of stem defects under consideration for this purpose. Lastly, our results showed that the rate that vigorous trees develop defects increased with increasing diameter, more so than the probability of surviving. Thus, assessing the risk of retaining large trees should not only be based on survival, but also on the risk of developing defects that reduce the growth and value of trees.

1. Introduction

Northern hardwood forests occur throughout the Great Lakes – St. Lawrence region of North America, from northern Minnesota in the United States to Ontario, Quebec, and New Brunswick in Canada. These forest ecosystems are located near an important market for wood products and are composed of valuable tree species that yield a variety of timber products, including veneer, lumber, and residues (Nyland 1998). Across the northern hardwood range, many stands have a history of diameter-limit cuttings, which consists in harvesting only merchantable trees above stand- or species-specific size thresholds (Nyland 1998, Bédard and Majcen 2001, Kenefic et al. 2005). These cuts were often biased toward the harvest of the most valuable trees without much consideration for the residual stands (Nyland 1998, Kenefic et al. 2005). In many areas, such high grading —i.e. stem removal targeting the highest quality trees— repeated over decades has resulted in degraded stands dominated by trees of low quality and vigour (Nyland 1998, Raymond et al. 2009).

To rehabilitate degraded forest stands that still have the potential of producing high-quality trees, selection cutting has been implemented using tree marking strategies that prioritize the removal of low vigour trees (Nyland, 1998, Bédard and Majcen 2001). To codify these strategies, several classification systems have been developed to help tree markers visually assess tree vigour based on the presence of individual defects, including pathological symptoms and evidence of mechanical or biological damage, as well as tree form and crown condition (Arbogast 1957, Majcen et al. 1990, OMNR 2004, Boulet & Landry 2015, Pelletier et al. 2016). Thus, vigorous trees that are expected to grow fast and survive until the next harvest can be retained, whereas trees that are at risk of dying or growing comparatively slowly are considered low vigour and prioritized for removal (Arbogast 1957, Majcen et al. 1990, OMNR 2004, Boulet & Landry 2015). In addition to vigour, most of these classification systems evaluate tree quality, i.e. the volume and value of products that can be recovered from each tree, which is also judged by the presence and extent of defects (Pothier et al., 2013; Cecil-Cockwell and Caspersen, 2015). Trees are thus divided into two to eight classes

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of harvest priority based on the severity of the risk associated with the presence of particular defects on both vigour and quality (Arbogast 1957, Majcen et al. 1990, OMNR 2004, Boulet & Landry 2015, Pelletier et al. 2016).

Deciding which defects should be used to assess vigour is typically based on field experience and expertise in forest pathology. However, few studies have examined whether commonly used defects affect tree growth (Moreau et al. 2020a) or survival (Guillemette et al. 2008). Thus, it remains uncertain whether many of the evaluated defects should be used to assess vigour and whether numerous classes are required to capture the observed variation in risk among trees (Guillemette et al. 2008, Moreau et al. 2018). To date, most of these studies have concluded that numerous classes are not warranted because many defects have little to no effect on tree vigour (Guillemette et al. 2008; Hartmann et al. 2008; Moreau et al. 2018; Moreau et al. 2020a).

Empirical validation of classification systems should utilize longitudinal inventory data because there could be a substantial lag between the appearance of a defect and its effects on tree growth or survival (Guillemette et al. 2008). Moreover, to ensure operational relevance, the inventory data should span at least one complete partial harvest cycle (25–30-years) and a large portion of the northern hardwood range (Moreau et al. 2020a). However, suitable long-term inventories that span large areas are rarely available, especially where classification systems have evolved over time. Hence, previous attempts to validate classifications systems have been limited to retrospective dendrochronological approaches (Hartmann et al 2008, Moreau et al. 2018, 2020a), or longitudinal data over short time series (Guillemette et al. 2008, 2015; Morin et al. 2015).

In this study, we assess tree vigour using repeated measurements of growth and survival collected as part of long-term silvicultural trials established in the early 1980s (Majcen et al. 1994, Bédard et Majcen 2001, Guillemette et al. 2008) and 1990s (Guillemette et al. 2013) throughout the northern hardwood region of Quebec, Canada. We used these data to determine whether the defects that are commonly used for classification have a significant effect on both growth and survival. Multi-model selection was conducted to select a parsimonious set of defects for identifying trees that grow slowly or are at risk of dying. We also conducted a retrospective analysis to quantify the rate at which vigorous trees develop defects, and to test whether the rate increases as trees grow larger and older.

2. Materials and methods

2.1. Sampling sites

The inventory dataset was collected by the Direction de la Recherche Forestière of the Ministère des Ressources naturelles et des Forêts du Québec, which carried out two different silvicultural trials between 1980 and 2005 in the province of Quebec, Canada. The first dataset included 87 square permanent sample plots (PSPs) of 0.5 ha that were established in 18 experimental study sites between 1983 and 1999 (Bédard and Majcen 2001, Guillemette et al. 2008), while the second dataset included 528 circular PSPs of 400 m^2 that were established in 149 operational study sites between 1995 and 1999 (Guillemette et al. 2013, 2017). These two sets of plots were established throughout the entire northern hardwood forest zone of the province of Quebec. This zone runs east–west between 78°00′W to 65°00′W and north–south between 44°00′N to 48°00′N, across an area of approximately 200,000 km^2 (Fig. 1). The main surface deposits are shallow or deep tills of glacial origin, and the topography is characterized by rolling hills and gentle slopes (Robitaille and Saucier 1998). The mean annual temperature for the study sites is 1.8–4.0 °C and the mean annual precipitation is 920–1,420 mm (Régnière et al. 2014). The regional climatic variables follow a geographic gradient, with the southwestern areas being warmer and drier than the northeastern areas. All sampling sites were located in uneven-aged northern hardwood stands dominated by sugar maple (*Acer saccharum* Marsh.), with yellow birch (*Betula alleghaniensis* Britt.) and American beech (*Fagus grandifolia* Ehrh.) as the most common associated species. All stands regenerated naturally following past harvests, which employed partial harvest methods, including diameter limit cutting as well as single tree selection; all stands were harvested at least once in the last 50 years.

2.2. Experimental design and data collection

We used data from stands of which a part had been treated by

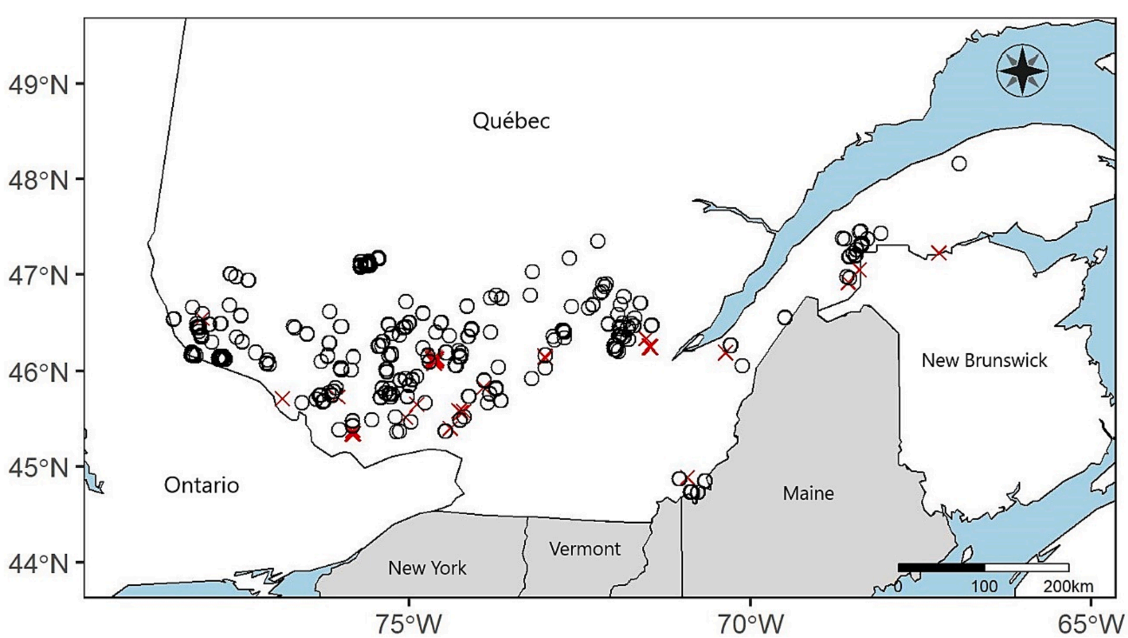

Fig. 1. Location of study sites in northern hardwood forests of Quebec. Black circles represent operational study sites in which circular PSPs of 400 m^2 were established between 1995 and 1999, while red crosses represent experimental study sites in which square PSPs of 0.5 ha were established between 1983 and 1999. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

selection cutting while another part had remained untreated. Selection cuts were conducted in each of the study sites, with a mean removal of about 30 % of the merchantable basal area of the stand. The objectives of the treatment were to decrease mortality losses and improve stand quality, while maintaining an uneven-aged structure in the residual stand (Majcen et al. 1990). A part of each stand was left untreated as a control, and PSPs of 0.5 ha or 400 m^2 were established in both the untreated and the treated parts of every stand, within the 12 months following the harvest. Plot basal area averaged 25 m^2/ha in control plots and 18 m^2/ha in treated plots at the time of their establishment. All trees with a diameter at breast height (DBH) $\geq$ 9.1 cm were numbered during plot establishment. The PSPs were inventoried periodically at a mean interval of five years: during each inventory, tree species was recorded, DBH was measured using a diameter tape, and the presence of crown and stem-related defects was also recorded (Guillemette et al. 2008). For the analysis, these individual defects were regrouped into 12 categories that are commonly used for tree marking in Quebec (Guillemette et al. 2008), and also in northern hardwood forests across North America (see Table 1).

2.3. Statistical analysis

Vigour has been variously defined as the ability of a tree to growth fast and survive to the next partial harvest (Arbogast 1957, Majcen et al. 1990, Boulet & Landry 2015, Pelletier et al. 2016). Thus, we analysed both survival and growth to provide a comprehensive assessment of tree vigour. We focused on sugar maple and yellow birch because they are the most abundant trees in the study. We excluded trees<20 cm in diameter from the analysis because they rarely contain sawlogs, so they are not typically marked for harvesting (Fortin et al. 2014, Delisle-Boulianne et al. 2014). The maximum diameter was set to 60 cm because silviculture guidelines used in North American hardwood forests typically recommend that trees greater than 60 cm be removed during selection harvest, regardless of vigour (Anderson and McLean 1970, OMRN 2004, Leak et al. 2014, Guillemette et al. 2016). The final dataset consisted of 9,338 sugar maple and 1,316 yellow birch trees that were periodically remeasured over a span of 17 to 36 years.

2.4. Survival

The survival or death of each tree was recorded through time, but the exact time of death could only be approximated (i.e. death occurred at some point between two surveys), so its occurrence was treated as an interval-censored variable and analyzed using survival functions (Cox and Oakes 1984). Death and survival were also treated as binary outcomes, taking a value of 1 if a tree died and a value of 0 if a tree survived over a given time interval. The probability of survival was modelled at the tree level using the Cox proportional hazards model, with plot included as a random frailty effect (Cox and Oakes, 1984). These models describe the probability of tree survival up to a particular point in time, which in this case was the next remeasurement. Although survival was recorded through time using repeated measurement, all candidate explanatory variables were fixed at the time of plot establishment for modelling process.

Independent predictor variables included the initial DBH (cm), crown dieback (%), and 11 additional stem defect categories (Table 1), which were included as two-level categorical variables (presence/absence). We also included five plot-level variables; tree density was quantified directly using plot basal area (BA, m^2/ha) at the time of plot establishment, and indirectly as a categorical treatment variable (harvested/unharvested), as suggested by Guillemette et al. (2008). The soil water availability was also expressed as categorical variable (xeric, mesic, or hydric) based on field evaluation. Lastly, the mean annual temperature (°C) and precipitation (mm) for 1970–2000 were also tested (WorldClim database (V.2), Fick and Hijmans 2017).

Table 1
Definitions of defects adapted from Guillemette et al. (2008) and their use in various tree classification systems.

Defect	Definition	Classification system
Crown dieback	The proportion of dead crown due to dieback or lost due to crown breakage (%). The death of lower branches due to self-pruning was not included.	Boulet & Landry (2015), OMNR (2004), Pelletier et al. (2016), Schomaker *et al.* (2007)
Fungus	The presence of a fungus on the stem. Although the species was not recorded, the most common fungi are: *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.	Arbogast (1957), Boulet & Landry (2015), OMNR (2004), Pelletier et al. (2016)
Canker	The presence of a canker on the stem. Although the species was not recorded, the most common fungi causing a canker are: *Eutypella parasitica* (Davidson and Lorenz) and *Neonectria galligena* (Bres.) Rossman and Samuels.	Arbogast (1957), Boulet & Landry (2015), OMNR (2004), Pelletier et al. (2016)
Crack	The presence of a crack on the stem.	Arbogast (1957), Boulet & Landry (2015), OMNR (2004), Pelletier et al. (2016)
Form	Tree that is leaning (greater than10°), arched or bended	Arbogast (1957), Boulet & Landry (2015), OMNR (2004), Pelletier et al. (2016)
Deformity	Presence of an excrescence, protuberance, deep fold of the surface on the stem.	Arbogast (1957), Boulet & Landry (2015), OMNR (2004), Pelletier et al. (2016)
Branch	The presence of pruning and branching defects	Arbogast (1957), Boulet & Landry (2015), OMNR (2004), Pelletier et al. (2016)
Wound of biological origin	Any part of the stem where the bark has been removed and the sapwood exposed because 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).	Boulet & Landry (2015), OMNR (2004), Pelletier et al. (2016)
Wound of mechanical origin	Any part of the stem 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.	Arbogast (1957), Boulet & Landry (2015), OMNR (2004), Pelletier et al. (2016)
Decay	Presence of significant decay in a knot, crack, seam or wound.	Arbogast (1957), Boulet & Landry (2015), OMNR (2004), Pelletier et al. (2016)
Root injury	The presence of roots having been injured by logging equipment.	Boulet & Landry (2015), OMNR (2004), Pelletier et al. (2016)
Uprooting	Living tree uprooted due either to windthrow or logging.	Boulet & Landry (2015), OMNR (2004)

Note: The classification system Boulet (2007) is being used in the province of Quebec (Canada), OMNR (2004) in the province of Ontario (Canada), Pelletier et al. (2016) in the province of New Brunswick (Canada), Arbogast (1957) and

Schomaker et al. (2007) in the states of New England, New York, Michigan and Minnesota (United Sates). No trees had fire scars.

2.5. Growth

The growth of individual trees was quantified as annual basal area increment (BAI, dm^2/yr) and analyzed using a mixed-effects linear model with a plot-level random effect nested in a site-level random effect. The random effects were specified to account for trees within the same plot not being spatially independent from each other. Tree-level BAs were computed from the first and last measurements; then we subtracted the values and divided by the number of years to obtain mean periodic BAI for the entire study period. The BAI was log-transformed (using the natural logarithm) to lower the weight of very high growth values and ensure the normality of residuals. The independent variables were the same as used for the survival model.

2.6. Model selection

Preliminary analyses indicated that sugar maple had significantly lower BAI and greater survival probabilities than yellow birch trees ($p < 0.05$). The two species were therefore treated separately in further analysis of both growth and survival. Considering the large number of potential tree-level explanatory variables, the analysis was performed in four steps (Hartmann et al. 2008, Moreau et al. 2020a).

First, the initial DBH and crown dieback were included successively in the model, as they are respectively the only size- and crown-related variables. The interaction between the two candidate explanatory variables was also tested. The resulting models were systematically compared with an intercept-only model (null model). The selection of the most plausible model was based upon Akaike's information criterion (AIC). Second, all five plot-level candidate variables were added individually to the model. Third, the 11 stem defects described in Table 1 were added individually to the model. Only the defects whose individual inclusion resulted in any model improvement (lower AIC) were retained as additional candidate explanatory variables for the fourth step. In the fourth and final step, all the previously retained stem defects were added to the model, and interactions between stem defects were also tested. The interactions between the retained stem defects and both the DBH and crown dieback were also tested, as well as the interaction with plot-level variables. During each iteration of the fourth step, a model averaging procedure was performed to compute unconditional 95 percent confidence intervals for parameters of interest when the AIC weight of the model was lower than 90 percent (Mazerolle, 2006; Mazerolle, 2017). Only variable parameters with confidence intervals excluding zero were considered to be good predictors (Mazerolle, 2006). To compare models, we also computed the delta AIC and the conditional coefficient of determination (R^2). In the case of the survival model, we computed the pseudo-R^2 related to the Cox survival analysis.

2.7. Probability of remaining vigorous

The model selection process described above identified all defects that significantly reduced tree vigour by reducing growth and survival. Using only the "major" defects that had a large effect size, we also assessed whether the probability of remaining vigorous varied with any of the other predictor variables (other than the defects). For each remeasurement period, all initially vigorous trees (i.e. not displaying one of the major defects) that showed the first sign of decline (i.e. the development of one or more of the major defects during the measurement period) were identified. The probability of remaining vigorous was then modelled at the tree level using the Cox proportional hazards model, with plot included as a random frailty effect. The candidate explanatory variables were the initial DBH and the five plot-level variables described above. Model selection was used to select the most plausible model based upon AIC, as described for growth and survival above (Mazerolle, 2006; Mazerolle, 2017).

All statistical analyses were performed in the R statistical programming environment (Version 3.5.2, R Core Team, 2019). While the *lme* function of the *nlme* package (Pinheiro et al., 2015) was used to develop our linear mixed effects models, the *coxph* function of the *survival* package (Therneau & Lumley 2014) was used for the Cox proportional hazards models. For the mixed-effects linear model, the model assumptions (i.e. homogeneity of variance, normality of residuals and the presence of outliers) were validated with graphical analyses of the residuals. For the Cox proportional hazards models, the proportional hazard assumption was tested using the *cox.zh* function of the *survival* package. The generalized variance inflation factor (GVIF) was calculated between candidate variables with GVIF < 5 as the threshold to avoid multicollinearity using the *vif* function of the *car* package (Zuur et al., 2010). Correlation matrix and Chi-square test of independence were also performed to help detect potential multicollinearity. Finally, model selection based on AIC and multi-model inference were performed using the *AICcmodavg* package (Mazerolle, 2017).

3. Results

3.1. Occurrence of defects

The occurrence of all defect categories was generally well distributed across DBH and species (Table 2). Overall, 74 percent (n = 981) of the sampled yellow birch trees had at least one stem defect at the time of plot establishment, while 16 percent (n = 211) had two stem defects and 46 percent (n = 609) had more than two defects of any kind. These proportions were similar for sugar maple trees, with 65 percent (n = 6,169) of the sample trees that had at least one stem defect at the time of plot establishment, while 15 percent (n = 1,491) had two stem defects and 46 percent (n = 3,560) had more than two defects of any kind. The most abundant stem defects for both sugar maple and yellow birch trees were stem deformities and the presence of pruning and branching defects, while the least abundant were the presence of root injuries and uprooting (Table 2). For both species, the occurrence of stem defects on trees showed low correlation with each other ($R_{Pearson} < 0.15$), except for the presence of decay and cracks ($R_{Pearson} = 0.47$) or form defects ($R_{Pearson} = 0.53$). Crown dieback also appears to be mostly independent to the presence of stem defects, as it was only slightly correlated with the occurrence of each individual defect ($R_{Pearson} < 0.15$) and the number of stem defects on trees ($R_{Pearson} = 0.10$). These overall low correlations agreed with significant Chi-square test of independence among categorical predictor variables and with an absence of multicollinearity among all the predictor variables based on GVIF analysis. Therefore, all predictor variables were included in the models.

3.2. Survival

For sugar maple, the most plausible model included DBH, crown dieback, presence of cankers, presence of fungi and initial plot basal area, with an AIC weight of 0.92 and a R^2 of 0.68 (Table 3). Uprooting was also included in the model, but its effect was not significant (model-averaged $\beta \pm$ unconditional SE = 0.21 ± 0.22; 95 % CI: −0.23, 0.64), indicating that it did not significantly contribute to explaining the variation in survival for sugar maple. No interactions were retained in the models. Survival decreased drastically with increasing crown dieback, with the survival probabilities reduced to only 10 % after three decades for sugar maple initially affected by crown dieback of 80 % (Fig. 2A). For comparison, the survival probabilities of trees with no dieback were 86 % after three decades (Fig. 2A). The survival probabilities were 12 % lower for trees affected by cankers (Fig. 2C) and about 8 % lower for trees affected by a fungus (Fig. 2D). The model also showed that trees with a DBH of 60 cm had survival probabilities 13 % lower than that of trees with a DBH of 20 cm (Fig. 2B). Lastly, the survival probabilities decreased slightly with increasing initial plot density,

Table 2
Number of observations in each defect category at the time of PSPs establishment, listed by species and diameter class.

Species	Sugar maple				Yellow birch			
DBH (cm)	[20–29]	[30–39]	[40–49]	[50–60]	[20–29]	[30–39]	[40–49]	[50–60]
Crown dieback	593	411	214	120	56	81	55	17
Fungus	240	153	62	46	21	26	12	12
Canker	268	116	74	44	7	14	10	6
Crack	644	557	379	186	69	75	68	30
Form	1898	1068	525	188	300	250	126	41
Deformity	2460	1245	556	173	154	139	63	25
Branch	1247	519	210	70	219	189	97	26
Wound of biological origin	394	199	75	27	7	17	7	9
Wound of mechanical origin	583	305	137	50	59	66	28	12
Decay	1210	652	363	134	195	177	101	33
Roots injury	100	67	48	24	13	17	8	4
Uprooting	151	82	19	2	15	12	10	4
Any defect	3219	1765	855	320	374	344	187	76
No defect	1626	924	472	157	160	103	54	18
Total of trees	4845	2689	1327	477	534	447	241	94

Table 3
Statistics for the 5 most plausible models predicting the survival of sugar maple and yellow birch. The variables that had a significant effect on survival are indicated in bold.

Survival					
Sugar maple					
Model	Variables	AIC	Δ_i	Wt_i	R^2
1	**DBH** + **CDBK** + **Canker** + **Fungus** + Up + **PBA**	21525.89	0.00	0.98	0.68
2	DBH + CDBK + Canker + Fungus + PBA	21533.64	7.76	0.02	0.68
3	DBH + CDBK + Canker + PBA	21551.25	25.36	0.00	0.67
4	DBH + CDBK + Fungus + PBA	21575.63	49.75	0.00	0.66
5	DBH + CDBK + PBA	21598.81	72.92	0.00	0.65
Yellow birch					
Model	Variables	AIC	Δ_i	Wt_i	R^2
1	**CDBK** + **Canker** + Fungus + Crack + WB	2867.17	0.00	0.54	0.75
2	CDBK + Canker + Fungus + Crack	2868.66	1.50	0.26	0.74
3	CDBK + Canker + Fungus + WB	2870.15	2.98	0.12	0.74
4	CDBK + Canker + Fungus	2871.83	4.66	0.01	0.74
5	CDBK + Canker + Crack	2875.08	7.94	0.01	0.73

Note: the Δ_i is the delta AIC, Wt_i: AIC weight, R^2: pseudo-R^2 related to the Cox survival analysis, CDBK: Crown dieback, WB: Wound of biological origin, up: Uprooting, PBA: Plot basal area (m^2/ha).

in a way that after three decades, the survival probabilities were 2 % lower in stands of 25 m^2/ha when compared to stands of 18 m^2/ha.

The survival of yellow birch was best explained by the model that included crown dieback, presence of cankers, cracks, fungi, and wounds of biological origin, with an AIC weight of 0.54 and a R^2 of 0.75 (Table 3). The second most plausible model included crown dieback, presence of cankers, cracks, and fungi as predictors, with an AIC weight of 0.26 and a R^2 of 0.74 (Table 3). No interactions were retained in the models. Model averaging indicated that the presence of cracks (0.34 ± 0.23; 95 % CI: −0.11, 0.8), fungi (0.34 ± 0.28; 95 % CI: −0.21, 0.90) and wounds of biological origin (0.30 ± 0.38; 95 % CI: −0.44, 1.04) were not significant. Consequently, none of these stem-related defects were considered as good predictors of yellow birch survival. The survival probabilities of yellow birch trees decreased substantially with increasing crown dieback (Fig. 3A) and were 14 % lower when affected by cankers (Fig. 3B).

3.3. Growth

For sugar maple, the best growth model included DBH, crown dieback, presence of cankers, cracks, fungi, deformities, the initial plot basal area, and the categorical treatment variable harvested/unharvested. No interactions were retained in the models. The best model resulted in an AIC weight of 0.95 and a R^2 of 0.35 (Table 4), and shows that BAI increased with DBH, and decreased with increasing crown dieback (Fig. 4A). Although significant, the effect sizes of stem defects on BAI were low (Fig. 4B). Cankers were the stem defect that had the greatest effect on growth, reducing BAI by approximately 20 % (Fig. 4B). The initial plot basal area had a negative effect on sugar maple BAI, and trees from untreated plots showed 16 % lower BAI than trees from treated plots.

For yellow birch, the growth model with the lowest AIC included DBH, crown dieback, the presence of cankers, fungi, cracks, and initial plot basal area, with an AIC weight of 0.98 and a R^2 of 0.38 (Table 4). No interactions were retained in the models. As for sugar maple, BAI increased with DBH and decreased with increasing crown dieback (Fig. 5A). However, the presence of stem defects had a stronger effect on the BAI of yellow birch (Fig. 5B). The presence of cracks, fungi and cankers decreased BAI by approximately 20 %, 40 % and 50 %, respectively (Fig. 5B). Lastly, BAI decreased with increasing initial plot basal area. For example, the BAI were 17 % lower in stands of 25 m^2/ha when compared to stands of 18 m^2/ha.

3.4. Probability of remaining vigorous

Based on the survival and growth analysis, the first sign of decline in tree vigour was defined as occurring when crown dieback first exceeded 20 %, or a canker or fungus first appeared on the stem: these “major” defects were chosen because of their substantial effects on both survival and growth. Considering trees that survived during the study period, 36 % of sugar maple and 30 % of yellow birch that were initially vigorous developed at least one of these major defects. For both species, the model that best explained the probability of remaining vigorous only included DBH: none of the plot-level variables were good predictors of a decline in tree vigour. As expected, the probability of remaining vigorous decreased with increasing DBH (Fig. 6). The effect size of DBH was greater for sugar maple (Fig. 6A), for which the probability of remaining vigorous was 38 % higher for small trees (20 cm DBH) than large trees (60 cm DBH). For yellow birch, the probability of remaining vigorous was 33 % higher for small trees than large trees (Fig. 6B).

4. Discussion

The primary objective of this study was to identify a parsimonious set of defects for assessing whether northern hardwood trees are at risk of dying or declining in growth before the next harvest. Our results show that among all the studied defects, crown dieback is by far the best indicator of vigour for both sugar maple and yellow birch trees. This result confirms those of previous studies conducted across northeastern North America, including Quebec (Guillemette et al. 2008, Moreau et al.

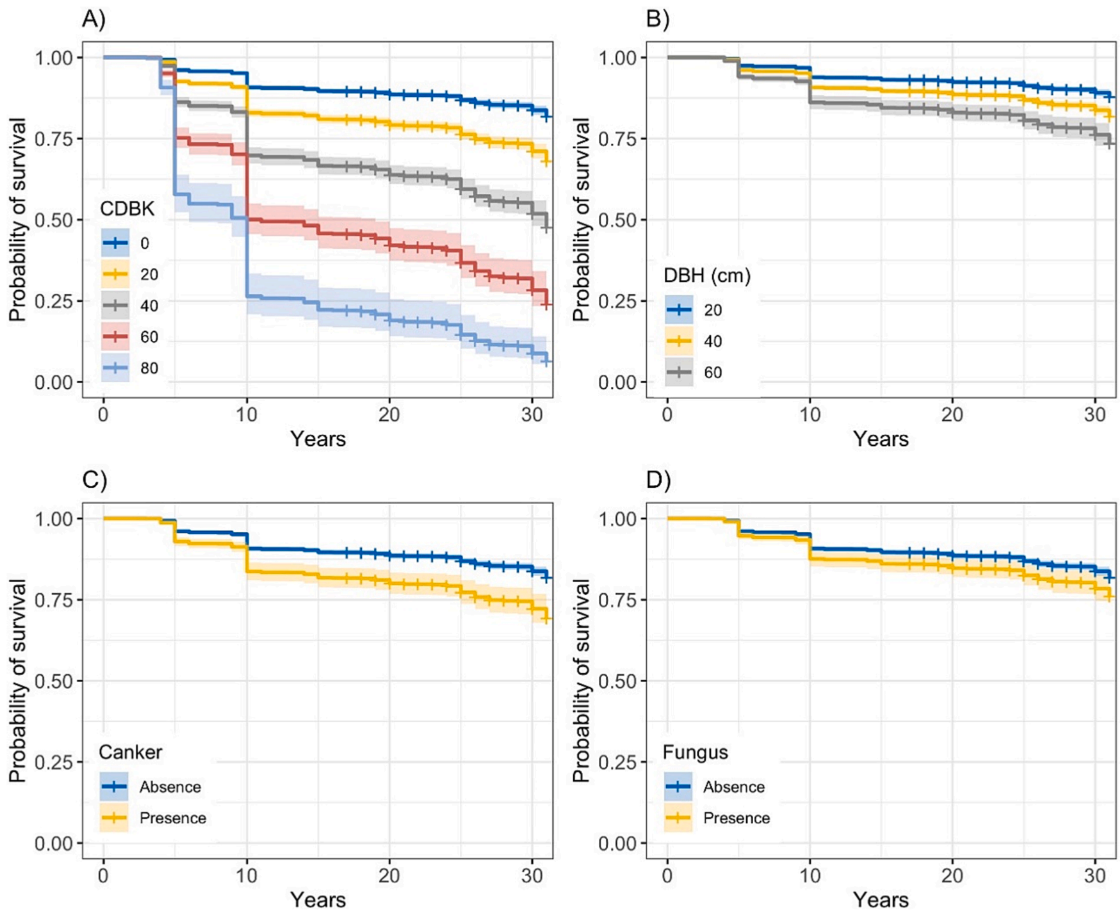

Fig. 2. Effect of A) crown dieback (CDBK), B) DBH, C) the presence of canker and D) the presence of fungus on sugar maple survival probabilities (when calculating the effect of a given defect, other defects were assumed to be absent, and other covariates were kept constant at their mean values).

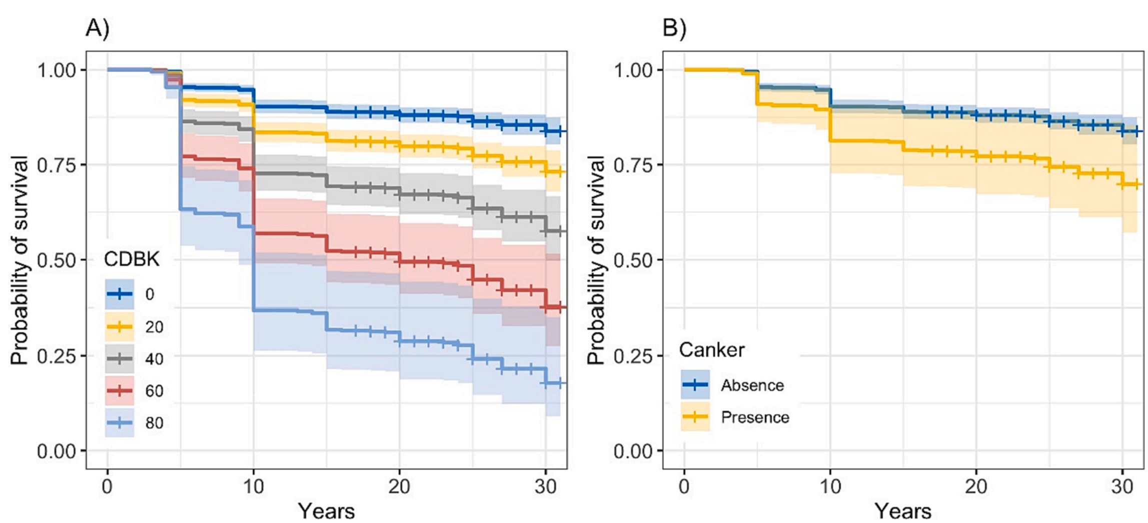

Fig. 3. Effect of A) crown dieback (CDBK) and B) the presence of canker on yellow birch survival probabilities (when calculating the effect of a given defect, other defects were assumed to be absent, and other covariates were kept constant at their mean values). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2020a), Ontario (Tominaga et al. 2008) and the northeastern United States (Morin et al. 2015), all of which found that hardwood trees with healthy crown have the highest rates of growth and survival. This result also supports the idea that no matter the inciting biotic or abiotic stressor, a decline of tree vigour will result in crown dieback (Schomaker et al. 2007, Moreau et al. 2020a), because maintaining photosynthetic potential is one of the first priorities of tree resource allocation (Waring, 1987). Consequently, crown dieback indicates that the amount of carbon available for allocation is not enough to maintain such a priority, or that it is being allocated to even higher priorities, which in both cases implies a loss of vigour.

Crown dieback was the only indicator of crown condition provided

Table 4
Statistics for the 5 most plausible models predicting the basal area increment of sugar maple and yellow birch trees. The variables that had a significant effect on survival are indicated in bold.

Model	Variables	AIC	Δ_i	Wt_i	R^2
Basal area increment					
Sugar maple					
1	**DBH** + **CDBK** + **Canker** + **Fungus** + **Crack** + **Deformity** + **PBA** + **TREAT**	17585.73	0.00	0.95	0.34
2	DBH + CDBK + Canker + Fungus + Deformity + PBA + TREAT	17591.58	5.84	0.05	0.34
3	DBH + CDBK + Canker + Deformity + PBA + TREAT	17600.03	15.19	0.00	0.34
4	DBH + CDBK + Canker + Fungus + PBA + TREAT	17604.20	18.47	0.00	0.33
5	DBH + CDBK + Canker + Crack + PBA + TREAT	17608.77	23.03	0.00	0.33
Yellow birch					
Model	Variables	AIC	Δ_i	Wt_i	R^2
1	**DBH** + **CDBK** + **Fungus** + **Canker** + **Crack** + **PBA**	2651.29	0.00	0.97	0.38
2	DBH + CDBK + Fungus + Crack + PBA	2658.32	7.03	0.03	0.37
3	DBH + CDBK + Fungus + Canker + PBA	2670.03	18.73	0.00	0.37
4	DBH + CDBK + Fungus + PBA	2677.79	26.49	0.00	0.36
5	DBH + CDBK + PBA	2706.17	54.88	0.00	0.33

Note: The Δ_i is the delta AIC, Wt_i: AIC weight, R^2: conditional coefficient of determination, CDBK: Crown dieback, PBA: Plot basal area (m^2/ha), TREAT: the variable treatment as categorical variable (2 levels).

by the inventory dataset used in this study. While several other indicators of crown condition exist (Schomaker et al. 2007), crown dieback was identified as the best predictor of survival for most hardwood species in North America (Morin et al. 2015). Yet, for sugar maple, crown density, which is defined as the amount of crown branches, foliage, and reproductive structures that block the transmission of light through the projected crown outline, has been found to be an even better indicator of tree vigour (Morin et al. 2015; Moreau et al. 2020a). However, an important drawback of using crown density is that it can only be measured during the leaf-on season, whereas crown dieback can be evaluated throughout the year.

Compared to crown dieback, stem defects did not explain much of the variation in growth and survival. Indeed, cankers were the only stem defect that had a significant effect on both the growth and survival of both species, with an effect size comparable to crown dieback of 20–30 %. Fungi also reduced the growth of both species, but the effect size was much larger for yellow birch (40 %) compared to sugar maple (10 %). Previous studies have found that cankers and fungi have a significant effect on survival as well as growth (Davis et al. 1997, Guillemette et al. 2008), presumably due to cambium necrosis and the resulting need to allocate resources to compartmentalize the affected portion of the stem (Shigo et al. 1985). Based on these results, the presence of cankers and fungi could be used in conjunction with crown condition to assess vigour.

However, stem defects should not be used as the main indicators of tree vigour, as they are in some classification systems such as Boulet & Landry (2015) and Pelletier et al. (2016). These systems are based on the principle that most stem defects (such as fungi, cankers, deformities, cracks, wounds, and decay) increase the likelihood of mechanical failure and further infection by pests, thereby reducing growth and increasing the risk of mortality (Boulet & Landry 2015, Pelletier et al. 2016). However, our results demonstrate that except for cankers and fungi, stem defects only have a negligible effect on growth and survival of sugar maple and yellow birch when assessed over a full harvest cycle. Thus, trees with stem defects should not be assigned the highest harvest priority when assessing tree vigour for stand improvement. Furthermore, existing classification systems should be simplified by reducing the number of stem defects under consideration (Guillemette et al. 2008; Cecil–Cockwell and Caspersen 2015, Moreau et al. 2018), while prioritizing crown condition as the focus of assessing vigour (Morin et al. 2015, Moreau et al. 2020a). This would leave tree markers with ample room for stand improvement, given that after three decades of monitoring, 45 % of all sugar maple and 35 % of all yellow birch trees were affected by at least one of the major defects related to tree vigour (crown dieback ≥ 20 % and presence of cankers or fungi). Disregarding the other defects would also streamline marking operations because the percentage of trees with major defects far exceeds the proportion of merchantable basal area that can be harvested outside of the trails (≤20 %) during selection cutting (Moreau et al. 2019, 2020b). These results underscore once again the unnecessary complexity of current classification systems for assessing tree vigour. Indeed, defect categories that were not significantly related to either growth, survival or tree value could be removed from current classification systems (see Table 5).

Despite being only weakly related to tree vigour, some stem defects are good indicators of the value of sugar maple and yellow birch trees (Havreljuk et al. 2014, Cecil–Cockwell and Caspersen, 2015). While

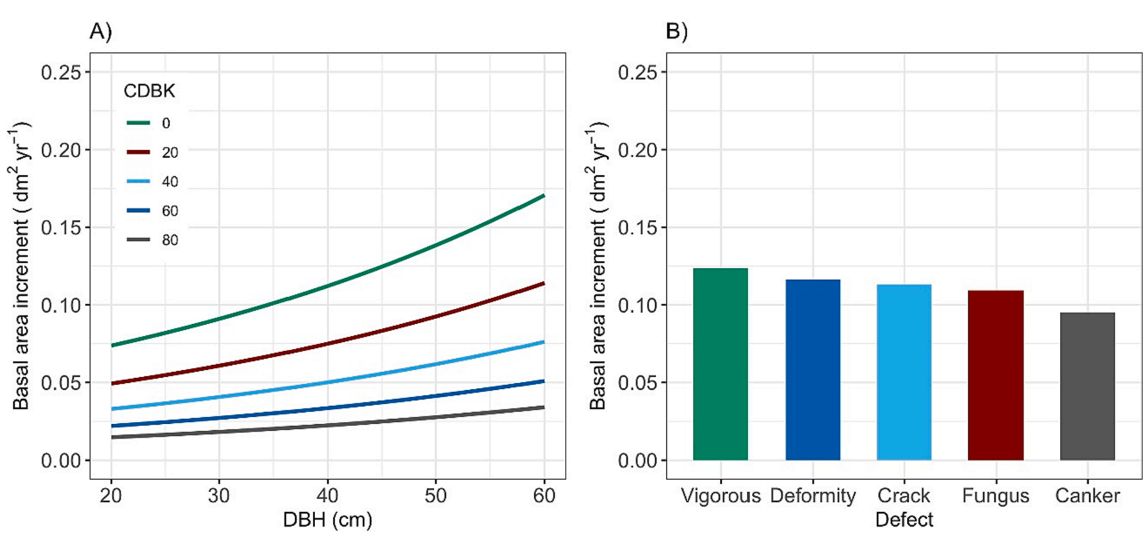

Fig. 4. Effect of A) crown dieback (CDBK) and B) the presence of a deformity, crack, fungus, and canker on the basal area increment of sugar maple (when calculating the effect of a given defect, other defects were assumed to be absent, and other covariates were kept constant at their mean values). Accordingly, ''Vigorous'' refers to trees without any dieback or stem defect.

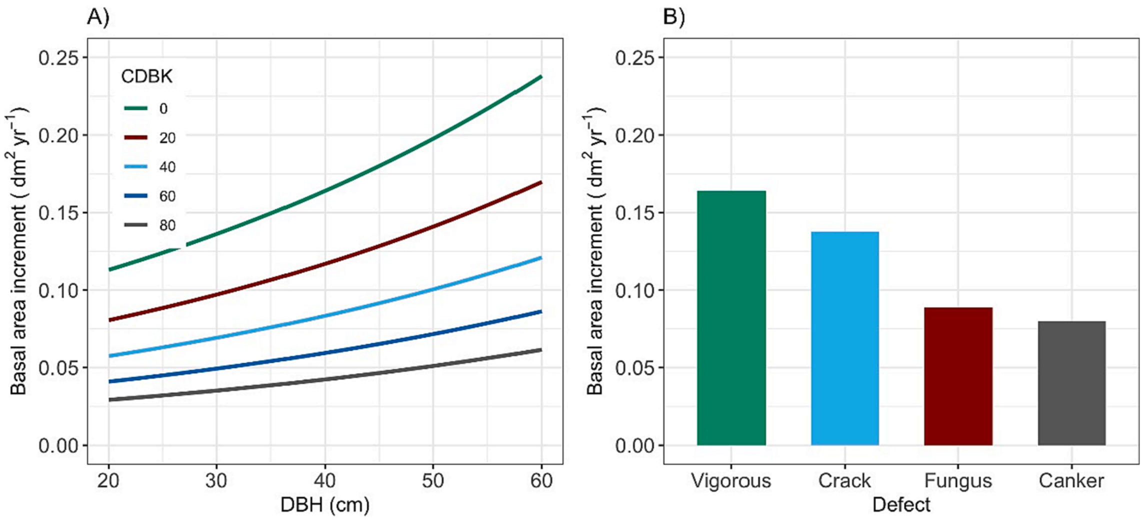

Fig. 5. Effect of A) crown dieback (CDBK) and B) the presence of a crack, fungus, and canker on the basal area increment yellow birch (when calculating the effect of a given defect, other defects were assumed to be absent, and other covariates were kept constant at their mean values). Accordingly, ''Vigorous'' refers to trees without any dieback or stem defect. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

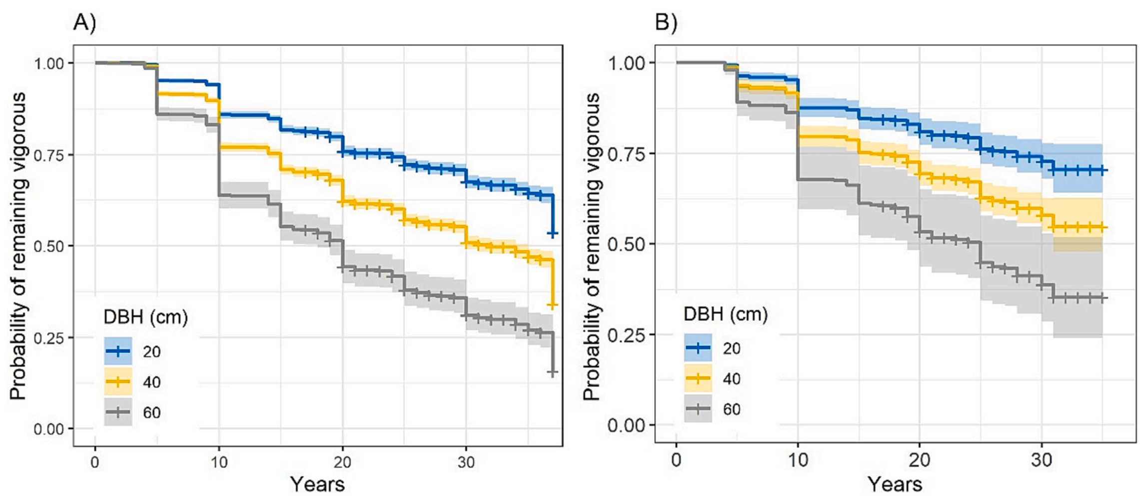

Fig. 6. Predicted probability of remaining vigorous for A) sugar maple and B) yellow birch trees that survived during the study period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

results from Cecil–Cockwell and Caspersen (2015) showed that the presence of cankers, decay, and deformities account for 22 %, 20 % and 18 % of the variation in gross product value, Havreljuk et al. (2014) also showed that the presence of cracks and fungi can reduce tree value by as much as 60 %. These few stem defects should therefore be assessed along with crown condition to ensure that tree marking meets both the silvicultural and economic objectives of the harvest operations. For example, in degraded forest stands, tree marking should prioritize harvesting trees that exhibit crown dieback, but do not have stem defects that affect value (Table 5). In this case, prioritizing the removal of trees that are low vigour and high value will increase to the yield of subsequent harvests, while also salvaging the current value of defective trees before they die or decline in growth (Pothier et al. 2013). Indeed, because crown dieback was only weakly correlated with the occurrence of stem defects, prioritizing the removal of trees free of stem defects but that have begun to exhibit dieback represent a great opportunity to increase both the yield of subsequent harvests and tree value recovery in the current one, by allowing tree markers to easily identify low vigour but high value trees (Pothier et al. 2013).

Our results also showed that selection cuts only had a modest effect on growth and survival of sugar maple and yellow birch trees, which is in line with previous observations in the province of Quebec (Guillemette et al. 2013,2017, Moreau et al. 2020b). Moreover, the absence of interactions between the individual defects and the treatment suggests that defects had a similar effect on growth and survival among treated and untreated plots. These results support previous observations that trees that are non-vigorous at the time of harvest do not benefit from a reduction of competition (Moreau et al. 2019) and that trees that die after selection cutting were mostly already weakened (Hartmann and Messier 2008, Moreau et al. 2019, 2020b). These results underscore the great importance of accurately identifying and removing low vigour trees during partial cutting operations to maximise the productivity of managed northern hardwood stands.

4.1. Probability of remaining vigorous

The other objective of this study was to quantify the rate that vigorous trees develop defects and test whether it varies with tree size. As expected, the probability of remaining vigorous decreased with increasing DBH (Fig. 6), more so than the probability of surviving

Table 5
Summary of the empirically validated impact of defects on tree vigour, including the severity of impacts on both growth and mortality (this study), as well as the severity of impacts on actual tree value (Cecil-Cockwell and Caspersen 2015, Havreljuk et al. 2014).

Defect	Survival	Growth	Value
Crown dieback	Severe	Severe	Not significant
Canker	Moderate	Moderate	Moderate
Fungus	low	Moderate	Severe
Crack	**Not significant**	low	Severe
Deformity	**Not significant**	low	Not significant
Decay	**Not significant**	**Not significant**	Moderate
Branch	**Not significant**	**Not significant**	**Not significant**
Wound of biological origin	**Not significant**	**Not significant**	**Not significant**
Wound of mechanical origin	**Not significant**	**Not significant**	**Not significant**
Form	**Not significant**	**Not significant**	**Not significant**
Root injury	**Not significant**	**Not significant**	**Not significant**
Uprooting	**Not significant**	**Not significant**	**Not significant**

(Fig. 2). Assessing the risk of retaining large trees should not only be based on the probability of survival, but also on the risk of developing defects that may reduce both growth and value of the tree. For example, consider vigorous sugar maple trees with a DBH of 60 cm: of the 75 % that will survive over three decades (Fig. 2B), only 32 % are likely to remain vigorous (Fig. 6A). When these two risks are considered together, <25 % of all initially vigorous sugar maples with a DBH of 60 cm are likely to survive and remain vigorous. Thus, when considering overall risk alone, retaining sugar maple trees until they reach a diameter of 60 cm may be unacceptable. These results are in line with the smaller maximum diameters (between 43 and 45 cm) that were proposed for vigorous sugar maple across the province of Quebec (Guillemette 2016) and highlight the importance of considering the probability of remaining vigorous when establishing the maximum diameter of hardwood species. Future work on this topic should consider the risk of trees developing defects that affect value or growth (as opposed to the risk of trees dying), taking into account additional risk factors such as crown position. This would increase our understanding of how and why tree vigour declines over time, and improve our ability to assess both the biological and financial risks associated with the retention of large trees.

Our results also showed that sugar maple develops defects faster than yellow birch, even though sugar maple is less likely to die over the same time period. This is consistent with previous observations that sugar maple can endure decades of declining growth without dying (Moreau et al. 2019). To our knowledge, such prolonged decline has never been reported for yellow birch, which is known to have lower survival probabilities following partial cutting (Fortin et al. 2008, Martin et al. 2014, Moreau et al. 2020b). This distinction may also reflect differences in the biotic or abiotic stressors that afflict the two species. Guillemette et al. (2008) reported the most frequently observed pathogens responsible for the development of fungi and cankers on sugar maple are *Oxyporus populinus* (Sokum.: Fr.) Donk, *Phellinus igniarius* (L.: Fr.) Quel., *Inonotus glomeratus* (Pk.) Murr., *Kretzschmaria deusta* (Hoff.: Fr.) Martin and *Eutypella parasitica* (Davidson and Lorenz), while yellow birch is most commonly infected by *Phellinus cinereus* (Niemelä) Fr., *Inonotus obliquus* (Pers.: Fr.) Pilat. and *Neonectria galligena* (Bres.). More studies with additional species are needed to understand why tree species differ in their ability to remain vigorous following partial harvesting.

5. Conclusion

This study confirms that crown condition, as measured by crown dieback, should be used as the main indicator of tree vigour in the northern hardwood forests of North America. Because most stem defects did not explain much of the variation in growth and survival, existing classification systems should be simplified by reducing the number of stem defects under consideration. However, since some stem defects pose a high financial risk, they could be used in conjunction with crown condition to ensure that tree marking meets both silvicultural and economic objectives. The data we used to quantify and predict vigour were collected over a large portion of the northern hardwood range, encompassing various sites and stand conditions, as well as steep climatic gradients. Thus, we believe that our recommendations apply to other parts of the northern hardwood range, particularly in jurisdictions that rely on numerous stem defects to assess vigor, because the complexity of such classification systems could detract from their efficacy. Moreover, considering that tree vigor was more related to crown dieback than to stem defects in much the same way for both sugar maple and yellow birch, and that strong relationships between crown conditions and tree vigour were consistently reported among American and European hardwoods (e.g., Guillemette et al. 2008, Morin et al. 2015, Gagen et al. 2019), we believe that our conclusions apply to many more hardwood species.

Although the main objective of this study was to improve tree marking systems, the utility of visual assessments of tree vigour goes far beyond this purpose and includes any application where managers need to assess tree and forest health, such as in urban forests, wildlife reserves, and recreational properties (Morin et al. 2015). The visual assessment of tree vigour using crown condition is also relevant for other forest-related industries, like the production of maple syrup (Wilmot et al. 1995). Moreover, in the context of global change, there is an increasing need to monitor forest health in near real time, as part of early warning systems for identifying stresses such as drought and the presence of invasive pests (Achim et al., 2021). This critical monitoring effort will certainly benefit from improved knowledge of the visual assessment of tree vigour.

CRediT authorship contribution statement

Guillaume Moreau: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. **Malcolm J.L. Cecil-Cockwell:** Conceptualization, Writing – review & editing, Funding acquisition. **David Pothier:** Conceptualization, Writing – review & editing. **Alexis Achim:** Conceptualization, Writing – review & editing, Funding acquisition. **Steve Bédard:** Conceptualization, Writing – review & editing, Investigation, Data curation. **François Guillemette:** Conceptualization, Writing – review & editing, Investigation, Data curation. **John Caspersen:** Conceptualization, Writing – review & editing, Funding acquisition, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data could be made available upon reasonable request.

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