Vigor and Nutrition vs. Sap Sugar Concentration in Sugar Maples

Timothy R. Wilmot *and* **Philip W. Brett,** *Proctor Maple Research Center, University of Vermont, P.O. Box 233, Underhill Center, VT 05490; and* **Melvin T. Tyree,** *Proctor Maple Research Center, University of Vermont, P. O. Box 233, Underhill Center' VT 05490 and Aiken Forestry Sciences Laboratory, USDA Forest Service, P.O. Box 968, Burlington, VT 05403*

ABSTRACT. Although maple dieback has received considerable recent attention in the Northeast, little has been reported about the relationship between sap sugar yield and crown health or crown nutrition. We measured sap sugar concentration (sweetness) in six northern Vermont maple stands in the springs of 1990-1992, and sap volume yield from tapholes at one stand in 1991. The stands differed in average crown dieback, canopy transparency, density, and mean dbh, as well as cation exchange capacity (CEC) of upper soil horizons. Sweetness of individual trees was correlated with sweetness measured the previous year ($r > 0.72$, $P < 0.001$) and with dbh ($r > 0.45$, $P < 0.001$), but correlations between sweetness and crown dieback or canopy transparency were low ($r < 0.14$). Sap volume was negatively correlated with crown dieback ($r = -0.51$, $P = < 0.001$). Possible explanations for these findings are discussed. Foliar nutrient status of trees was not well correlated with sap sweetness ($r < 0.30$). Affects of soil amendments, primarily cations, on sap sugar concentration were studied at three stands with low CEC. There were no treatment-dependent changes in sap sweetness 2 yr after the first fertilizer application. North. J. Appl. For. 12(4):156-162.

Although the variable nature of 'sap sugar yield from a random selection of sugar maples is well documented (Jones et al. 1903, Taylor 1956, Blum and Gibbs 1968), there is considerable uncertainty regarding the sources of this variability. Anatomical differences among trees relating to starch storage capacity (Morselli et al. 1978, Wallner and Gregory 1980) apparently account for a minor portion of the observed variability in sap sugar concentration (sweetness). Crown size and light interception have long been linked to phenotypical differences in sap sugar concentration (Moore et al. 1951, Morrow 1955, Blum 1971) although the relationship has never proved robust. Recent studies of the effects of early and late season defoliation (Gregory and Wargo 1986, Kolb et al. 1992) have shown little difference in sweetness between undefoliated and defoliated trees, implying that short-term differences in leaf area may not be well correlated with sweetness.

Reports of sugar maple decline in the northeastern U.S. and Canada during the past decade (McLaughlin et al. 1985, Vogelmann et al. 1985, Bernier et al. 1989, Millers et al. 1989) have heightened the concern of syrup producers for the loss of production due to tree mortality; but little has been reported recently concerning the relationship between tree health and sugar yield. Associated with the recent reports of maple decline have been numerous reports of soil and foliar nutrient deficiencies in sugarbushes (Bernier and Brazeau 1988a, Bernier and Brazeau 1988b, Adams and Hutchinson 1992). Programs of fertilization to restore the health of nutrient deficient stands have been underway for several years (Hendershot 1991, Ouimet and Fortin 1992); these studies have focused on crown condition, foliar nutrition, and radial growth, while the effects of nutrient deficiencies on sap characteristics have not been explored.

The first objective of this study was to document sap sugar concentrations and sap volume yield among trees that differed in a number of physical characteristics, including crown dieback and canopy transparency. Tree-to-tree variability in the efficiency of sugar production, storage, and exudation may ultimately control a great deal of the variability of sap sugar yield. Nevertheless, the association between sugar yield and identifiable physical traits that may be linked to these mechanisms is important from a perspective of management for syrup production. Our second objective was to examine the relationship between sap sugar concentration and tree nutrient status, and to determine whether certain soil nutrient amendments, primarily cations, would increase sap sugar. As the concentration of sap sugar is of considerable economic importance to syrup producers, information concerning possible response to fertilizer should be useful in decisions concerning forest management.

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Materials and Methods

Study Area

The six maple stands used for this study were located in northwestern and north-central Vermont, either in the Lake Champlain lowlands, or on the lower slopes of the Green Mountains, at elevations ranging from 165-535 m. This region has a continental climate, with warm summers and long, cold winters. Annual precipitation averages 850 mm in the lowlands, with greater amounts in the Green Mountains, and drought during the growing season is unusual (Lautzenheiser 1959). Stands are S, E, or W facing, and slope varies from 7 to 25%. Table 1 summarizes selected stand characteristics; a more detailed description of these stands is presented elsewhere (Wilmot, et al. 1995). Although this region generally supports mixed northern hardwoods (Braun 1950), all of these stands have been managed for maple syrup production for at least the past 2 decades, and removal of nonmaple species has resulted in an overstory that is predominantly sugar maple.

Selection criteria for the stands included uniform management practices by landowners, including the use of plastic tubing for sap collection, lack of recent disturbance such as grazing or logging, and commitment from the owner not to disturb the study plots for the duration of the experiments. The six stands used in this study were a subset of seven stands we had previously selected for an examination of the nutritional status of northern Vermont sugarbushes. These seven stands were initially chosen to represent differing states of crown dieback. The seventh stand used in the nutritional study was not included in this study because it was too far from our field station. A description of the soil and foliar nutrient status of the seven stands is presented in Wilmot et al. (1995). Soils at all stands are spodosols, and were developed on glacial till of mixed mineral origin (Allen 1974). Cation exchange capacity of the upper, highly organic soil horizons (0 and A), determined in 1989, was low at all stands except stand 2 (Table 1); while soil extractable calcium was low at stands 3, 4, 5, and 6 (average 939 mg kg^{-1}) and much higher at stands I and 2 (average 2572 mg $kg-^{1}$).

Experimental Design

In 1989, we established clusters of 1-4 plots, 30 m x 50 m on a side, in portions of each stand that were structurally and compositionally similar. Individual plots were separated from each other by 30 m buffer strips which were not sampled. Within each plot, approximately 20 dominant or codominant sugar maples were randomly selected for analysis. All measurements, including sap sugar concentration, were made on these trees. Crown dieback and canopy transparency were estimated yearly in July according to the methods of the North American Maple Project (Millers et al. 1991). Ground observers estimated the percentage of recently dead branches (branches with fine twigs still attached) and the percentage of the canopy outline that was not obscured by leaves (transparency) to the nearest 5%, or the nearest 2.5% if the percentage was less than 10. Diameter at 1.4 m (dbh) was measured in 1989. Basal area and the number of stems in each size class were estimated in 1991 by taking 10-15 points ha^{-1} with a 10 factor prism (1 m^2 ha^{t} is approximately equal to 4.4 ft^2 ac^{-t}). Yearly sampling for foliar nutrients was conducted in each plot in August.

Sap Sugar Determination

Sap sugar was measured during the spring sap flow season (generally early March to mid-April) in the spring of 1990-1992. We modified the tubing used for sap collection by installing snap fittings (Quick-Lock, Small Bros., Swanton, VT) on the line leading to an individual spout in each of the dominant or codominant trees in the plots. These snap fittings could be unfastened to allow a drop of sap to be placed on a temperature-corrected, handheld refractometer (Atago Co. Ltd, Tokyo). The concentration of solids in the sap, to the nearest 0.1%, was then immediately determined [solids in sugar maple sap are> 99% sucrose in the spring (Gregory and Hawley 1983)]. Sap from a single taphole per tree was monitored, and the compass direction of the taphole was noted. Sap sugar determinations for 40-90 trees in a stand could be made in 30-90 minutes, and two people making measurements could visit all of the stands in an afternoon, thus minimizing the effects of variation in sweetness over the course of the sap season. Because sap sugar in any tree can vary considerably during the course of the sap flow season (Taylor 1956), we repeated sap measurements on all trees every 3-7 days when the sap was running.

Sap Volume Determination

Total sap volume from single tapholes was measured over the course of the sap flow season in a single stand (stand 5) in 1991. The close proximity of this stand to our field station allowed us to closely monitor daily sap flow. In March 1991, 49 trees with a range of crown dieback symptoms (measured in the summer of 1990) were selected. A single 7 cm deep taphole 1.1 cm diam was drilled in each tree, and a metal spout and bucket were attached. All tapholes were placed on the south side in a section of the bole with healthy white

Table 1. Description of study sites in northern Vermont. Age refers to the approximate age of dominant sugar maples. Dieback is the average percent dieback of the dominant or codominant sugar maples for the period 1989 through 1992, and transparency is the average percent canopy transparency of the dominant or codominant sugar maples. CEC is the cation exchange capacity in mill-equivalents/ 100 g of the upper 5-6 cm of soil.

Site	Location	Age lyr)	Dieback 1%)	Transparency [0/0)	CEC
1	Fairfield	> 200	2.8	12.3	15.9
2	Huntington	70	3.7	13.9	29.3
3	Johnson	110-170	4.4	20.5	11.7
4	Craftsbury	65-100	8.9	19.7	14.6
5	Underhill	125-145	10.1	22.1	16.9
6	Fletcher	150-170	17.0	26.2	13.4

sapwood as indicated by the drill shavings; in a few of the trees with a high incidence of crown dieback, the deterioration of the bole necessitated placement of the taphole in the SW or SE quadrant. The volume of new sap from each tree was measured daily, or more often during times of heavy sapflow.

Fertilization

In May 1990 and May 1991, stands with 4 plots (stands 3, 4, and 5) each received one of three fertilizer treatments, while a fourth plot was maintained as a control. Fertilizer treatments were composed primarily of cations: (1) a mixture of K_2SO_4 , $CaCO_3$, and $CaMg(CO_3)_2$ (percentage N, P, K, Ca, Mg = 0, 0,-29, 11, 2) at 400 kg ha-^{1}; (2) mix #1 plus 3000 kg ha^{-1} $CaCO_3$; and (3) Maple Gro fertilizer (Canagro Agricultural Products Ltd, Elmira, Ontario) a blend of blood and bone meal (percentage N, P, K = 3, 4, 8), at 200 kg ha^{-1}. Determination of sap sugar concentration in fertilized plots was the same as described above. A description of the effects of fertilization on the nutrition and growth of these trees will be presented elsewhere (Wilmot et al. unpubl.).

Statistical Analysis

Analysis of variance (SAS Institute Inc. 1987) using the general linear model procedure for repeated measures analysis was used to test for differences in sap sweetness between sites over time and between fertilizer treatments over time. Sap data also were subjected to correlation analysis with dbh, foliar nutrients, and crown condition.

Results and Discussion

Sap Sugar Concentration and Sap Volume in Unfertilized Trees

Differences among stands for sap sugar concentration were large ($F = 44.7$, $P < 0.001$), when averages for the years 1990–1992 were combined (Figure 1). In contrast, variability across the 3 yr within stands appeared to be small. Although there were some stand by year interactions (in particular stands 4 and 6 changed over the 3 yr period), when all stands were combined, there were no significant differences among years for sap sugar ($F = 0.89$, $P = 0.44$). The sap sugar concentrations (sweetness) of our six stands were about as variable as those that described by Taylor (1956); he also found considerably greater differences among stands than among years at each stand. Using the average of all six stands, according to the Rule of 86 (Jones 1967), 40.6 gallons of 1990 sap, averaging 2.12%c sugar concentration, would have been required to make a gallon of syrup (86/2.12); in 1991, 39.3 gallons would have been required, and in 1992, 38.6 gallons. In terms of the economics of maple syrup production, this would have resulted in only small changes in the average fuel consumption necessary to concentrate a gallon of syrup. On the other hand, the stand-to-stand differences could play a large part in the profitability of a sugaring operation: during the years 1990–1992 an average of 33.6 gallons of sap was required for each gallon of syrup produced at stand 1, while an average of 55.1 gallons was required at stand 2.

Given the wide variation among our stands for average sap sugar concentration, it would be useful to identify any characteristics of stands or individual trees that could predict relative sweetness. This also was the goal of several previous studies (Moore et al. 1951, Morrow 1955, Blum 1971, Laing and Howard 1990), although none of these studies considered the health or nutritional characteristics of trees. We attempted to make comparisons between some indices of stand stocking and mean stand sweetness (Table 2) using averages from each of our six stands (a larger sample of stands would be necessary to examine these trends statistically). Mean dbh of tapped trees was greatest at the sweetest stand and least at the least sweet stand, otherwise it did not appear to be associated with sweetness. Basal area of stems above 20 cm dbh seemed to follow no trend in relation to sweetness. On the other hand, there was an apparent negative association between the density of trees in the canopy (a tree of canopy height was arbitrarily defined by us as having a dbh > 20 cm) and stand sweetness. This follows the widely observed trend for more open-grown trees; i.e., trees with large crowns tend to have higher sap sugar than trees in a closed canopy. The low sweetness of stand 6. however, cannot be explained on this basis. Using more labor-intensive measurements than ours, such as calculations of live crown ration, or crown diameter. Morrow (1955) and Blum (1971) attempted to correlate sap sweetness with crown exposure of individual trees: both authors were able to account for only a small portion of the variability in sweetness with these methods.

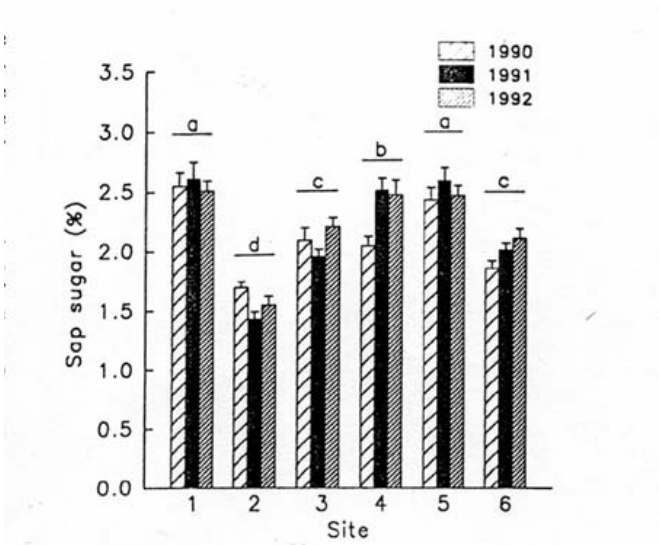

Figure 1. Mean sap sugar concentration (vertical bars represent ±1 se) at six sites. Sites are arranged in descending order of crown dieback. Letters above means are the same when sites are not significantly different for the three years combined, using the Student Neuman Keuls test.

Yearly sap sugar determinations used to test correlations between sweetness and dbh or crown condition of individual trees (Table 3) are from the same 116 trees represented in Figure 1. A strong relationship is shown between a tree's sap sugar concentration one year and that of the next. This supports the findings of Taylor (1956) and others that trees tend to maintain their ranking in sap sugar concentration from

Table 2. Sap sugar concentration and stand characteristics of study sites in northern Vermont. Sap sugar is the mean concentration for the period 1990-1992. Dbh and n refer to the mean diameter (at 1.4 m) and number of sugar maples tapped yearly for sap sugar determinations. Basal area and density are for stems > 20 cm dbh only, and refer to all species in the stand.

Stand	Sap sugar (%)	dbh (cm)	Basal area ($m^2 ha^{-1}$)	Density (sterns ha ')	n
1	2.56	50.0	20.7	174	19
5	2.49	43.0	25.5	151	21
4	2.34	38.3	19.8	199	17
3	2.08	46.6	25.2	223	23
6	1.98	48.9	23.7	148	19
2	1.56	27.3	22.4	344	17

one year to the next relative to their neighbors'; i.e., a sweet tree will almost always stay a sweet tree. It also supports the results of Morrow (1955), Blum (1971), Laing and Howard (1990) that sap testing of individual trees within a stand is a superior method for predicting future sweetness over the measurement of physical parameters such as crown size, or live crown ratio. Diameter appeared to be about half as efficient as previous sap testing in predicting sap sweetness of an individual tree (r^2 = 0.25 vs. r^2 0.59 in 1992). Generally, sap of > 3% sugar concentration came from trees over 60 cm dbh. This can probably be explained by a combination the larger crown size of large diameter trees, and the fact that sugar maple, a species with a large proportion of functional sapwood (Gregory 1982), would have proportion-ally much greater starch storage capacity in a large bole than a small bole.

Correlation in individual trees between sap sugar concentration and either crown dieback or canopy transparency from the previous growing season was poor (Table 3). Ranking the stands for crown dieback (Figure 1) also showed no real relationship to mean stand sweetness. In interpreting these findings, we caution that canopy transparency is not a measure of crown size, but of the density of leaves in the crown. Presumably, canopy transparency can be influenced by defoliation and leaf damage from insects such as pear thrips, by weather events such as spring drought, as well as by a general lack of vigor in the tree. Accordingly, the transparency can change from year to year in any tree; we observed these changes in many trees in our study plots over the course of 4 yr.

Our findings about the lack of a relationship between dieback and canopy transparency and sweetness are supported by the conclusions of Renaud and Mauffette (1991), who found no difference in total stem carbohydrate concentration between mature sugar maples exhibiting various levels of decline, and differences in total root carbohydrates that were unrelated to crown condition. They are in contrast with the hypothesis of Gabriel and Seegrist (1977) that declining or "stressed" trees have sweeter sap than healthy trees. These authors classified stands of trees as "ungrazed. "grazed," or "roadside," and attributed the greater sap sugar concentration in the latter two groups to greater amounts of stress, although larger crown size, particularly in roadside trees, was a more likely reason. We were surprised to find no correlation between sap sugar concentration and canopy transparency. As sap sugar is a consequence of the mobilization of photosynthetically produced carbohydrates before budbreak (Gregory and Hawley 1983), it would seem more likely that sweetness would be lower in thin-crowned trees. Kolb et al. (1992) found that trees subjected to early season defoliation by pear thrips stored fewer root carbohydrates, but their findings about the relationship between thrips damage and sap sweetness were inconclusive. Our findings could be explained by two physiological symptoms of thin-crowned trees acting in concert: (1) less production of carbohydrates; and (2) less utilization of stored sugars due to reduced growth, particularly when the thin crown is a symptom of general decline.

At site 5 in 1991, the relationship between crown dieback and sap volume was highly significant, (r=-0.509, P<0.001) indicating that declining trees yielded less sap (Figure 2). While these data were limited to one stand and one year, they imply that a regionwide maple decline might have an effect on overall syrup production. An explanation of this relationship could be the decrease in the number of small branches which are necessary to recharge sap volume in the crown during freezing (O'Malley and Milburn 1983, Tyree 1983). In addition, Bauce and Allen (1992) reported a large decrease in fine roots accompanying trees with moderate crown dieback; presumably this could reduce water uptake and sap flow in the spring.

Table 3. Linear correlation coefficients (and Pvalues) for sap sugar concentration vs. sap sugar for a different year, tree diameter, and crown health. Data from unfertilized trees; n = 116 for each value listed.

	Sap sugar 1990	Sap sugar 1991	Sap sugar 1992
Sap sugar 1990		0.721 (0.001)	0.744 (0.001)
Sap sugar 1991			0.768 (0.001)
Dbh	0.520 (0.001)	0.451 10.001)	0.495 (0.001)
Dieback 1989	-0.064 (0.4391		
Dieback 1990		0.060 (0.523)	
Dieback 1991			0.139 (0.138)
Transparency 1989	0.032 (0.749)		
Transparency 1990		0.027 (0.775)	
Transparency 1991			-0.017 (0.857)

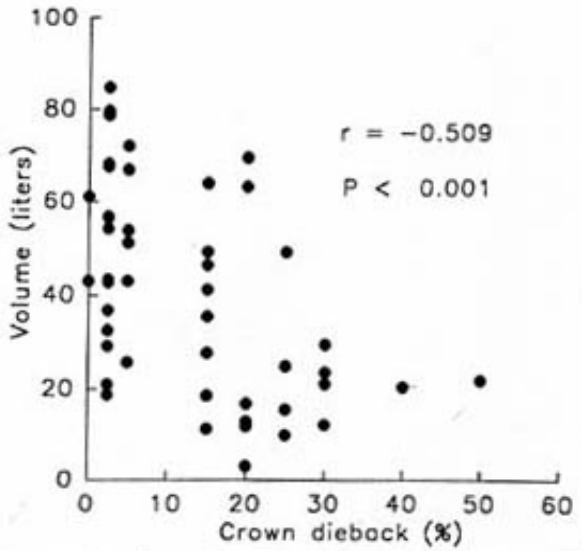

Figure 2. Total spring sap volume from one taphole vs. percent crown dieback (measured the previous summer) in unfertilized sugar maples.

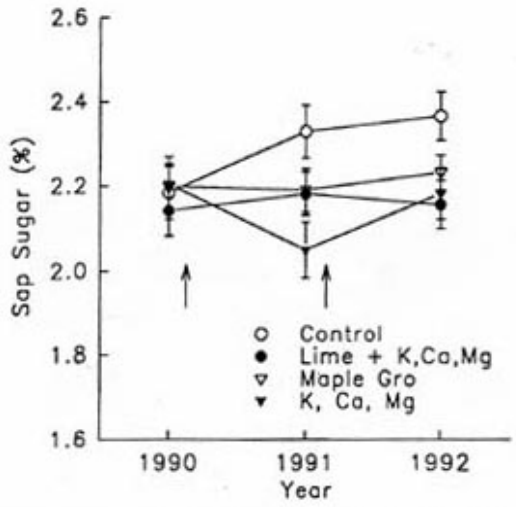

Figure 3. Mean sap sugar concentration (vertical bars represent ±1 se) for three fertilizer treatments and control; *n* = 230. Sap sugar concentration measured March–April. Arrows indicate time of fertilizer application (May).

Sap Sugar Concentration and Stand Nutrition

Correlation between sap sugar concentration and foliar macronutrients from the previous summer is presented in Table 4 (these data come from unfertilized trees). Correlations were weak or absent with $r^2 < 0.08$ in all cases. The apparent negative association with N was probably caused by the high foliar N at stand 2, where trees were generally small diameter, with low sap sugar concentrations.

Lack of any strong relationship between foliar nutrition and sap sweetness may explain the general low level of success reported by previous researchers in improving stand sweetness by the use of fertilizers (Kriebel 1961, Watterston et al. 1963, Yawney and Walters 1973). In this study, fertilization of trees in three stands prior to the 1990 and 1991 growing season produced no change in sap sugar concentration from the baseline determined in the spring of 1990 (Figure 3). A highly significant treatment by stand interaction was seen ($F = 11.29$, $P < 0.001$), indicating that the effect of fertilization was not the same in each stand. For all stands combined. however, the treatment by year interaction was not significant ($F = 1.28$, $P = 0.337$), indicating that the apparent changes in 1991 and 1992 were not treatment dependent.

Table 4. Linear correlation coefficients (and P values) for sap sugar concentration vs. foliar nutrient concentration from the previous August. Data from unfertilized trees; n = 55 for each value listed.

	Sap sugar 1990	Sap sugar 1991	Sap sugar 1992
N	-0.240 (0.714)	-0.280 (0.039)	-0.190 (0.164)
Ca	0.048 (0.727)	0.078 (0.570)	0.020 (0.884)
Mg	-0.170 (0.216)	0.221 (0.104)	0.251 (0.065)
P	-0.257 (0.058)	-0.121 (0.378)	-0.068 (0.662)
K	-0.005 (0.972)	-0.101 (0.463)	-0.136 (0.322)

It is difficult to compare our results following fertilizer treatment with those of past researchers. Our treatments were primarily cations, applied to three stands with low soil cation exchange capacity (Table 1, stands 3, 4 and 5). Watterson et al. (1963) and Yawney and Walters (1973) reported applications of N, P, K fertilizers (up to 6740 kg ha^{-1}) in central New York and Vermont, respectively, but did not mention soil nutrient availability prior to treatment; neither of these studies resulted in an improvement in sap sugar concentration. Kriebel applied 674 kg ha^{-1} N to stands in Ohio: nutrient availability prior to treatment was not reported but the stands were described as "in need of thinning." Although a slight increase in sap sugar concentration occurred over a 3 yr period, Kriebel speculated that thinning would have been a more cost effective treatment. None of these reports discussed the treatment of stands with unhealthy crowns.

Conclusions

Sap sugar concentrations varied considerably among six maple stands exhibiting varying levels of crown dieback and canopy transparency. When comparisons were made using averages for the whole stand, or for individual trees, there was apparently little relationship between sap sweetness and either crown dieback or canopy transparency. The results from one stand indicate that crown dieback may negatively influence sap volume.

Foliar nutrition also was poorly correlated with sap sweetness. Fertilizer application (mostly K, Ca and Mg) did not have a significant effect on sap sweetness within 2 yr of the first application.

Tree diameter, which may be both a measure of crown size and potential for carbohydrate storage, was positively associated with sweetness. In addition, density of the stand, as

measured by us, seemed to be correlated with the mean sweetness of the stand. Nevertheless, the fact remains that the cause of most of the differences in sweetness among individual sugar maples is unexplained. Although relative sweetness is predictable from one year to the next by sap testing, it may not be readily subject to prediction by physical inspection or to manipulation by landowners.

Management Implications

The results of this study confirm those of others that the association between physical characteristics of individual trees in a stand and sap sugar concentration is imprecise at best. We saw no evidence that a temporary decrease in canopy density, which in Vermont is frequently caused by pear thrips feeding in the spring, caused a decrease in sap sweetness. None of our stands were heavily defoliated, how-ever, and damage was mostly limited to a single year; therefore we cannot say that severe or repeated foliar damage has no influence on sweetness. Although we saw no relation-ship between crown dieback and sap sweetness, the likely reduction in sap volume produced by declining trees may make these trees less valuable to sugarmakers.

Landowners who wish to thin a dense sugar maple stand with the object of improving mean sap sweetness need to determine which are the sweeter trees. In terms of predicting sweetness, while larger diameter trees tend to be sweeter, according to our results, sap sugar would be better forecasted by sap testing. In terms of optimum basal area or density, we found no relationship between the basal area of all trees > 20 cm dbh and sap sweetness (when basal area was between 20 and 26 m^2 ha^{-1}) but we did find an apparent negative association between the density, defined by us as the number of stems > 20 cm dbh, and sweetness. This could be used as an indicator of when to thin, although we caution that there was no precise relationship between density and sweetness.

Fertilization to improve sap sugar has generally shown little success in the past. This also was true of our efforts. However, this paper did not address issues of crown vigor (dieback, canopy density, growth, etc.) before and after fertilization. Some maple producers may wonder whether fertilization will halt maple decline, thereby preserving the source of their maple sugar. Because fertilization trials in maple stands have rarely shown a long-lasting effect on crown vigor, there are neither widely accepted recommendations for the composition (which should be based on specific nutrient deficiencies in the stand) or timing of fertilizers for maple, nor is there an accepted level of crown dieback that would warrant immediate action. In addition, anyone at-tempting fertilizer treatments should carefully weigh the possible benefits with the costs, in terms of materials, labor, and possible disturbance to root systems if mechanical equipment is used.

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