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Landscape and Individual Tree Predictors of Dark Heart Size in Sugar Maple

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The high value of sugar maple logs and lumber depends on the wood being light-colored and clear of defects. Predicting the size of dark hearts in trees before they are harvested is very important to foresters, forest landowners, and sawmills. We investigated many possible predictors of the heart size of sugar maple in 10 sites in New York State. Heart size ratios by site ranged from 12 to 42%, averaging 23%. At the site level, trees with large hearts were more common on more acid soils ($P = 0.04$). Flaky bark, poor crown ratios, and lower grade stems were correlated with large hearts across the sample of 265 trees. Visible tree injury, competition, and tree diameter were not consistently related to heart size ratios of trees. Steep slopes were associated with large hearts. Other physiographic factors (slope and landform) differed in their effect by site, possibly due to local histories of storm damage. In conclusion, predicting dark heart in sugar maple is likely to remain challenging.

Keywords: heartwood, wood procurement, wood discoloration, logging damage, forest management

Sugar maple (*Acer saccharum* Marsh.*)*, sometimes called hard maple, is one of the most commercially important hardwoods in the United States and Canada. It is found on a variety of soils but grows best in loamy, moist, and well-drained soils that are not too acid (Horsley et al. 2002). Sugar maple can be found as far west as Missouri and Manitoba, as far north as Nova Scotia, and as far south as the Carolinas, covering an area of approximately 31 million acres (Horsley et al. 2002). The greatest commercial volumes of standing sugar maple timber are currently in Michigan (12.8 billion board feet [bbf]), New York (12.8 bbf), Pennsylvania (8.3 bbf), Vermont (6.5 bbf), Wisconsin (6.4 bbf), Maine (5.5 bbf), and New Hampshire (2.1 bbf) (USDA Forest Service 2013).

A dark discoloration, which is referred to as "dark heart" or "heartwood" by the forest products industry, commonly forms in the center of sugar maple trees (Havreljuk et al. 2013). This discoloration poses a serious concern because sugar maple wood is highly prized for its creamy white color, and a big heart is a quality defect that greatly reduces its commercial value. Veneer-quality sugar maple trees can have a stumpage value of up to $5,000 per thousand board feet (mbf), whereas sawlog-grade stumpage averages $500–600 per mbf, depending on the region and market conditions (New York State Department of Conservation 2014). Forest managers in Scandinavia face the same issues with silver birch (*Betula pendula* Roth.), the region's most important commercial hardwood species (Hallaksela and Niemisto 1998). In central Europe, the species of concern is European beech (*Fagus sylvatica* L.) (Wernsdorfer et al. 2005), and in Canada paper birch (*Betula papyrifera* Marsh.) and yellow birch (*Betula alleghaniensis* Britton), in addition to sugar maple, experience value reductions for lumber and veneer when logs are marred by large dark hearts (Giroud et al. 2008). Ironically, the dark hearts of black cherry (*Prunus serotina* Ehrh.) and black walnut (*Juglans nigra* L.) are highly valued, and the whitewood is considered undesirable.

Hardwood tree grades are designed to help landowners, foresters, and loggers predict factory lumber yields for commercial hardwood species, providing the basis for

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stumpage value. Tree grade is determined by the best 12-ft section in the 16-ft butt log. The key grading factors are dbh, diameter at the top of the grading section, the number of estimated clear cuttings (without knots), and cull deduction. When grading, it is customary to grade the second worst face (of four faces) of the 12-ft section. A grade 1 tree requires a minimum dbh of 16 in., top diameter of 13 in., clear cuttings (no knots) totaling 10 ft, and less than 10% scaling defect (i.e., crook or sweep) (Miller et al. 1986). However, a promising tree based on these grade specifications can produce low-quality logs due to the size of the heart. Significant value reductions occur when the dark heart exceeds one-third of the diameter of sawlogs (Wiedenbeck et al. 2004).

Information on value reductions from tree grade to log grade related to the amount of dark heart is sparse, but a study in Michigan found that half of the grade 1 sugar maple trees decreased in log grade after harvest because of large dark hearts; most of the tree- to log-grade reductions occurred in larger diameter trees (Erickson et al. 1992). A study conducted in Ontario, Canada, also reported a positive relationship between dark heart size and stem diameter (D'eon and Hamilton 2013). Many studies have focused on the cause of this dark heart and techniques that can be used to detect it in standing trees (Shigo 1966, 1974, Ohman 1968), but few have tried to associate dark heart size to external tree factors and landscape characteristics.

True heartwood is formed when sapwood dies, and cell contents are converted into enzymes, toxins, and preservatives, which can cause wood to become darker in color, as in the wood of northern red oak (*Quercus rubra* L.) or black walnut (Bosshard 1968, Shigo and Hillis 1973). Sugar maple is a species in which heartwood may not be dark in color; heartwood that is not dark is called ripewood (Panshin and de Zeeuw 1980). In sugar maple, the dark brown color found at the center of the tree is induced by injury, which allows an entry point for fungi and bacteria to initiate a wood discoloration process (Shigo 1974, Houston 1994). Wood anatomists classify this discoloration as facultative heartwood, which is common in diffuse-porous hardwoods such as maple, birch, and beech (Shigo and Hillis 1973).

In a healthy tree, the infection and resulting discoloration that develop after injury are compartmentalized. In the absence of further injury, discoloration will tend not to spread into the wood that forms after the injury. Thus, the extent of the dark heart reflects the size of the tree at the time of injury, the spread of the infection over time since the injury, and the effectiveness of compartmentalization to resist its spread (Shigo 1974). Characteristics of the microbiological agents of infection may also be important. The amount of lightwood further depends on the time since injury and the growth rate of the tree.

Unfortunately, these factors are not apparent from the exterior of the tree. Past injury, whether due to logging damage or weather-related crown damage, is not easy to detect decades after the event. Indicators of tree health and growth rate, such as crown ratio, crown class, and competition from other trees, might provide clues as to dark heart size. Forest managers and wood procurement foresters anecdotally make use of other indications of dark hearts, such as soil chemistry, landscape position, and bark characteristics. The literature offers little empirical evidence to support any of these theories. It would be extremely valuable to be able to predict the amount of dark heart in sugar maple using easily measured tree or site characteristics.

In this study, we quantified the fraction of otherwise high-quality stems that lost value between tree grading and log grading after harvest in 10 sugar maple sales in different regions of New York State. We evaluated the history of land use and natural disturbances caused by weather or pests, so far as this information was available, because logging damage and other sources of injury contribute to the development of large hearts. We also evaluated tree and site characteristics that have been purported to predict the amount of discoloration in sugar maple before trees are harvested. We hypothesized that large hearts would be found on steep and exposed terrain and on more acid soils. We hypothesized that healthy trees, indicated by high tree grade, crown ratio, crown class, and tight bark, would tend to have small hearts. We also evaluated the relationship of dark heart size to tree diameter, which is relevant to whether heart sizes are increasing and reducing log value as trees age.

Methods

Study Sites

We identified 10 sites with a high proportion of sugar maple that were scheduled to be harvested within the time frame of the study (Table 1). An attempt was made to locate harvest sites in different regions of New York State (Figure 1), on various soil types, and with different management and disturbance histories. From 2006 to 2010, timber sales with a high proportion of sugar maple were sampled, and stand history of up to 60 years was described by landowners and foresters (Table 1). Recent disturbances in these forest stands included thinning, ice storms, and insect defoliation.

Preharvest Measurements of Tree and Site Variables

A point sample inventory was conducted using a 10-factor wedge prism to determine species composition and site basal area. Seven to 10 sample points were established, depending on the size of the site. Dbh, species, crown ratio (nearest 5%), crown class (codominant or dominant), and the status of growing stock (acceptable or unacceptable) (Nyland 2007) were recorded for each tree inventoried. Sugar maple trees were graded using the US Department of Agriculture (USDA) Forest Service Hardwood Tree Grades (Miller et al. 1986). We chose grade 1 and 2 sugar maple trees

Management and Policy Implications

Sugar maple is one of the most important commercial hardwood species in the United States and Canada. Its wood is highly valued because of the light color and even grain. A large dark heart greatly reduces the value of sugar maple logs and lumber. Unfortunately, it is difficult to predict the sizes of dark hearts in standing sugar maple. Our study found different factors to indicate dark heart size at different sites, but, overall, sites with less acid soils had fewer large hearts. We found no evidence that the proportion of dark heart increases with tree diameter. Consequently, forest managers should use well established silvicultural practices to minimize dark heart in forest stands, including crop tree selection based on grade, bark type, and crown ratio, all of which are good predictors of dark heart. These crop trees can be tended over several decades until economic maturity. Foresters attempting to place a value on sugar maple stumpage could take advantage of soil tests or soil maps, in addition to individual tree predictors, to minimize the value reduction resulting from dark heart.

Table 1. Characteristics of the study sites, including information on stand history provided by landowners or foresters.

Site	Region of New York State	Total basal area (ft^2 ac^{-1})	Sugar maple dominance (% of basal area)	No. of sampled trees	Logging history before study harvest	Crown damage
1	Allegheny Plateau	105	85	40	1955: D-limit cut to 12 in.	1992: Gypsy moth defoliation
2	Central Lowland	113	67	7	1979: Thinning 1995: Thinning	2003: Heavy ice
3	Central Lowland	137	57	20	No harvest	Unknown
4	Central Lowland	150	59	16	1955: Thinning	Unknown
5	Finger Lakes	40	81	35	1987, 1997: High grading*	2001–2007: Forest tent caterpillar
6	Northern Adirondacks	95	87	27	Early 1980s: Thinning Early 1990s: Thinning	1998: Heavy Ice
7	Southern Adirondacks	96	74	29	1979, 1993: Light single tree selection	Unknown
8	Southern Adirondacks	105	65	30	1980, 2001: Light single tree selection	Unknown
9	Catskills	130	72	34	1960s: High grading*	2006: Forest tent caterpillar
10	Catskills	97	40	27	No harvest	Unknown

*In high grading, the highest value stems are removed, leaving small and low-quality trees in the residual stand.

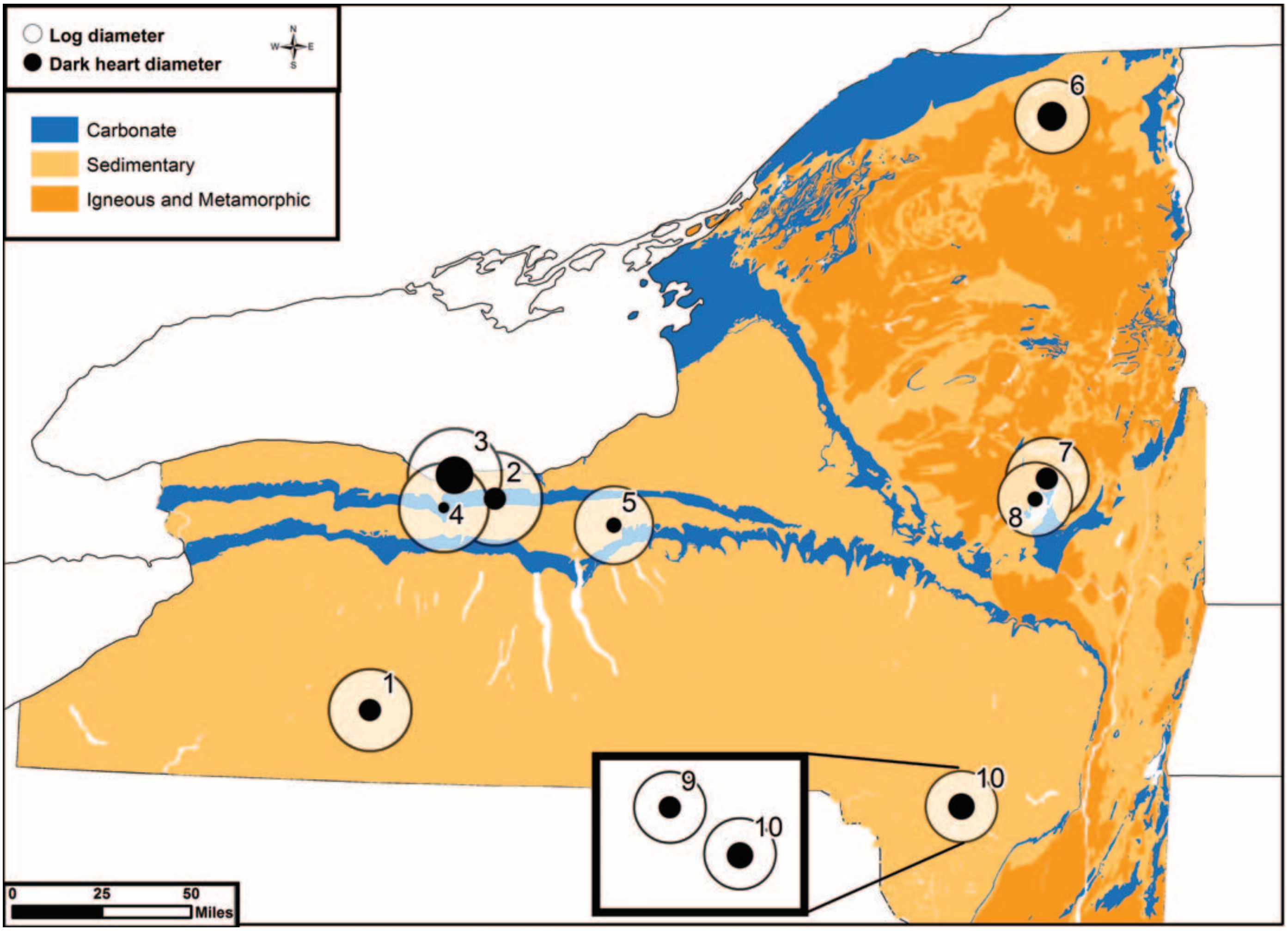

Figure 1. Locations of the study sites across New York State showing bedrock geology, with symbols indicating the average size of dark hearts and stump diameters. Carbonate rocks include limestone, dolomite, and marble. Sedimentary rocks are mainly shales and sandstone. Soils are formed in parent materials that may not correspond to bedrock geology in a glaciated landscape.

marked for harvest from each site for detailed individual tree and landscape measurements. In all, 10 sites were used with a total of 328 trees sampled.

Visible damage to the lower bole, upper bole, and canopy was rated using the 2008 USDA Forest Service Forest Health Monitoring protocol (Potter and Conkling 2013). Injuries include logging wounds to the tree, insect defoliation, dead or broken branches, and cracks or seams on the tree bole. This rating was used to define three injury classes: no injury, injury to the lower bole, or injury to the upper bole and canopy.

Bark type was rated as flaky, medium, or tight (Figure 2), following the types described by Sajdak (1968).

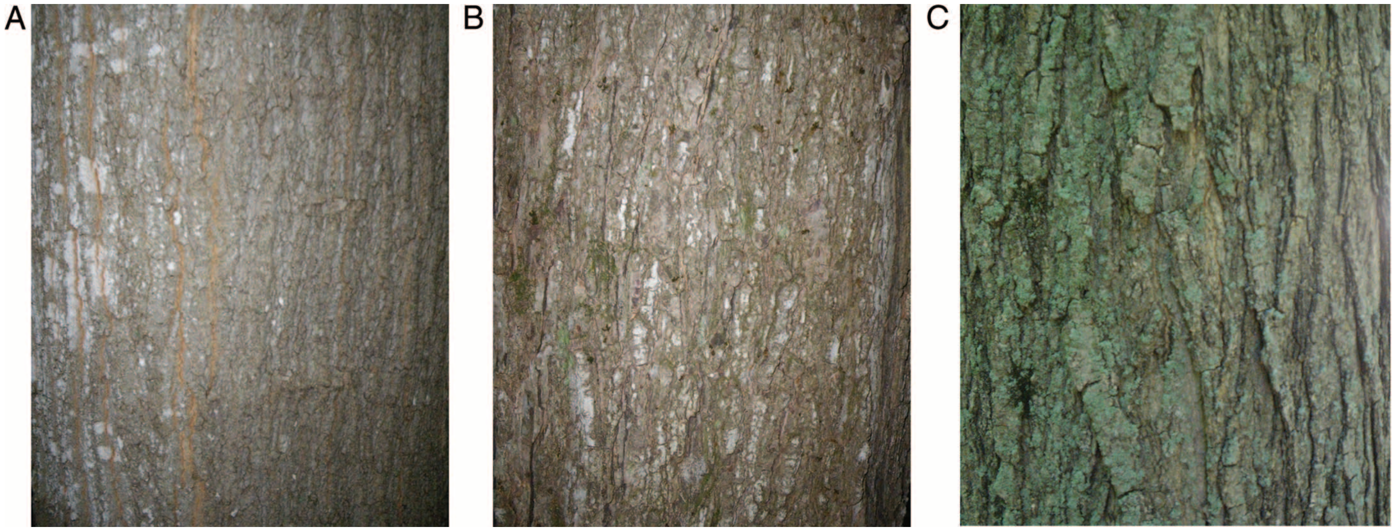

Figure 2. Tight (A), medium (B), and flaky (C) bark types.

The competitive environment around each tree was characterized as the sum of basal area estimated by a 10-factor wedge prism reading taken at the tree.

To describe topographic position, we did not use a subjective classification of landforms (e.g., Bailey et al. 2004). Instead, we used a quantitative approach. Landform index measurements were taken using a clinometer to determine the angle to the horizon in the eight principal compass directions (adapted from McNab 1989, 1993). Terrain shape index measurements followed the same methodology, but measurements were taken by sighting out a distance of approximately 50 ft from the sample tree. The eight values measured at each tree were averaged for both the landform and terrain shape index values. Smaller landform values indicate an area less sheltered by the surrounding landscape, whereas higher values indicate a more sheltered site. Negative terrain shape values indicate an area where water would flow away, whereas positive values indicate areas where water might collect. Slope was calculated as the average of the uphill and downhill slopes from the terrain shape index measurements. Aspect was also measured at each tree.

Heart Size Measurements

We did not have access to the logs harvested from our study sites. Instead, we measured dark hearts on the stump, presuming that they indicate the proportion of dark heart in the first log (Erickson et al. 1992). Of the 328 trees that were studied preharvest, 265 (81%) were relocated and measured as stumps. The others were too damaged to use or could not be found, probably because they were buried under debris and slash. Stumps were measured by taking two perpendicular diameter measurements on the stump, avoiding butt flares. Dark heart dimensions were measured along the same axes. We report dark heart as the ratio of the dark heart diameter to tree (stump) diameter, because this is the measure used in scaling and grading logs, rather than the ratio of the cross-sectional areas. Grade 1 trees with dark heart sizes greater than one-third of the stump diameter were counted as trees that would have a reduction in grade after harvest.

Soil Collection and Analysis

Two to four soil pits were dug at each site, placed to cover the elevational range and to avoid skid trails or other obvious signs of disturbance. Samples were taken from the A and B horizons. Samples were air-dried and sieved through a 2-mm mesh. Soil pH was measured with a glass electrode with a soil/water ratio of 1:2. Cations were extracted using 5 g of soil and 100 ml of 1 M NH_4Cl (Fernandez et al. 2003). Extracts were analyzed for calcium, magnesium, potassium, sodium, and aluminum using inductively coupled plasma-optical emission spectrometry (Optima 33000DV; Perkin-Elmer, Wellesley, MA). Manganese, iron, and phosphorus were analyzed from all but one of the sites. Nitrogen was measured using a Flash EA 1112 Elemental Analyzer (Thermo Fisher Scientific, Delft, The Netherlands). There was insufficient sample to analyze for nitrogen in the B horizon of sites 1 and 9 or the A horizon of sites 6 and 9.

Data Analysis

Heart size differences among sites were analyzed by analysis of variance (ANOVA) using multiple comparison tests with $\alpha = 0.10$ (SAS Institute, Inc. 2009). Heart size was represented as a square root transformation of the ratio of heart diameter to stump diameter in all of the analyses to meet the assumption of normality of the residuals.

We compared the relationship of tree size to heart size within sites. We used linear regression to describe the heart size ratio as a function of log diameter. We then tested whether the slopes of these 10 regressions were different from zero using a *t*-test.

Spearman's rank correlations were examined between heart size ratio and the candidate predictive variables measured for 265 trees. Diameter, crown ratio, competition, landform index, terrain shape index, slope, and aspect were treated as continuous variables. Aspect was represented by the sine (north-south) and cosine (east-west) of the angle. Crown class and tree grade were class variables with two classes; injury had three classes. Bark type had three classes and was treated as an ordinal variable, as medium was assumed to be intermediate between tight and flaky.

We tested for relationships within sites between heart size ratios and the suite of predictive variables described above using simple linear regression with Tukey's honestly significant differences, except for bark type, which was analyzed using a Kruskal-Wallis test with Dunn's multiple comparison. We report differences significant at $\alpha = 0.10$.

We included trees from all sites in a search

Table 2. Soil characteristics of study sites.

Site	Region of New York State	Horizon	pH	Ca	Mg	K	Na	Al	Mn	Fe	N	P
				. . . .	. . . .	. . .cmol$_c$ kg$-^1$	. . . .	. . . .	. . . .	. . . .	. .mg kg^{-1}	. .
1	Allegheny Plateau	A	4.2	2.8	0.56	0.40	0.06	5.9	NA	NA	6.1	NA
		B	4.6	0.8	0.21	0.22	0.05	5.9	NA	NA	NA	NA
2	Central Lowland	A	4.5	4.5	0.85	0.11	0.03	0.8	0.30	0.02	2.8	22.4
		B	4.8	1.4	0.30	0.04	0.03	1.4	0.06	0.04	1.1	11.9
3	Central Lowland	A	4.3	2.0	0.45	0.11	0.08	3.1	0.23	0.09	4.1	16.8
		B	4.5	1.1	0.25	0.09	0.07	2.7	0.10	0.04	2.6	11.5
4	Central Lowland	A	4.3	1.3	0.37	0.11	0.07	3.0	0.14	0.11	3.5	3.4
		B	5.1	0.6	0.19	0.08	0.13	2.7	0.04	0.10	2.2	7.6
5	Finger Lakes	A	3.6	4.4	0.72	0.16	0.07	4.2	0.63	0.12	5.5	27.3
		B	4.4	1.5	0.29	0.13	0.07	3.9	0.21	0.05	2.2	14.0
6	Northern Adirondacks	A	4.0	0.8	0.13	0.08	0.02	0.3	0.02	0.11	NA	12.4
		B	4.3	0.6	0.16	0.05	0.06	1.2	0.02	0.12	1.0	8.4
7	Southern Adirondacks	A	4.4	0.9	0.19	0.15	0.02	1.9	0.23	0.04	3.7	9.9
		B	4.8	2.4	0.37	0.14	0.08	1.7	0.22	0.03	2.0	17.9
8	Southern Adirondacks	A	4.1	0.7	0.22	0.17	0.03	3.8	0.09	0.26	5.3	8.6
		B	4.4	0.8	0.08	0.05	0.03	2.3	0.03	0.07	2.8	8.3
9	Catskills	A	3.9	2.0	0.37	0.11	0.03	2.9	0.04	0.10	NA	2.4
		B	4.1	1.1	0.19	0.10	0.03	5.1	0.09	0.04	NA	1.3
10	Catskills	A	3.7	2.8	0.43	0.17	0.03	1.3	1.16	0.05	2.7	25.2
		B	4.0	2.1	0.38	0.07	0.02	1.7	0.60	0.06	2.4	19.1

Some values are not available (NA) because not enough sample remained for N analysis or because only the major cations were analyzed.

for predictive models of heart size ratios, including site as a main effect. General linear models were used to evaluate the candidate predictor variables described above. We used stepwise regression with forward selection and backward elimination with $\alpha = 0.10$ for both directions. The interactions of site with each of the other variables were also entered into the model for selection.

At the site level, simple correlations were examined between heart size and candidate predictor variables. Heart size was the proportion of trees having hearts larger than one-third of the stump diameter. Soil variables were pH, nitrogen concentration, concentrations of exchangeable cations, the sum of base cations (calcium, magnesium, potassium, and sodium), and the ratio of base cations to aluminum; each of these variables was measured in both the A and B horizons. Other site-level variables were sugar maple dominance (percentage of basal area) and the average of variables measured at the tree level (landform and terrain shape indices, slope, aspect, and live crown ratio). We did not apply a regression model to the site-level variables because the number of sites was small compared with the number of candidate predictor variables.

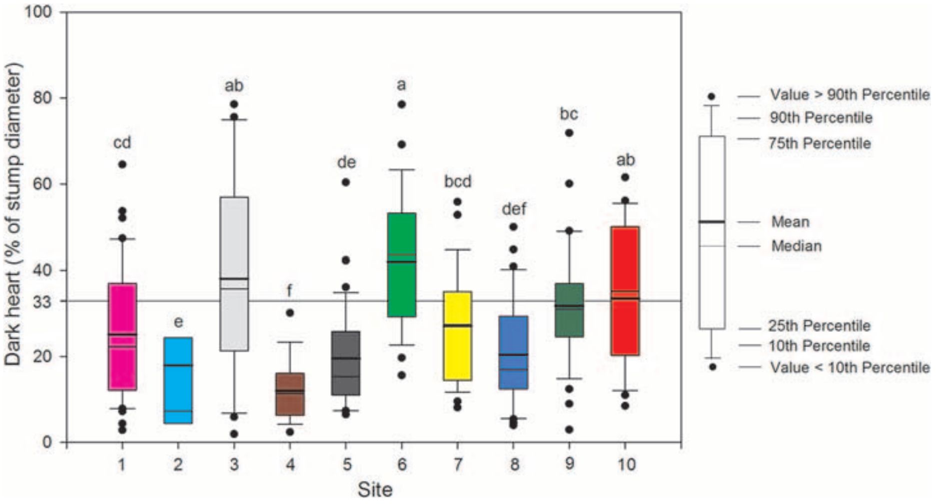

Figure 3. Dark heart size as a percentage of stump diameter at 10 study sites in New York State. The line shows the heart size at which logs suffer a reduction in grade due to dark heart. Sites sharing a letter were not significantly different at $\alpha = 0.10$ based on ANOVA with multiple comparison tests.

Results

Heart Size by Site

Dark heart sizes, described as the proportion of stump diameter that was dark in color, varied across the 10 sites we studied ($P < 0.01$) (Figure 1). The smallest hearts, averaging 12% of the stump diameter, were found at site 4 in the Central Lowlands, which had the least acid soils (Table 2). The site with the largest hearts, site 6 in the northern Adirondacks, averaged 42% (Figure 3).

The information we were able to obtain about site history did not explain average dark heart size by site. Sites 9 and 10, located in the Catskill region, were geographically close to each other (within 1 mile) and had similar dark heart sizes but did not have similar histories (high grading versus no treatments) (Table 1). Site 6 had the highest average dark heart size (42%), much higher than those of the other two Adirondack sites, site 7 (27%) and site 8 (20%), despite similar histories of forest management (all of them received two crown thinnings over the past three decades). Site 6 did experience crown damage from the 1998 ice storm. The second highest average dark heart size (38%) was recorded on site 3, former farmland with no prior harvesting or known crown damage. The smallest average dark heart size (12%) was found on site 4, which was thinned about 60 years ago.

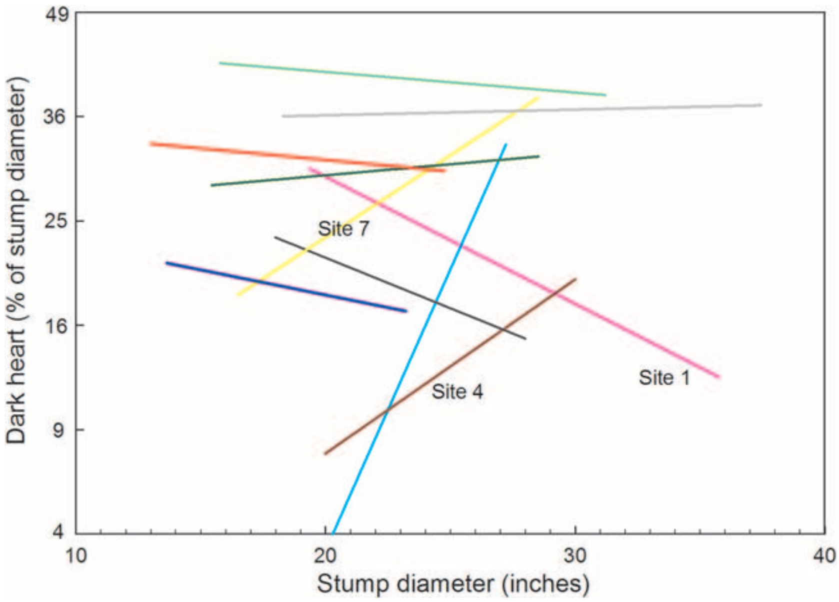

Figure 4. The relationship of dark heart size to tree diameter (linear regression) within 10 study sites in New York State. Few sites have a significant relationship between heart size and tree diameter. Sites 4 (brown) and 7 (yellow) have positive relationships, whereas site 1 (purple) has a negative relationship ($P = 0.07$). Line colors are consistent with those in the other figures.

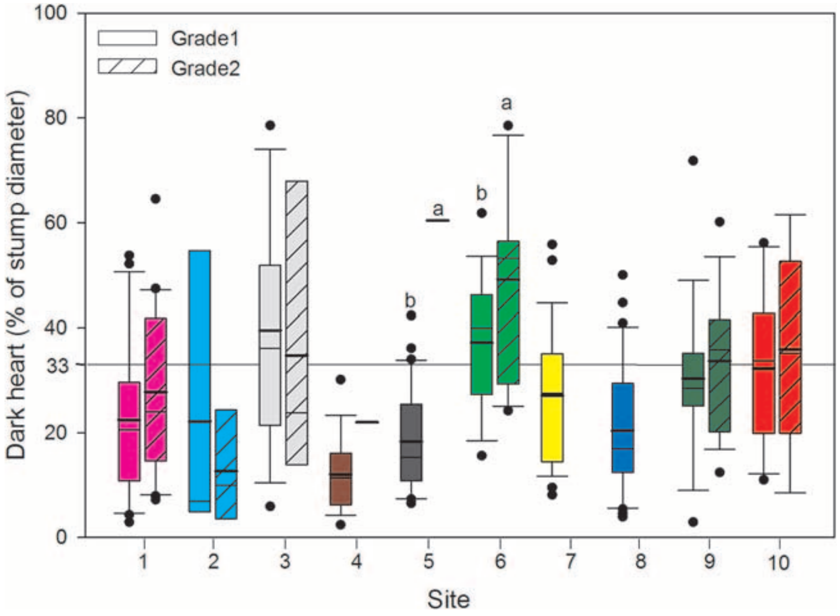

Figure 5. Dark heart size for grade 1 and 2 trees at 10 study sites in New York State. There was only one tree selected for study at site 4 that was rated as grade 2. Letters indicate Tukey's honestly significant differences within site at $\alpha = 0.10$. Grade 1 trees produce grade 2 logs if heart sizes exceed 33% of the log diameter.

Tree-Level Predictors

The proportion of dark heart was not consistently related to tree diameter within sites (Figure 4). There were three sites that had marginally significant relationships ($P = 0.07$) of heart size to stump diameter: Sites 4 and 7 had positive slopes, but site 1 had a negative slope. Taken together, the slopes were not significantly different from zero ($P = 0.37$), with five sites showing an increase and five sites showing a decrease in heart size as stump diameter increased (Figure 4).

We examined correlations between the heart size ratio of the 265 trees in this study and each of the candidate predictors at the tree level. Tree grade was significantly related to dark heart across all sites, with those trees rated before harvest as grade 1 having smaller dark hearts, on average, than grade 2 trees ($\rho = 0.22$, $P < 0.001$). When the hearts were measured, 26% of the grade 1 trees had greater than one-third of the diameter in dark heart, resulting in a reduction in log grade after harvest (Figure 5). The worst site had 64% of grade 1 trees having this reduction; the best had 0%, and the average had 29%. Within site, the relationship of tree grade to heart size was significant at two sites, where grade 1 trees had significantly smaller hearts than grade 2 trees ($P \leq 0.10$) (Figure 5).

Across all sites, trees with more flaky bark tended to have larger dark hearts ($\rho = 0.17$, $P < 0.01$), as expected, flaky bark being a sign of slow growth. Within site, this relationship was significant at site 2 ($P = 0.08$) and site 5 ($P = 0.07$) (Figure 6).

A high live crown ratio indicates a healthy tree (Cole and Lorimer 1994), and these trees tended to have smaller hearts ($\rho = -0.21$, $P < 0.001$) (Figure 7). Within site, this relationship was significant at site 8 ($P = 0.07$).

We expected trees in dominant crown positions to have smaller dark hearts, due to higher growth rates, but, instead, trees in subordinate positions had smaller hearts ($\rho = 0.14$, $P = 0.03$), perhaps because they were less exposed to crown damage. Within site, this relationship was significant at site 8 ($P = 0.04$).

The relationship between visible tree injury and dark heart was not significant across all the trees in the study ($\rho = -0.08$, $P = 0.18$). There was one site in which trees with injury to the lower bole had larger hearts than trees with injury to the upper bowl or crown ($P = 0.06$) (Figure 8).

Physiographic factors were also significant predictors of heart size across all 265 trees. As expected, trees on flatter slopes ($\rho = 0.19$, $P < 0.01$) had smaller hearts (Figure 9). Within site, this relationship was significant at sites 1 and 9 ($P \leq 0.09$). However, trees in more sheltered landform positions had larger hearts ($\rho = 0.26$, $P < 0.0001$), which is not what we expected (Figure 10). Within site, this relationship was significant at site 9 ($P = 0.08$). It is important to note that many sites had little variation in landform index or slope.

Aspect was not correlated with dark heart across all of the trees ($P \geq 0.55$). Aspect was significant in explaining variations among trees at five sites, but the direction of these effects differed by site. There were two sites in which trees on more westerly aspects

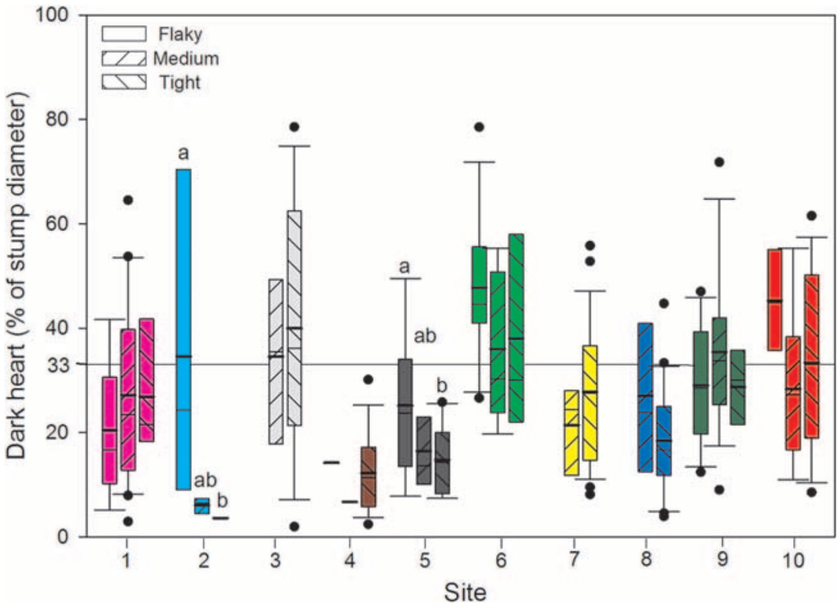

Figure 6. Dark heart ratios by bark type at 10 study sites in New York State. Bark types sharing a letter are not significantly different at $\alpha = 0.10$ based on a Kruskal-Wallis test with Dunn's multiple comparison.

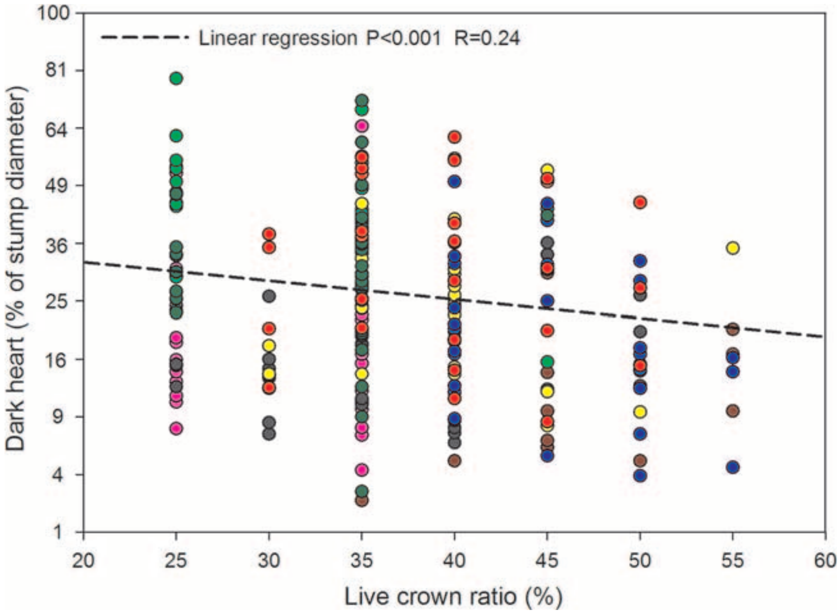

Figure 7. Dark heart ratios as a function of crown ratio across 10 study sites in New York State. Crown ratio was measured to the nearest 5%. Symbol colors are consistent with the other figures.

had smaller hearts ($P \leq 0.05$), two sites in which trees on more northerly aspects had smaller hearts ($P \leq 0.10$), and one site in which trees on more southerly aspects had smaller hearts ($P = 0.02$).

The other candidates for tree-level predictors, namely tree diameter ($\rho = 0.08$, $P = 0.22$), terrain shape ($\rho = 0.10$, $P = 0.12$), and basal area of competitors around each tree ($\rho = 0.04$, $P = 0.88$), were not significantly correlated with heart size ratios across all 265 trees.

In the best model from stepwise multiple regression, none of the tree-level predictors was significant as a main effect. The interaction of site with aspect was significant ($P < 0.001$), because the relationship of aspect to heart size varied widely across sites, as described above.

Site-Level Predictors

Soil variables were measured at each site, not at each tree. The pH in the upper B horizon was negatively correlated with the proportion of hearts larger than one-third of the stump diameter ($\rho = 0.65$, $P = 0.04$), with small hearts more common on less acid soils, as expected (Figure 11). None of the other soil variables were significantly correlated with heart size at the site level. The average values for physiographic variables were also not significantly related to the frequency of dark hearts at the stand level (landform index, terrain shape index, slope, or aspect) ($P \geq 0.23$). Small hearts were more prevalent in sites where the trees we sampled had high live crown ratios ($\rho = -0.68$, $P = 0.06$).

Discussion

In this study, the average dark heart was 23%, considerably smaller than that in a regional study that measured sugar maple butt logs in sawmill logyards across six northeastern states (37%) (Yanai et al. 2009). The smaller hearts in this study may be partly due to the requirement that sampled stems had to meet grade 1 or 2 specifications, which excluded lower grade trees with potentially large hearts. Tree grade was a strong predictor of dark heart size.

Because foresters must base value on tree grade, changes from tree grade to log grade are relevant to timber value estimates. Typically, the grade assigned to the butt log of a standing tree is a good estimate of the log grade assigned at a sawmill (Hanks et al. 1980). The only new information acquired after trees are cut is the amount of dark heart and rot. This can drastically change the log grade, as shown in a Michigan study where the number of grade 1 trees after harvest declined by 50% due to the presence of dark heart (Erickson et al. 1992). In our study, only 26% of grade 1 trees would be reduced by their heart size to grade 2 logs. Regardless of site characteristics or forest management history, the grade of the butt log was a good predictor of dark heart size (Figure 3). This relationship was extremely significant when viewed across all 265 trees in our study ($P < 0.001$). Within site, where the number of trees ranged from 7 to 40, statistical power was less, and only two sites showed significant differences within site by tree grade. We focused only on the best trees in this study; trees of lower grades may well have had larger hearts.

Others have found proportionately larger hearts in larger trees, raising the possibility that trees could be declining in value as they age (Erickson et al. 1992, D'eon and Hamilton 2013, Havreljuk et al. 2013).

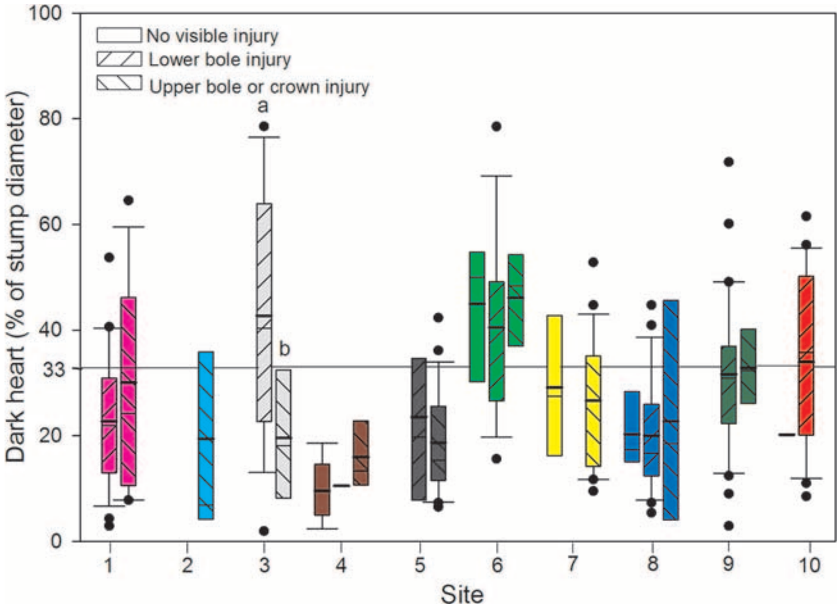

Figure 8. Dark heart ratios by injury category at 10 study sites in New York State. Letters indicate Tukey's honestly significant differences within site at $\alpha = 0.10$.

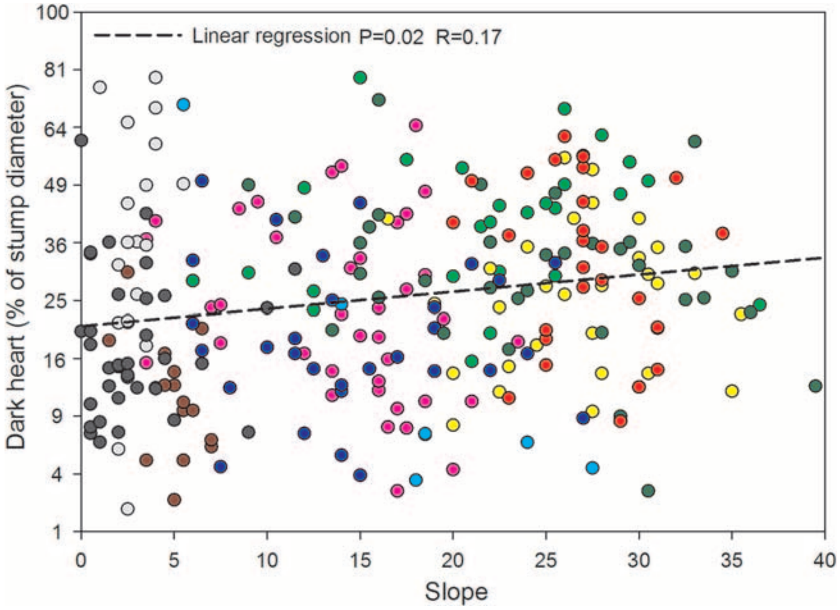

Figure 9. Dark heart ratios as a function of the slope measured at each tree. Symbol colors are consistent with the other figures.

Similar patterns have been reported for European beech in central Europe and paper birch in Canada (Wernsdorfer et al. 2005, Giroud et al. 2008). However, in a study of 53 sites across the northeastern United States, hearts were proportionately smaller in larger trees in most sites, based on the dimensions of the top end of the butt log (Yanai et al. 2009). In the 10 sites in this study, based on the dimensions of the stump, there was no consistent pattern of heart size ratio as a function of tree diameter (Figure 4), nor was there a significant relationship with diameter across all 265 sample trees. Again, the sampling of only grade 1 or 2 logs probably influenced our results; other studies sampled a wider spectrum of grades (Erickson et al. 1992, D'eon and Hamilton 2013, Havreljuk et al. 2013). More measurements of heart size and tree diameter would be useful, and they are relatively easy to obtain.

During the study, many of our cooperating foresters suggested that flaky bark was an indicator of heart size in sugar maple. Foresters and log buyers not involved with the study agreed. They were correct; tighter bark was associated with smaller dark hearts across all the trees in our study. Sajdak (1968) reported that sugar maple with tight, "platy" bark grew more rapidly than sugar maple stems with bark described as "corrugated," "ropy," or "flaky." We suggest that healthy trees with fast growth rates, as indicated by tight bark and high crown ratios (Cole and Lorimer 1994), better compartmentalize wounds and limit the spread of discoloration (Shigo 1966). Studies of heart size in sugar maple (Havreljuk et al. 2013) and paper birch (Giroud et al. 2008) in Quebec also found larger heart size in stems with poor crown ratios.

We expected to find the healthiest sugar maple and the smallest heart sizes on soils developed from carbonate parent materials and larger hearts on more acid soils (Yanai et al. 2009). Depletion of soil base cations, especially calcium, have been implicated in sugar maple declines (Horsley et al. 2000). Sugar maple decline has been reversed by applications of lime or dolomite in the Allegheny Plateau (Long et al. 1997). Similarly, in New Hampshire, an experimental addition of calcium silicate resulted in healthier canopies, increased diameter growth, and more fit germinants and seedlings (Juice et al. 2006). The best soils in the region, including those on carbonate soils, have tended to remain in agriculture, and we failed to find a maple sale on soils with free carbonate. However, we did find a significant relationship with soil pH, with more large hearts in sites with more acid soils (Figure 8). It seems possible that liming could improve the quality of sugar maple timber. To our knowledge, heart size has not been examined in any of the sugar maple studies involving calcium additions.

Aspect was a significant predictor of heart size in five of our sites, which was impressive, considering that differences within site were relatively rare (slope and tree grade were significant within two sites; other factors were significant within at most one site). However, the favorable aspect differed by site, which makes it difficult to use aspect as a predictor in new sites. The site-specific effect of aspect might be explained by crown damage during extreme weather events, which would reflect individual storm patterns unique to each site.

The remaining significant relationships with dark heart were associated with physiographic position. We found smaller dark hearts on gentler slopes, as predicted. We expected a sheltered landform position to support trees with smaller dark hearts, but the opposite proved significant. A more sub-

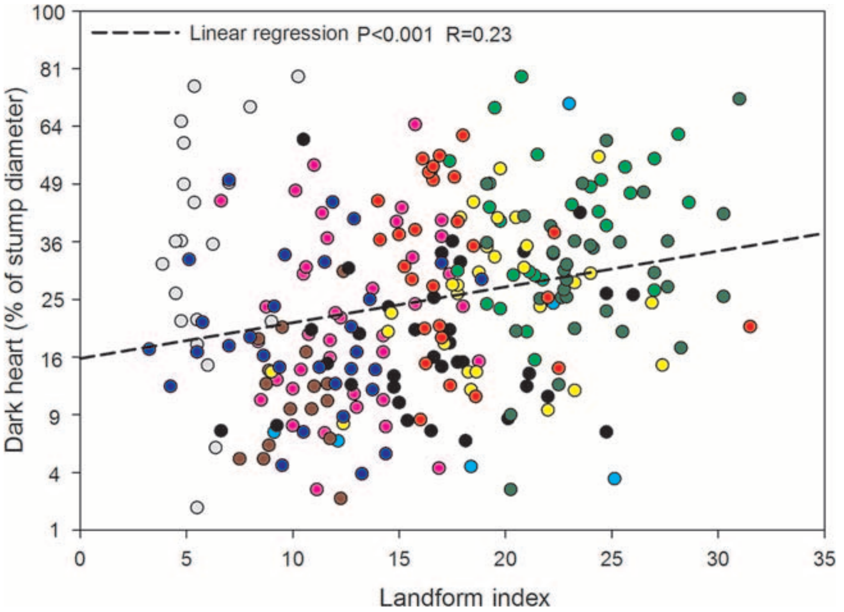

Figure 10. Dark heart ratios as a function of landform index. A high landform index represents a more sheltered environment. Symbol colors are consistent with the other figures.

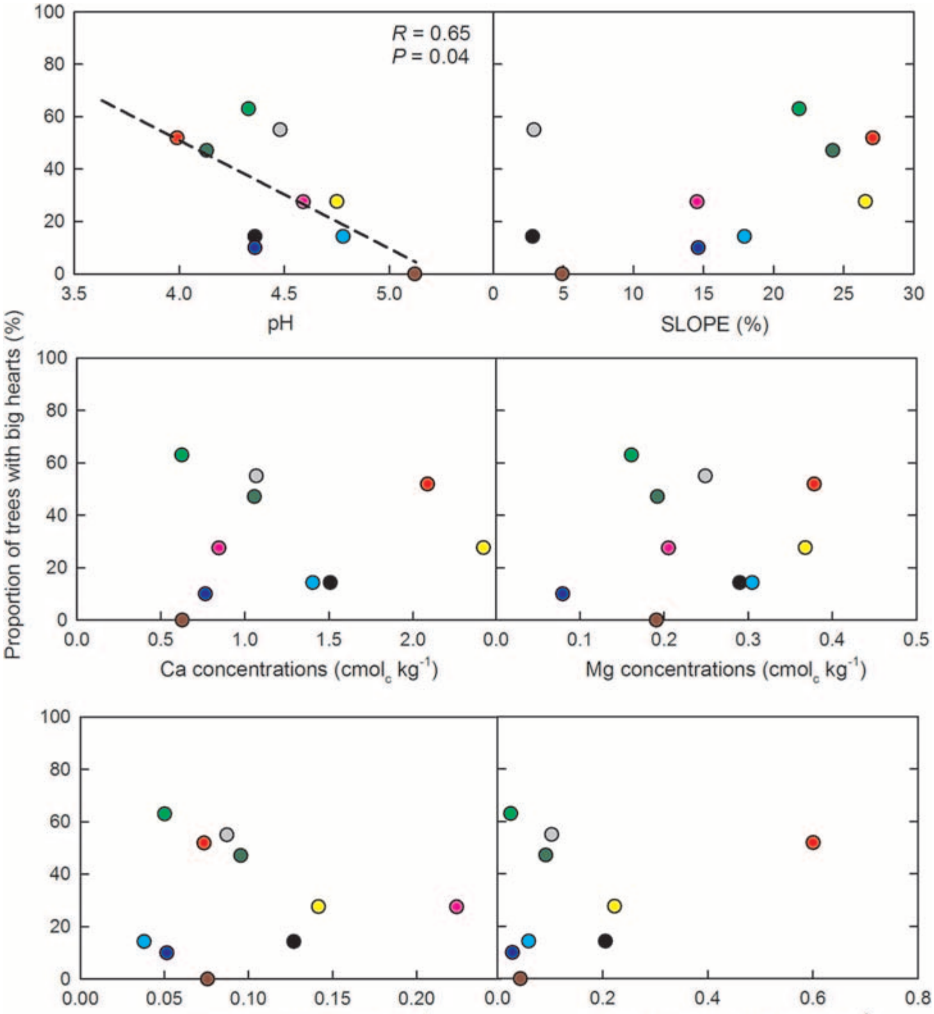

Figure 11. Proportion of trees with big hearts (less than one-third of stump diameter) in each study site graphed against soil properties in the B horizon (pH and exchangeable cations) and the average slope. Symbol colors are consistent with the other figures.

jective method of landform classification might have been more useful (Bailey et al. 2004); the terrain shape index and landform index used in this study were based on sighting slope at 50 ft or at the horizon (McNab 1989, 1993), which could fail to capture important local variation such as a topographic bench.

Our analysis did not find a relationship between visible injury and the amount of discoloration in sugar maple (Figure 8), despite the role of injury in the development of discoloration in diffuse-porous hardwoods (Shigo 1966). Dead and broken branches were related to dark heart of silver birch in Finland (Hallaksela and Niemisto 1998) and European beech in Germany (Wernsdorfer et al. 2005). We observed many injuries to the lower bole from prior logging activities, which is the most common injury that could initiate columns of dark heart in sugar maple (Seablom and Reed 2005). However, the injuries we observed probably occurred within the last 10 years, whereas it may take decades for injury to result in discoloration. Ohman (1970) found no increase in discoloration of sugar maple 10 years after logging, despite wounds inflicted on the lower bole and roots.

Similarly, with respect to crowns, the damage we documented was probably from relatively recent ice storms or wind events (Yanai et al. 2009), which would not yet have developed into discoloration. Ice events occur at various intensities two to eight times per decade in the northeastern United States, with the degree of damage varying widely with both latitude and altitude (Horsley et al. 2002). Past crown damage may well be responsible for much of the variation we observed in heart size, but this damage is generally no longer visible. Our site records were not sufficiently detailed to provide a long-term history of crown damage, except in the case of extensive ice damage recorded in 1998 to the site with the largest dark hearts in the Northern Adirondacks.

Our study builds on the scarce literature related to dark heart in sugar maple. We confirmed that tree grade, bark type, and crown ratio are good predictors of dark heart and ultimately tree value. We also found that stands on more acid soils had more trees with large hearts. Although stem and crown injury are undoubtedly involved in dark heart formation, it would require a long-term study on sites with detailed documentation of land use, forest management activities, pest and pathogen infestations, and weather events to predict heart size based on the history of injury.

As long as sugar maple logs and lumber remain commercially valuable for domestic and export markets (Luppold and Bumgardner 2013), the ability to predict dark heart will be an important issue for both forest managers and the forest products industry. Silviculture is a long-term investment with both biotic and abiotic risks; the potential of dark heart is one of many. Our results suggest that forest managers should not prematurely harvest their sugar maple crop trees for fear of increasing percentage of dark heart with age. The stakes are equally high for hardwood sawmills as they find their woodsheds growing and procurement costs rising (Anderson and Germain 2007) due to a combination of high grading and parcelization across the northern hardwood region (Germain et al. 2007, Munsell et al. 2008). As procurement foresters are traveling ever farther for high-quality sugar maple, the ability to better predict dark heart when estimating stumpage value would improve short-term profit margins and the overall competitive advantage.

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