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Overstory and understory leaf area index as indicators of forest response to ice storm damage

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Abstract

Leaf area index (LAI) was measured with the tracing radiation and architecture of canopies (TRAC) optical instrument in three consecutive summers from 1999 to 2001 in sugar maple forests across eastern Ontario to monitor recovery from ice storm damage suffered in January 1998. The study sites were experimental blocks of the Ontario Ministry of Natural Resources (OMNR) designed for measurement and monitoring of the effects of fertilizer and lime treatments on maple recovery. Understory vegetation survey data, collected in 1999 and again in 2001, were converted to understory gap fraction, and processed in the same manner as the TRAC data to obtain understory LAI. Subtraction of understory LAI from total LAI measured with the TRAC allowed monitoring of productive, overstory trees tapped for syrup production. Annual LAI measurements and LAI change were evaluated in relation to percent crown loss estimates and plot treatments. Understory, overstory and total LAI increased from year-to-year in most plots. Of the single year measurements, total LAI measured in 1999 was significantly related to damage, while 2000 and 2001 LAI accounted for progressively less of the variation in damage, indicating a change in canopy condition between seasons. Understory LAI increased dramatically in response to overstory crown loss, while overstory increased more in absolute terms, but less in relative terms. Between-season LAI change was more significantly related to damage than any of the annual LAI measurements to which it was compared, indicating that LAI response is a better indicator of damage than single year LAI. LAI change was not, however, significantly related to plot treatment.

Keywords: Leaf area index; Ice storm; Forest damage; Understory; Overstory

1. Introduction

Between 4 and 9 January 1998, up to 100 mm of freezing rain fell in eastern Canada and the northeastern United States. The area of ice accumulation was approximately 10 million ha, although forest damage was highly variable and patchy (Irland, 1998). Such ice storms typically result when a moist warm air mass over-rides a near surface air mass of below zero temperature. Rain froze on impact causing ice to build up on surfaces (Stewart and King, 1990), resulting in downed hydro lines and broken tree branches and bent or broken boles. Damage was dependent on species, crown height and morphology, and ice accumulation. Ice storms are one of the few recurring regional scale natural phenomena in eastern temperate forests that are responsible for damaging trees. They generally occur

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with high frequency (every 20–100 years) in the eastern United States and the region from eastern Ontario to the Atlantic Provinces of Canada. However, a storm of the magnitude and spatial extent of the 1998 ice storm is estimated to have a return period of at least 500 years (Smith, 1998). Forest response and adaptation to such damage has not been rigorously studied over the long-term (Stabb, 1998).

Following the 1998 ice storm, the Ontario Ministry of Natural Resources (OMNR) embarked on a project designed to examine the potential to aid the recovery of sugar maple bushes managed for syrup production. A 'maple experiment' was designed, consisting of fertilizer and lime treatments over a range of sugar maple site and damage classes (Lautenschlager and Nielsen, 1999). In addition, in some unmanaged stands, herbicide treatments were applied. Response to treatments was evaluated from 1999 to 2001 in relation to damage. Specific components examined (Lautenschlager and Nielsen, 1999) included: (1) sap and root starch amounts and composition; (2) soils and foliar nutrition; (3) crown condition (Lautenschlager and Winters, 2001); (4) ground and understory vegetation composition and cover (Lautenschlager et al., 2003); and (5) in this paper, understory and overstory leaf area index (LAI).

This paper presents the results from summer LAI measurement in the maple experiment plots from 1999 to 2001, coupled with understory vegetation survey data collected in 1999 and 2001. Results of total LAI change between 1999 and 2000 were presented by Olthof et al. (2001). In that paper, increasing LAI beyond the 95% measurement precision bounds was observed in 10 of the 32 plots measured, while non-significant increases were noted in an additional 18 plots. LAI change was unrelated to plot treatment, but weakly related to damage and understory abundance in the 0–7 m height range (Olthof et al., 2001). This paper builds on that work by monitoring the response of different vertical layers to damage, exploring the effects of drought on LAI measurement and examining longer-term trends.

The objective of this part of the maple experiment was to develop methods for monitoring canopy change in relation to both the damage sustained and treatments, and to identify potential causes for observed variations. Specific objectives of this study were to:

1. measure total canopy LAI using optical instrumentation for the 1999, 2000 and 2001 growing seasons;
2. determine understory LAI from line intercept vegetation data for the 1999 and 2001 growing seasons;
3. separate understory LAI (objective 2) from total canopy LAI (objective 1) to obtain overstory LAI for 1999 and 2001;
4. evaluate relations of annual LAI and LAI change in the plots with initial crown loss estimates made following the storm, and assess fertilizer and lime treatment effects on LAI change.

2. Leaf area index as an indicator of canopy response to damage

Forest damage is often assessed by aggregating individual tree-based visual estimates of crown loss to a plot or stand level (Irland, 1998; Boulet et al., 2000; Lautenschlager and Winters, 2001). While such measurements can estimate the damage of a particular set of trees, they do not represent damage of the entire canopy. Critical canopy damage information exists in gaps between crowns and in the three-dimensional foliage distribution that individual crown loss estimates do not capture. Visual estimates of crown loss can provide consistent (precise) damage assessment immediately following the disturbance event. However, their use can be problematic in monitoring recovery from damage because they are determined relative to an estimated pre-disturbance crown volume. Shortly after a damaging event, wounds and within-crown gaps from broken branches can easily be seen from the ground to estimate pre-disturbance crown volume. As crowns fill in or die back further, pre-disturbance crown volume becomes increasingly difficult to visualize. Additionally, wounds may become obscured by new growth and stain so that they are not easily seen from the ground.

For these reasons, visual estimation of crown loss cannot be effectively used as a response indicator of structural change following the damage event. A suitable indicator for monitoring the response to damage must be: (1) significantly related to the initial damage condition (accurate) and (2) repeatable (precise) through time. Conceptually, instrument-based measurement should be more accurate and precise than visual estimates because bias for a given assessor or among assessors is not present as long as instrument calibration and use remain constant (Olthof et al., 2001). Therefore, an instrument-based measurement that is significantly related to initial damage estimates should provide the best indicator for monitoring canopy response to damage. To meet these criteria, optical instrument measurement of leaf area index, defined as half the total leaf area per unit ground surface area (Chen and Black, 1992), was selected for this study to complement individual tree-based damage measurements and to monitor canopy response to damage.

2.1. Summary of the theory and instrumentation for LAI optical measurement

Instrument-based optical measurement of the canopy gap fraction and gap size distribution has been widely applied to assess forest structural parameters such as LAI (Welles, 1990; Chason et al., 1991; Chen and Cihlar, 1995; Herbert and Fownes, 1997; Kucharik et al., 1998). Two broad categories of optical instruments exist for measuring LAI that either sample the canopy hemispherically or along transects. The former category of instruments is most widely used, and includes the LiCor, 1989 LAI-2000 (Licor Inc., Lincoln, NE) and hemispherical photography (Planchais and Pontailler, 1999). These instruments obtain the canopy gap fraction at multiple zenith and azimuth angles simultaneously to estimate LAI. Measurements with these instruments are most reliable when performed under diffuse sky conditions to minimize direct scattering of sunlight off leaves and trunks. Such sky conditions occur at dawn and dusk or in rare instances when cloud cover is low and uniform. The LAI-2000 instrument also requires an above canopy reference measurement (usually taken in a nearby clearing) to calculate the canopy gap fraction. In an operational setting where measurements need to be performed in many plots separated by large distances, as was the case in this study, the required sky conditions for hemispherical canopy measurement can be a constraint.

The second category of optical instruments makes use of direct sunlight transmitted through gaps in the canopy. Such instruments include the tracing radiation and architecture of canopies (TRAC; Third Wave Engineering, Nepean, Ont.) used in this study. Measurements are acquired at a rate of $32\,s^{-1}$ along transects to obtain a profile of light penetrating the canopy. Sunflecks that are projected onto the sensor where canopy gaps occur in the sun's direction are proportional to the sizes of the gaps being measured. Therefore, below canopy sunfleck information can be used to obtain the gap fraction and distribution of gap sizes in the canopy (Chen and Cihlar, 1995). This type of optical instrument requires direct sunlight to produce sharp and consistent sunflecks and shadows, however scattered clouds can be tolerated if they do not pass in front of the sun during measurement. These operational conditions were less constrictive for this study than the necessary sky conditions for hemispheric canopy measurement.

Whether canopy gap information is obtained from hemispheric or line-transect measurements, the gap fraction is converted to LAI and mean leaf inclination angle (the average angle between leaves and the zenith angle) based on the relationship noted by Miller (1967). Gap fraction measurements at multiple zenith angle are necessary to obtain an exact measure of foliage angle distribution or its projection coefficient $G(\theta)$ on a plane perpendicular to zenith angle θ (Welles and Norman, 1991). In the case of line-transect, measurements must be performed several times over the course of the day to obtain data for multiple zenith angles since the gap fraction is derived from data acquired at a single (solar) zenith angle. When this is not operationally feasible as was the case in this study, a spherical foliage orientation distribution is assumed, because it represents many real canopy types well and its projected foliage surface remains (almost) constant ($G(\theta) = 0.5$) with angle θ (Warren-Wilson and Reeve, 1959).

Effective LAI (LAI_e) is obtained from the gap fraction and projection coefficient (Eq. (1)), and assumes a random spatial distribution of foliage elements (Chen and Cihlar, 1995).

$$LAI_e = -\frac{\cos\theta}{G(\theta)} \ln[GF] \tag{1}$$

The assumption of random foliage distribution in space is met only in specific types of vegetation. A number of techniques have been devised to account for the effect of non-randomness, or foliage 'clumping' on effective LAI estimates. The most reliable estimate of foliage clumping is obtained through both direct and indirect estimates of LAI, with the clumping index equal to the ratio of indirect to direct measurement (LAI_e/LAI) (Kucharik et al., 1997). This clumping index (Ω) can then be used to convert effective LAI obtained from hemispherical measurement by most commercial instruments such as the LAI-2000 (Chen and Cihlar, 1995), to real LAI for the non-random case using Eq. (2). Both Eqs. (1) and (2) assume that the contribution from woody material is negligible.

$$LAI_e = \Omega \, LAI \quad (2)$$

Methods exist to estimate clumping from either the gap size distribution (Chen and Cihlar, 1995) or the ratio of indirect and direct LAI measurement (Kucharik et al., 1997). Regardless of the method, the clumping index ranges from 0 for a non-random distribution (extreme case: stacked foliage) to 1 for a perfectly random distribution. Thus, for random canopies, LAI_e equals LAI. In clumped canopies, LAI_e underestimates LAI, as leaves are grouped more in bundles than the random case with the same gap fraction, and there is usually a greater proportion of larger gaps. Underestimations of LAI using indirect measurement have been reported consistently in forests with non-random foliage distributions (Planchais and Pontailler, 1999; Kucharik et al., 1998; Herbert and Fownes, 1997; Chen and Black, 1992; Chason et al., 1991).

LAI may be a more suitable indicator for damage monitoring than effective LAI due to the relation between clumping and damage. Damage tends to decrease the degree of randomness (increased clumping) with which residual foliage is distributed through space (Olthof et al., 2001). Large gaps are more likely to result from damage where susceptible species or crown structures occur (Irland, 1998). Branches and trees that are highly susceptible to damage do not occur randomly over the scale of measurement in this study. The result is that damage tends to be 'patchy' or clumped in nature (Bruederle and Stearns, 1985).

A comparison between TRAC and hemispherical gap fraction measurement was conducted by Leblanc et al. (2002) in a mixed forest, and showed good agreement between the two when the hemispherical gap fraction was obtained at the same view angle as the solar zenith angle of the TRAC. In Leblanc and Chen (2001), a comparison was made between LAI_e values obtained from the LAI-2000 and TRAC instruments of deciduous canopies, and the measurements agreed when comparisons were made at similar zenith view angles through the canopy. Such direct comparisons are difficult, as line-transect and hemispherical instruments 'see' the canopy differently (Leblanc et al., 2002), making identical canopy sampling with both types of instrument impossible.

3. Methods

The OMNR established 38 treatment blocks in a variety of management, site and damage classes in sugar maple bushes across eastern Ontario (Fig. 1) to address the economic and ecologic concerns of maple syrup producers stemming from the 1998 ice storm (Lautenschlager and Nielsen, 1999). Each block is 100 m on a side and is divided into four 50 m × 50 m plots, consisting of one control and three randomly assigned fertilizer, lime, or fertilizer + lime treatments applied in the spring of 1999 (Table 1). In three of the blocks, herbicide was applied to evaluate its potential for suppression of understory growth and competition for resources with overstory trees.

3.1. Forest damage measurement

The OMNR provided visual damage estimates (percent crown loss) that had been acquired in the fall of 1998 for six focus trees in each plot. The plot average of these was used as the damage estimate in statistical

Table 1
OMNR plot treatments for sugar maple ice damage study in eastern Ontario

Treatment	
Non-herbicide blocks ($n = 34$)	
A	No treatment
B	500 kg dolomitic lime + 50 kg phosphorus + 50 kg potassium
C	50 kg phosphorus + 50 kg potassium
D	500 kg dolomitic lime
Herbicide blocks ($n = 3$)	
A	No treatment
B	500 kg dolomitic lime + 50 kg phosphorus + 50 kg potassium and herbicide (Vision®) control
C	500 kg dolomitic lime + 50 kg phosphorus + 50 kg potassium
D	Herbicide treatment (Vision®)

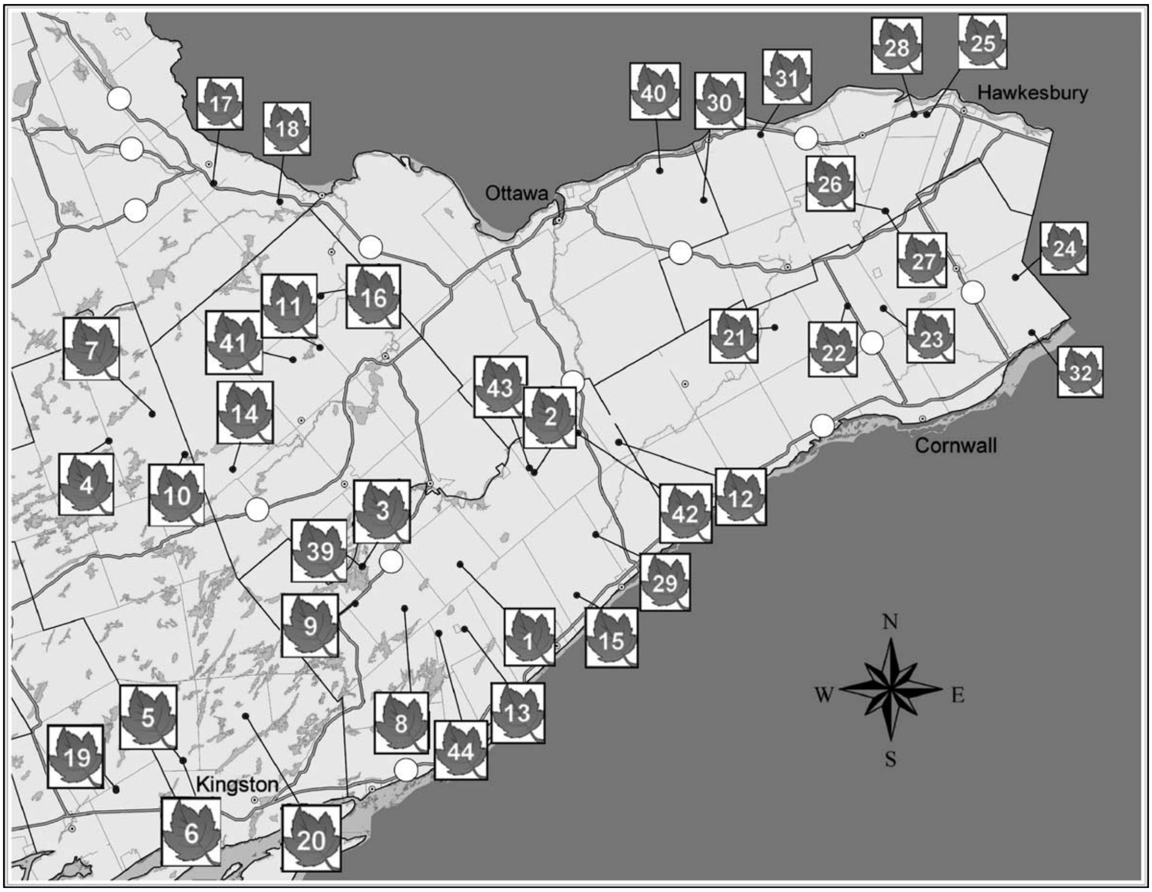

Fig. 1. Block locations and numbers in productive sugar bushes, across southeastern Ontario.

modelling. Table 2 shows the block average damage estimate (the average of the four plot damage estimates in each block). Estimates of crown loss were unavailable for three blocks (39, 41 and 44).

3.2. LAI measurement

Three parallel 50 m transects spaced 10 m apart were installed in each treatment plot in an east–west direction for LAI measurement. Measurements were taken along the same transects in three consecutive summers from 1999 to 2001. Metal flags marked 10 m intervals along the transects so that radiance profiles obtained with the TRAC could be registered to known distances in the forest. Transects were always set up in the northern portion of the plot to ensure that radiation incident upon the transect was passing through the canopy in the plot, as the solar zenith was always at approximately 40° during measurement.

Since the solar azimuth must be within 20° of perpendicular to the transect, and measurement must be performed under direct sunlight, transects were always set up east–west in a given plot before the day of measurement. This allowed measurements to be taken during a cloud free or partly cloudy period between 11 a.m. and 3 p.m. (±2 h of solar noon) when the solar azimuth was within an acceptable range relative to the transect orientation.

LAI was measured in 144 plots (36 blocks × 4 treatments per block) over the course of the three summers and was analyzed on a plot basis. Due to large distances between blocks, they could not all be measured each year; block subsets were analyzed for individual years and for analysis of LAI change between

Table 2
Blocks in which LAI was measured and for which LAI data were analyzed

Blocks	Damage (%)	Blocks where LAI was measured		
		1999	2000	2001
1	68	(x)		
2	69	x		x
3	41	x	x	x
5	10		(x)	(x)
6	9		(x)	(x)
7	34		x	
8	37		x	(x)
9	61	x	x	x
10	17		x	
11	60		x	(x)
12	64	x		x
13	51		x	(x)
14	70		x	(x)
15	37	x		x
16	56		x	(x)
17	21		x	(x)
19	10		(x)	(x)
20	10	(x)		
21	77	x		x
22	32		x	(x)
23	35	x		x
24	45	x		x
25	28	x		x
26	62	x		x
27	69	x		x
28	29	x		x
29	35	(x)		
30	72	x	x	x
31	6	x	x	x
32	12	x		x
39		x	x	x
40	35	x	x	x
41			x	(x)
42	64	x	x	x
43	46	x	x	x
44		x	x	x
N	33	23	22	31
Mean % damage	42	46	39	43

(x): removed from analysis, see Section 3.2.

years. Table 2 shows the blocks measured in each year. Twenty-three of the 36 blocks were measured in the summer of 1999, and the remaining 13 blocks were measured in 2000. Nine of the blocks that were measured in 1999 were re-measured in 2000 and 2001. In 2001, 31 blocks were measured, 20 of which had been measured in 1999, and 20 in 2000.

Every effort was made to re-measure blocks in 2000 and 2001 at the same time of day and on the same date as in 1999. In many plots, LAI was measured more than once during a single day or measured on a few days to evaluate the TRAC instrument precision and sensitivity to solar zenith angle (Olthof et al., 2001). Where such repeat measurements were taken, an average was calculated to represent LAI of the plot for that year.

3.2.1. *LAI samples analyzed*

Percent crown loss for samples of blocks in which LAI was measured in more than 1 year revealed differences among samples. The sample of 20 blocks used for the 1999–2001 change analysis had a higher mean percent crown loss than all blocks combined ($N = 33$), while blocks measured in 2000 had a lower percent crown loss. The net effect was that the two samples means were 1.86 standard scores apart. To mitigate this problem, three blocks (5, 6, 19) from the 2000 sample that had the lowest damage and that could not be used in the 1999–2001 change analysis (they were not measured in 1999) were removed. The remaining 19 blocks that were used as the 2000 LAI measurement sample had a similar distribution of damage scores to the 1999–2001 sample (Table 2). Other blocks were removed from the 1999 or 2001 sets if they were not measured both years.

3.3. *Ground vegetation survey*

Near-ground vegetation survey data were collected by the OMNR during the summer of 1999 (second growing season after the storm) and 2001 (fourth growing season after the storm). A line intercept method (Canfield, 1941) was used along randomly located lines in each plot.

In 1999, near-ground vegetation was surveyed along five 10-m lines per plot. In 2001, the number of lines was increased to 20 per plot, while each line measured 5 m in length. This change was made in order to better capture the species richness of near-ground vegetation in 2001, and was not considered to have produced any bias in ground vegetation cover between years. Vegetation was recorded by species and layers as well as the start–end distance in centimetres on each line. All green or mostly green vegetation less than 7 m in height that crossed the line (projected vertically) was recorded. A metre stick and height pole were used to determine vegetation heights, which were subsequently assigned to one of three layers (0.0–0.5, 0.5–2.0, and 2.0–7.0 m) (Lautenschlager et al., 2003). Because the TRAC was held at 1.5 m height, only the ground vegetation surveyed in the 2.0–7.0 m layer that was 'seen' by the TRAC was used in this analysis.

3.3.1. Calculation of ground vegetation LAI

Near-ground vegetation LAI was calculated using Eq. (1) and subtracted from the total canopy LAI above 1.5 m (hereafter termed 'total LAI') as measured by the TRAC. For Eq. (1), the understory gap fraction and $G(\theta)$ parameters had to be determined.

To determine understory gap fraction an analysis of the line-intercept ground vegetation data was conducted. Because near-ground vegetation distances were recorded along each line (L) by species (Sp) as well as by layer, plots could have overlap (Ov) between different species occurring in the same layer. A schematic illustrating such conditions is presented in Fig. 2. This resulted in percent cover values exceeding 100% in cases where the overlap between species exceeded the gap fraction. Therefore, overlap between species was eliminated on a plot-by-plot basis to obtain near-ground vegetation gap fraction estimates.

Start and end distances of ground vegetation interception on a line were provided in a spreadsheet for each species occurring in each layer. The data were sorted in ascending order by line number and by start distance along the line. A set of fields consisting of Boolean operators was used to determine overlap given all possible combinations of species occurrence within the layer. Total overlap was summed for all lines within a plot and was subsequently subtracted from the sum of distances obtained from the start and end points to obtain vertically projected cover of all species along all lines. Subtraction of cover from the summed length of all lines, divided by the summed length of all lines gave the understory gap fraction (Eq. (3)).

$$\mathrm{GF}_{\mathrm{understory}} = \frac{\left[\sum_{i=1}^{m} L_i - \left(\sum_{j=1}^{n} \mathrm{Sp}_j - \sum_{k=1}^{\mathrm{Ov}} \mathrm{Ov}_k\right)\right]}{\sum_{i=1}^{m} L_i} \tag{3}$$

where GF is plot gap fraction; L line length for lines $i = 1$ to m in a plot; Sp species intercept length along line L for intercept lengths $j = 1$ to n; and Ov is overlap length between species for overlap lengths $k = 1$ to Ov.

The projection coefficient, $G(\theta)$, varies slightly with zenith angle for an assumed spherical foliage distribution (Warren-Wilson and Reeve, 1959). Near-ground vegetation gap fraction was obtained vertically (i.e. at 0° zenith), while the TRAC data were obtained at a mean zenith angle of 40°. The projection coefficient, $G(\theta) = 0.5$, for the TRAC data assumed a spherical foliage distribution. For the understory vegetation, $G(\theta)$ was obtained from a graph in Welles and Norman (1991) showing changes in the projection coefficient with zenith angle for different mean leaf angles. The curve for which $G(\theta) = 0.5$ at 40° zenith angle corresponded to a mean leaf angle of 45°. This curve was

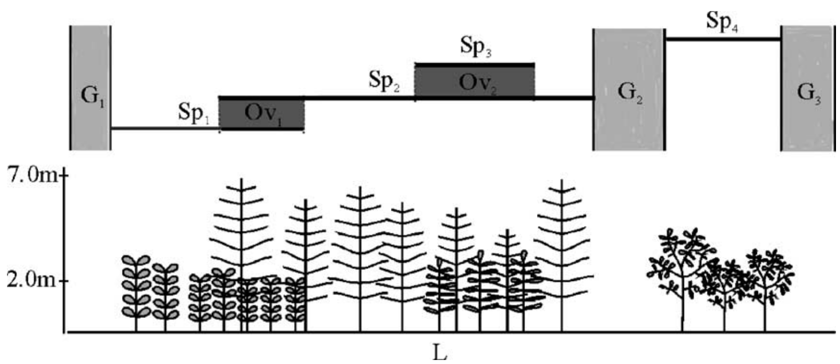

Fig. 2. Understory vegetation gap fraction (GF) calculation from line intercept data of length L. Species 1–4 intercept along segments Sp_{1-4}, with overlap between species 1 and 2 at Ov_1 and between species 2 and 3 at Ov_2.

projected to a zenith angle of 0° (vertically) to give $G(\theta) = 0.6$ for the understory.

To use Eq. (2) for conversion of effective LAI from Eq. (1) to actual LAI, clumping indices for understory vegetation in each plot had to be determined. The clumping indices obtained from TRAC measurements of the entire canopy above 1.5 m were assumed to be representative of the understory 2.0–7.0 m layer. Mean clumping values were 0.83 in 1999, increasing to 0.86 in 2001, which is not significant but may indicate a trend towards increasing gap size randomness since the ice storm. Typically, clumping values varied by less than 5% within a given year for a given range of solar zenith angles, producing similar variations in LAI calculated from effective LAI using Eq. (2). When subtracting understory LAI from total LAI, the effects of errors in the assumed understory clumping indices should not be great since understory contributions to total LAI were low compared to overstory contributions.

3.4. TRAC precision analysis

The repeatability of TRAC measurement is mainly influenced by: (1) deviations from the assumed random leaf angle distribution (with associated projection coefficient $G(\theta)$ of 0.5), (2) the portion of the canopy being sampled (which can vary during the 4 h measurement window), and (3) phenological stage. The first two are related to the time of day, while the latter is related to the date in the growing season that measurements are taken (given that phenology can vary year-to-year based on climate conditions). As a result, there is a certain amount of variability in TRAC LAI measurement, which can be quantified by repeatedly sampling single plots.

To address precision related to sun angle (1 and 2 above), Olthof et al. (2001) sampled 29 plots repeatedly (either two or three times) within the 2000 growing season. Eighteen of the 29 plots had repeated measurements taken at different times during the same day, while the remaining 11 plots had repeated measurements taken over a span of several days over which LAI was assumed to remain constant.

The differences of repeat TRAC measurements ($N = 112$) formed a precision distribution that was normal. The two-tailed 95% confidence limits for the precision distribution were determined, from the standard deviation ($\pm 1.96 \times \sigma$), to be ± 1.20, and were confirmed by 104 of 112 (93%) of repeat differences within the calculated 95% confidence interval. This error represents 23% of the mean LAI measured in 2000, and is similar to the 1σ range of 14% for broadleaf stands reported in Fernandes et al. (2001).

In evaluation of phenological effects, analysis of variance revealed that changes in solar zenith angle caused the largest variation in repeated differences, as within day repeated measurements exhibited greater variance than among dates (F-test, $\alpha = 0.08$) (Olthof et al., 2001). Leblanc and Chen (2001) showed seasonal LAI variation measured with the LAI-2000 under diffuse illumination conditions in two temperate deciduous forests. Between 13 June 1997 and 5 September 1997 (the typical summer growing season as used in this study) they found that LAI varied by 1.2 and 0.9 at the two sites, peaking in mid-July and gradually declining until mid-September. Olthof et al. (2001) also show that between-season LAI change after a disturbance such as the ice storm is great enough to mask within-season LAI variability due to phenology and the sun's position.

3.5. LAI change analysis

Total LAI change was evaluated between consecutive years and for the period from 1999 to 2001. For the 20 blocks (80 plots) measured in 1999 and 2001, the understory vegetation data were used to separate the contributions of understory and overstory layers to total LAI and to LAI change. Total LAI measured with the TRAC in 1999 and 2001 was converted to overstory LAI by subtracting understory contributions to LAI obtained from ground vegetation surveys in those years. LAI change was calculated by subtracting 1999 LAI from 2001 LAI ($2001_{LAI} - 1999_{LAI}$) on a plot-by-plot basis for overstory and understory layers separately. Positive change indicated an increase in LAI while negative change indicated a decrease in LAI in the 2-year period.

The significance of the observed change was evaluated using the TRAC precision distribution of repeat differences as determined in Olthof et al. (2001). Only overstory change was evaluated in this manner, and did not account for precision errors in the measurement of ground vegetation. It was assumed that since ground vegetation was measured directly, there would

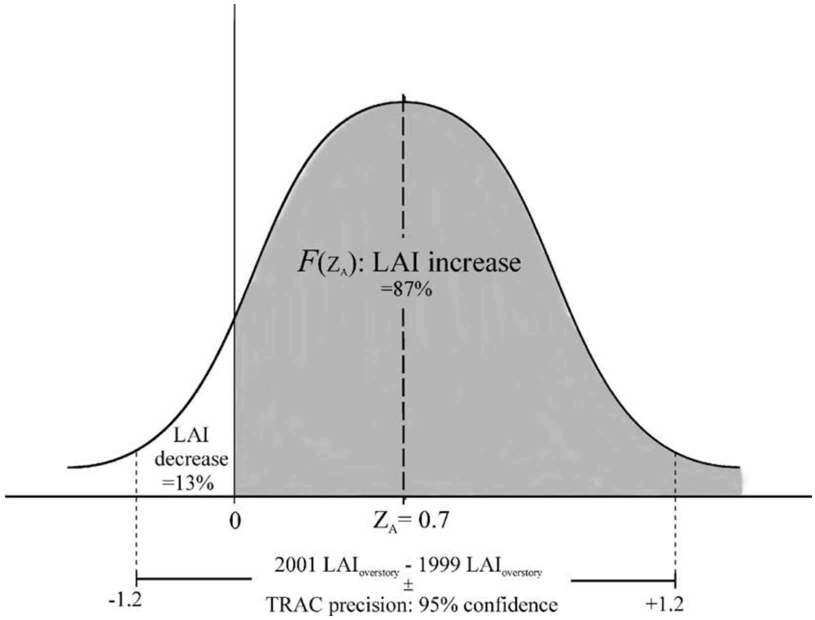

Fig. 3. Example of 1999–2001 LAI change ($Z_A = 0.7$ LAI increase) with 95% confidence interval of measurement precision indicating certainty of measured LAI increase in the grey area.

be relatively little error in its measurement. Percentage certainty with which LAI increased or decreased, based on a one-tailed normal probability distribution of repeat differences (precision) was assigned to each plot (Fig. 3).

3.6. Percent LAI change

The damage measure used in this study is a normalized measure of crown loss since it is estimated relative to a pre-disturbance crown volume. LAI change should also be normalized in order to make a comparison with damage more relevant and meaningful. Because pre-storm LAI data were unavailable, overstory and total LAI change were normalized by dividing the 2001–1999 LAI differences by the 2001 LAI data, which should most closely approximate pre-storm LAI due to an overall increase since the ice storm. Understory LAI was normalized in a similar fashion with 1999 understory LAI data, which should most closely approximate pre-storm understory LAI. However, in the field we noticed a very dynamic and immediate response of understory vegetation to increased light levels, leading to the suspicion that 1999 understory LAI may have changed too much since the ice storm to be a useful approximation of pre-storm LAI. By normalizing LAI change in this manner, percent crown loss was compared to percent LAI change, both relative to an estimated pre-storm condition.

3.7. Statistical analyses

Pearson correlation analysis was used to evaluate relations between 1998 crown loss (damage) as the dependent variable and the following variables: single date total LAI for 1999, 2000 and 2001, and absolute and relative change in overstory, understory and total LAI for the period of 1999–2001. The difference in measurement scales between damage estimated at the crown level, and single date canopy LAI was not expected to produce strong (predictive) relations between the two measurements. Relations were evaluated instead for the ability of LAI to act as an indicator of damage for monitoring recovery. Therefore, all significant ($P < 0.05$) relations are reported, regardless of their strength.

Separate two-way analyses of variance (ANOVA) were used to determine if understory or overstory

LAI change was related to plot treatment, with blocks as replicates in a randomized design (Snedecor and Cochran, 1980). Assumptions for ANOVA include normality of observations on the dependent variable within each group and homogeneity of variance (equal population variances) among groups. Because group sizes were constant at 20 plots per treatment and 4 treatments per block, neither within group variance nor normality were considered to significantly affect the actual type I error rate (Stevens, 1992). Scheffe's post hoc test assuming equal variances was used to determine if any significant differences existed between individual treatment pairs.

4. Results and discussion

4.1. LAI change

4.1.1. Aggregated results

Average total LAI increased from 4.54 in 1999 to 5.25 in 2000, and again to 5.52 in 2001 (Table 3). LAI increment was more than 2.5 times as great between 1999 and 2000 (0.71) as it was between 2000 and 2001 (0.27). This indicates that LAI may be stabilizing to pre-ice storm levels four growing seasons after the event. Lower LAI increment between 2000 and 2001 was also due to a drought that affected eastern Ontario in the summer of 2001 (Parker and Lautenschlager, 2002), causing many trees to shed leaves. Further analysis of its effect is given in 4.1.3.

LAI increases were noted between 1999 and 2001 for both understory and overstory layers separately, contributing to a mean total LAI increase of nearly 1.0 (Table 3). In absolute terms, understory LAI contributed about 0.44 to the increase in total LAI and overstory contributed the remaining 0.54. In relative terms, understory LAI increased by nearly 300%, while overstory increased by approximately 13%.

Table 3
From 1999 to 2001 average plot LAI by layer ($N = 80$)

	Understory		Overstory		Total		
	1999	2001	1999	2001	1999	2000[a]	2001
Minimum	0	0.19	2.63	2.59	2.87	2.99	3.16
Maximum	0.8	1.4	6.49	6.98	6.67	7.06	7.89
Mean	0.23	0.67	4.31	4.85	4.54	5.25	5.52

Understory vegetation survey was not conducted in 2000, thus only total LAI as measured with the TRAC is shown for that year.
[a] $N = 76$.

These results indicate that leaf area is recovering from damage suffered during the 1998 ice storm event in the majority of sugar maple plots. The dramatic increase in understory LAI was caused mainly by increased light levels reaching this layer (Parker and Lautenschlager, 2002), and is supported by the significant relation between damage and 2001 understory LAI (see below). It is suspected that much of the understory measured in 2001 was already established in 1999 but was too short to be detected by the TRAC. This is confirmed by a significant decrease in the 0.0–0.5 m ground vegetation layer abundance from 1999 to 2001, which is likely caused by increased shading from the layers above. These results are similar to those of King et al. (2002), for an ice storm study in southern Quebec, which showed that established near-ground vegetation took advantage of increased overstory openness, producing large increases in height and foliage in the 1998–2000 period, while new ground vegetation amounts decreased.

The contributions of understory and overstory to the overall increase in LAI correspond to light attenuation in forested canopies. Overstory layers, which receive the most direct sunlight have exhibited greater absolute increases in LAI, while understory layers immediately below have increased slightly less. Both layers respond to damage, with understory responding more than overstory in relative terms, while overstory has responded more in absolute terms.

4.1.2. Individual plot analysis of LAI change

Individual plot LAI response varied between 1999 and 2001 for both overstory and understory layers (Table 4). In 20 of 80 plots, overstory exhibited decreased LAI, while understory LAI decreased in only three plots. Although 25% of plots showed reduced overstory LAI, we were 95% certain in only four cases that the observed decreases were real based on the measurement precision of ± 1.2. Relaxing this strict confidence definition to a lower but still reasonable level of 80%, the number of plots showing real decreased overstory LAI was 10. If plot LAI responses are considered to be representative of block health, then block 15 appears to be declining, as three of four treatment plots have decreased LAI beyond 95%

Table 4
Understory and overstory LAI change (1999–2001) by treatment

Blocks	Treatment A			Treatment B			Treatment C			Treatment D		
	Understory	Overstory	Overstory significance (%)	Understory	Overstory	Overstory significance (%)	Understory	Overstory	Overstory significance (%)	Understory	Overstory	Overstory significance (%)
2	0.49	0.88	93	0.84	0.39	74	0.54	0.59	83	0.61	0.53	81
3	0.32	0.45	77	0.89	1.00	>95	0.60	−0.38	74	0.19	−0.03	52
9	0.49	1.49	>95	0.13	1.17	>95	0.56	2.34	>95	0.86	1.60	>95
12	0.45	0.92	94	0.24	2.63	>95	0.31	1.20	>95	0.83	0.39	74
15	0.41	−0.32	70	0.96	−1.46	>95	0.39	−1.52	>95	0.69	−1.03	>95
21	0.42	0.92	93	0.13	1.30	>95	0.09	1.04	>95	0.57	2.32	>95
23	0.52	0.85	92	0.70	0.97	95	0.79	0.54	81	0.84	1.44	>95
24	0.00	0.69	87	0.17	0.94	94	0.12	0.83	92	0.52	0.42	76
25	0.74	−0.63	85	0.17	−0.64	85	−0.18	0.06	54	−0.03	−0.27	67
26	0.39	1.14	>95	0.84	0.74	89	0.43	1.15	>95	0.42	1.70	>95
27	0.85	0.55	82	0.18	0.84	92	0.53	0.33	71	0.46	−0.06	54
28	0.22	−0.04	52	0.25	2.25	>95	0.30	0.09	56	0.70	−0.88	93
30	0.76	0.68	87	0.23	1.48	>95	0.55	0.98	>95	0.43	1.20	>95
31	0.06	0.53	81	0.26	0.06	54	0.31	0.32	70	0.04	0.43	76
32	0.28	−0.24	65	−0.01	0.52	81	0.26	0.48	78	0.15	0.72	88
39	0.54	0.52	81	0.31	−0.69	87	0.81	1.54	>95	0.44	0.09	56
40	0.11	0.51	80	0.30	−0.67	86	0.55	−0.07	54	0.20	0.80	91
42[a]	0.73	1.26	>95	1.04	1.01	>95	0.63	1.05	>95	0.89	0.38	73
43[a]	0.42	2.25	>95	0.59	0.16	61	0.20	0.60	84	0.75	−0.08	56
44[a]	0.25	−0.78	90	0.48	−0.26	67	0.48	−1.08	>95	0.37	0.37	73
Mean	0.42	0.58	83	0.43	0.59	83	0.41	0.51	80	0.50	0.50	79

The significance level of measured overstory LAI change is also noted based on the precision analysis described in the text.

[a] Herbicide blocks.

certainty, while the control plot has also declined though not as significantly. At 80% certainty, blocks 25 and 44 displayed decreasing LAI in two of four blocks.

Twenty-seven of 80 plots exhibited increased overstory LAI beyond the 95% certainty threshold. Blocks 9 and 21 improved by more than this threshold in all four plots, while blocks 12, 23, 26, 30, and 42 increased by at least this amount in three of four plots. At 80% certainty, the number of plots showing increased overstory LAI was 36. All plots in blocks 9, 21, 23, 26, 30, and 42 were deemed to have increased in LAI beyond the 80% threshold, while three of four plots increased in blocks 2, 12, and 24.

4.1.3. Effects of drought on 2001 LAI

To examine the effect that drought may have had on LAI in the summer of 2001, LAI measured in 2001 was plotted against the measurement day since 1 January 2001 (Fig. 4). A significant relation between LAI and measurement date ($R = -0.361$, $N = 124$) existed, indicating a trend of decreasing LAI later into the summer. This relation may simply have been due to bias in the selection of measurement dates for higher and lower LAI plots, or to changes in the sun's position over the course of the summer. However, when 1999 and 2000 LAI plot data were arranged in the order of the 2001 measurement date, the same decreasing trend was not observed. Therefore, no bias was introduced, suggesting that the trend of decreasing LAI late into the growing season must have been due to drought.

The effects of drought can also be assessed by examining Fig. 5. The intercept of a best-fit line through the data on the LAI change axis indicates that for an undamaged stand, a LAI decrease of approximately one was expected. The effects of the drought on LAI change were removed by regressing LAI change against damage, and adding the residual variation to a baseline LAI value obtained from the mean LAI of blocks 11, 39 and 41, which were measured in late June before the drought. A drought factor was obtained by calculating the percent increase of total LAI after the correction, and this factor was applied to understory and overstory LAI separately, assuming that both layers were equally affected.

An examination of the descriptive statistics of 2001 LAI measurements obtained after the drought was accounted for revealed an increase in total LAI between 2000 and 2001 of 0.54, which was closer to the 0.71 increase observed between 1999 and 2000 (Table 5).

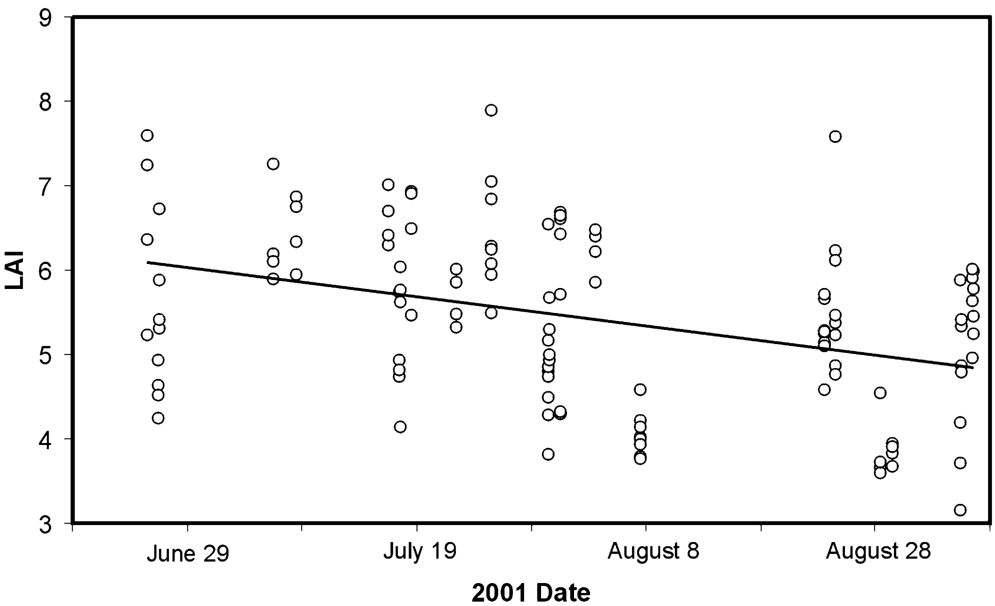

Fig. 4. LAI measurement through the summer of 2001 shows decreasing LAI late into the growing season. Julian day and month are shown on the *x*-axis.

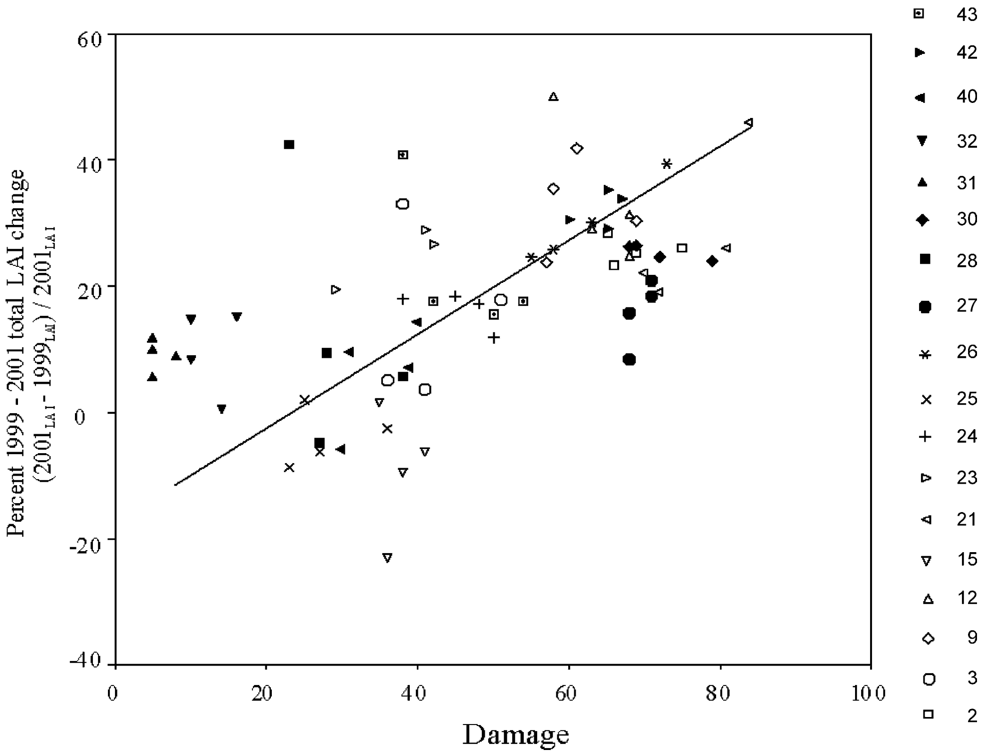

Fig. 5. 1999–2001 percent total LAI change vs. 1998 visual crown loss estimates (DAMAGE). Block numbers are noted on the right side, with the four plots per block represented by the associated symbols in the graph.

The intercept of LAI change plotted against damage was close to zero after the application of the drought correction. However, given the noise in the data presented in Fig. 5, the correction was not perfect and did not significantly improve 2001 LAI or LAI change relations with damage. Thus, all relations presented in this paper are of non-drought corrected data.

Fig. 4 shows mean LAI decreasing linearly from approximately six in late June to five in early September. Block 15 was measured on July 31 in 2001 at almost the midpoint of the 2001 measurement period. Therefore, we could expect approximately half a unit of leaf area decrease to be accounted for by the drought. The removal of the effect of drought from LAI decrease by applying the drought correction to block 15 reduced the number of plots in significant decline beyond the 95% confidence interval from three to two.

Table 5
2001 average plot LAI data after drought correction ($N = 80$)

	Understory	Overstory	Total
Minimum	0.22	3.13	3.94
Maximum	1.45	7.07	8.18
Mean	0.70	5.09	5.79

4.2. LAI and LAI-change relations with damage

4.2.1. Annual LAI versus damage

Table 6 shows significant relations between single year LAI measurements and damage. Overstory LAI and total LAI for 1999, and total LAI for 2000 were significantly ($P < 0.01$) related to 1998 crown loss estimates. The 2001 overstory LAI and total LAI were not significantly related to damage. This demonstrates that in the second and third summers following the ice storm, LAI is a good indicator of damage estimated in the autumn immediately following the ice storm event. As the canopy responds by recovering, stabilizing,

Table 6
Significant Pearson correlations (r) between damage and LAI ($N = 72$)

	1999		2000[a]	2001
	Overstory	Total	Total	Understory
Damage	−0.445	−0.448	−0.323	0.28
Significance (two-tailed)	<0.001	<0.001	0.007	0.017

[a] $N = 68$.

or declining further, LAI gradually explains less of the variation in the initial damage condition. By the fourth summer, LAI no longer accounts for a significant amount of variance in the 1998 damage estimate. The reduction in the amount of damage variance accounted for by LAI through time indicates progressive LAI change between seasons, so that by the fourth summer after the ice storm LAI is measuring a canopy condition that is different from the damaged condition immediately following the storm.

Understory LAI in 2001 was also significantly related to damage. This relation shows the response of understory vegetation to increased light levels caused by canopy damage. Thus, understory generally received more light in highly damaged plots (Parker and Lautenschlager, 2002) and responded with relatively high LAI increment.

4.2.2. 1999–2001 LAI change versus damage

The significant relations between damage and 1999–2001 LAI change in understory, overstory and total canopy layers (Table 7) indicate a dependence of LAI change on the degree of damage sustained. These direct relations show that more heavily damaged plots are responding with greater increases in LAI than less damaged plots and are therefore recovering in the short term. Percent LAI change of overstory and total canopy layers was more significantly related to damage than absolute LAI change. For understory LAI, absolute change was significantly related to damage, while percent LAI change was not. This confirms our suspicion of the inappropriateness of 1999 understory LAI as an approximation of pre-storm understory LAI due a time lapse of more than one full growing season between the storm and the 1999 understory vegetation survey, and the dramatic response of understory vegetation to overstory damage. Plots from block 15 appear below the best-fit line between damage and percent change in total LAI (Fig. 5) and have decreased overstory LAI (Table 4). Overstory LAI of the four plots from block 15 does not appear to be recovering from moderate damage sustained, while understory vegetation is increasing as in most other plots.

Results outlined above suggest that percent change in total canopy LAI is a better indicator of ice storm canopy damage than any of the single date measures to which it was compared. However, LAI measurements were only initiated in the second growing season after the ice storm and progressive change in LAI was noted between successive summers. If LAI were measured in the first growing season following disturbance, it alone may have been a good indicator of damage, and changes in LAI in subsequent years may have provided even stronger relations with damage than those found here. In addition, change in LAI over longer periods normalized to a future year when LAI is more certain to have stabilized should provide stronger relations with damage.

When forest damage needs to be assessed, a baseline of pre-event data is rarely available to determine the magnitude of change caused by any particular disturbance. Instead, LAI response can be monitored as an indicator of recovery, and to project back in time to estimate damage incurred. Such projections will not

Table 7
Pearson correlations (r) between damage and 1999–2001 LAI change ($N = 72$)

	Absolute LAI change			Percent LAI change[a]		
	Understory	Overstory	Total	Understory	Overstory	Total
Damage	0.351	0.422	0.518	0.159	0.445	0.561
Significance (two-tailed)	0.003	<0.001	<0.001	0.188	<0.001	<0.001

[a] See Section 3.6.

likely replace visual estimation of crown loss on an operational basis because the latter is easier to obtain. However, they will provide a means to study the cycle of LAI increase, stabilization, and decrease due to disturbance.

Sugar maples have no specific adaptations worth mentioning to cope with ice storm damage, though there is little doubt that they have developed a certain resilience, not to damage itself, as they have consistently been classified as intermediate to highly susceptible to damage from ice loading (Hauer et al., 1994; Van Dyke, 1999), but in their ability to recover better than certain other species, depending on site and vigour prior to damage (Boulet et al., 2000). On a suitable site for maple growth, trees can lose between 50 and 75% of their crown and may still survive with varying degrees of infection and growth suppression. Above 75% crown loss, trees have a low chance of survival (Coons, 1999; Boulet et al., 2000). In this study, 7 of 20 blocks used for the temporal analysis had greater than 50% crown loss, and one had more than 75% crown loss. Therefore, the probability of survival for the trees in this study is generally quite high, and the relations between damage and LAI change might not apply to more heavily damaged stands than those used in this study. However, because maples are shade tolerant causing a wide age distribution in natural stands, it is strongly suspected that there should almost always be sufficient sub-canopy maple for stand-level LAI to increase immediately following severe ice storm damage. In this study, the most heavily damaged block (#21), in which probability of tree mortality should have been high due to 77% average crown loss, experienced some of the largest increases in overstory LAI from 1999 to 2001.

4.3. Treatment effects on LAI change

Plot LAI response by treatment revealed slight differences among treatments for both overstory and understory layers (Table 4). Two-way analysis of variance revealed significant differences among blocks, but none among treatments. Scheffe's post hoc tests showed no significant differences between treatment pairs for any possible overstory or understory treatment combination. Therefore, no treatment effects on LAI response have been detected to date.

5. Conclusions

Optical measurement of LAI is a useful indicator for monitoring canopy response to structural damage suffered from a catastrophic disturbance, such as an ice storm. LAI measurement with the TRAC has been demonstrated to be sufficiently accurate as an indicator of damage, because it is significantly related to the initial damage condition in spite of discrepancies between the scales of crown and canopy measurements. Total LAI measured by the TRAC changed progressively through time, from the damaged condition following the event to one that is not significantly related to the initial damage estimate 4 years later. Between-season LAI change suggests that measurement immediately after a disturbance may be a better indicator of damage than measurement 1 year later, as was tested here. It can also be concluded that LAI change is a better indicator of damage than any of the single date LAI measurements to which it was compared. When all plots were combined, LAI increased in both understory and overstory layers through time, leading to the conclusion that overall, forests are recovering in the short term from ice storm damage. By examining LAI change on a plot-by-plot basis in relation to LAI measurement precision, a confidence level was assigned to the observed changes for each plot. Seasonal weather variation such as drought can affect LAI and perhaps mask the longer-term trend towards recovery in certain cases. Therefore, a longer temporal series of measurements is required to fully evaluate recovery relative to pre-disturbance LAI. Finally, no treatment effects on LAI response were observed, although this might also require a longer time series of LAI measurements.

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