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Report

Landscape fragmentation and ice storm damage in eastern ontario forests

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Abstract

With return times between 20 and 100 years, ice storms are a primary disturbance type for temperate forests of eastern North America. Many studies have been conducted at the forest patch and plot scales to examine relations between damage and variables describing site, composition and structure. This paper presents results from a landscape scale study of fragmentation relations with damage in eastern Ontario forests. Data previously collected for two independent and spatially non-overlapping patch level damage studies were used. A Generalized Linear Model (GLM) was used to analyse relations between damage and fragmentation metrics representing patch isolation, edge density, and the relative size and distribution of patches in the landscape. The metrics were applied using spatial extents of 1×1 km and 4×4 km, following analyses of the variability of numbers of patches and of the lacunarity of forest patterns over a range of extents. The results showed that patch isolation, as measured by the mean Euclidean distance between patches (ENN) was significantly related to damage.

Introduction

Study of the spatial variability of damage caused by large infrequent disturbances can contribute to the development of understanding of how such disturbances affect, or are affected by, landscape structure. They may 'interrupt ecosystem, community, or population structure and change resources, substrate availability, or the physical environment' (Turner 1989) on a much larger spatial and/or temporal scale than typical disturbances for a given region (Turner and Dale 1998). Due to interactions amongst biological and physiographic factors, damage and mortality are typically spatially heterogeneous (Foster et al. 1998; Turner and Dale 1998). Foster et al. (1998) suggest that a better understanding of disturbance interactions with landscape structure can improve our ability to interpret patterns of disturbance, reconstruct their occurrence, and predict their distribution in time and space.

Between January 5th and 10th, 1998, up to 100 mm of freezing rain was deposited over approximately 10 million hectares in eastern North America (Environment Canada 1998). The storm left many communities incapacitated, and large areas of forest severely damaged. Ice storms are considered to be a recurring disturbance type for the temperate forests of this part of the North American continent (Proulx and Greene 2001). Local ice storms occur with return times of 20–100 years, compared with similar types of natural disturbances, such as windstorms and fire, which have return times of 100–1000 years (Van Dyke 1999). Large-scale ice storms such as that of 1998 may, however, have return times of up to 500 years (Smith 1998), making an event of this spatial magnitude fairly unusual. This storm was the most spatially extensive ever recorded in North America and has been the subject of many studies of impacts on forest vegetation and of causal factors related to forest damage. Some characteristics relevant to this study are summarized below.

Ice storms generally occur as warm air rises over an area where the temperature has recently dropped below freezing. As the rain falls from the warm air mass through the cooler air mass, it becomes supercooled, and freezes as soon as it comes in contact with any surface that is below the freezing point (Lemon 1961; Hauer et al. 1994). Breakage of tree stems and branches from ice accumulation and wind is the most common type of damage incurred (Van Dyke 1999). Smith and Shortle (1998) state generally that trees with less than 50% crown loss should survive, while trees suffering 50–75% crown loss might experience long-term growth reduction, but most should survive. Greater than 75% crown loss is expected to result in only a small chance of survival. On the other hand, bending of branches is usually not fatal (Van Dyke 1999).

Forest damage following the 1998 ice storm was found to be highly variable and patchy over large regions (Pellikka et al. 2000) with significant spatial correlation of less than about 300 m (Millward and Kraft 2004). Plot and patch level research conducted after previous ice storms has found that the distribution of damage was related to numerous factors including elevation, slope aspect, and the direction and velocity of wind (e.g., Bruederle and Stearns 1985; Rhoads et al. 2002; Millward and Kraft 2004; Olthof et al. 2004; King et al. 2005). Studies of ice storm damage at forest edges versus interiors have shown either significant effects (Rhoads et al. 2002) or no effect (Proulx and Greene 2001; Millward and Kraft 2004) depending on the methods and scale of analysis. One factor that had not been directly investigated in such studies was whether landscape structure, specifically landscape fragmentation, could explain some of the regional variability of damage from the 1998 ice storm.

Research hypothesis and objectives

Urban and agricultural development across eastern Ontario has altered the landscape by reducing the amount of forest cover and patch sizes, while increasing the amount of forest edge (Wear and Greis 2002) and patch isolation. The research hypothesis was that forests in landscapes consisting of smaller, more isolated patches, with larger proportions of exposed forest edge to interior, were more damaged by the 1998 ice storm than forests in more homogeneous non-fragmented landscapes. The objectives were to: (1) determine the appropriate spatial extent surrounding each study site for calculation of fragmentation metrics, and (2) determine if forest damage was significantly related to metrics representing patch isolation, edge density, and patch size variability and distribution.

Methods

Study area and damage datasets

The study area of this research was eastern Ontario, Canada (Figure 1), an area of approximately 15,500 km^2. This region was ideal for studying the

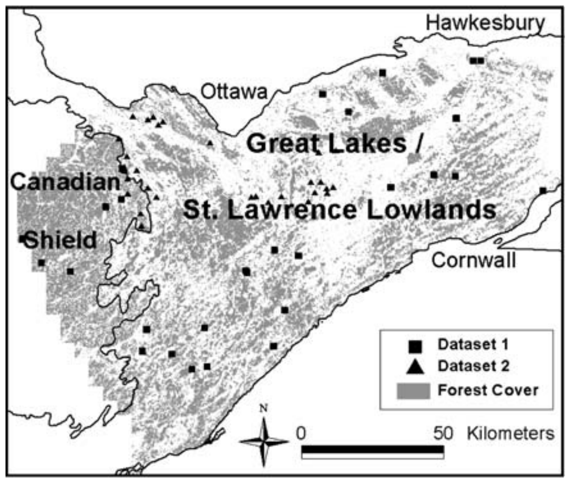

Figure 1. Forest/non-forest map of eastern Ontario, displaying the locations of study sites for Dataset 1 and Dataset 2, as well as physiographic region boundaries showing the Canadian Shield vs. Great Lakes/St. Lawrence Lowlands.

effects of landscape fragmentation as forest cover varied from about 60% in the north-western portion to less than 30% near the eastern boundary with Quebec (Lautenschlager and Nielsen 1999). Most forests in the region are dominated by sugar maple (*Acer saccharum* Marsh), with additional occurrences of other temperate hardwood species such as American beech (*Fagus grandifolia* Ehrh.), red oak (*Quercus rubra* L.), American basswood (*Tilia americana* L.), etc.

Two independent datasets were used. Dataset 1 consisted of visual crown loss estimates for thirty-eight 100 m $\times$ 100 m forest study blocks established by the Ontario Ministry of Natural Resources (OMNR) for a series of patch level studies on the ecological and economic impacts of the storm on maple syrup production (Lautenschlager and Nielsen 1999). Of the 38 study blocks, 27 were used that fell within the coverage of the OMNR forest/non-forest raster map (30 m $\times$ 30 m pixels) (Figure 1) that had been created from interpretation of 1991 1:10,000 air photos. For each block, the average of the damage estimates for 24 focus trees was used.

Dataset 2 was created by the Geomatics and Landscape Ecology Laboratory at Carleton University, Ottawa. It consisted of twenty-nine 1 km^2 landscapes (Figure 1) that had been established within approximately 60 km of Ottawa in 1997 for an unrelated seed dispersal study. After the ice storm, per cent crown loss was visually estimated for all trees with diameter at breast height (dbh) greater than 10 cm in 10 randomly located plots within each landscape (Charbonneau 2003). The average forest damage estimate for each landscape was used in this study.

Both datasets provided a wide range of average plot crown loss values from 6–77% (Dataset 1) to 6–59% (Dataset 2). However, they were acquired by different groups of field observers in completely different studies and no overlapping sites were available for cross-calibration. Thus, the damage values in the two datasets differed significantly.

Initial analysis of the OMNR forest map for the study region showed that the distribution of inter-patch distances decreased exponentially, as expected. Of 20,130 measured inter-patch distances, the maximum was 1.495 km, and only 10 patches were more than 1 km apart.

Determination of appropriate fragmentation metrics

The landscape metrics that were tested in this research were selected from the FRAGSTATS software package (McGarigal et al. 2002). From the many available metrics, a subset of four were used that represented complementary aspects of fragmentation. Mean Euclidean Nearest Neighbour Distance (ENN) and Edge Density (ED), two primary characteristics of fragmentation, were selected to represent patch isolation (average edge-to-edge distance of nearest neighbour patches) and the amount of forest edge per hectare, respectively. The other two metrics, Landscape Division Index (DIVISION) and Splitting Index (SPLITTING) are relatively new. McGarigal et al. (2002) pointed out that many metrics have been ‘criticized for their insensitivity and inconsistent behaviour’ across a wide range of fragmentation patterns. Jaeger (2000) introduced these two new metrics in order to overcome these limitations. DIVISION is based on ‘the probability that two randomly chosen places in the landscape are not situated in the same undissected patch’. SPLITTING is defined as ‘the number of patches one gets when dividing the total landscape into patches of equal size in such a way that the new configuration leads to the same degree of landscape division as obtained for the observed cumulative area distribution’ (see McGarigal et al. 2002 for more detail). Both of these metrics provide information on the degree of subdivision in the landscape, and are computed using the cumulative patch area distribution. Conventional measures of subdivision, such as mean patch size and patch density, are sensitive to very small patches, while these new measures overcome this, making the results more reproducible (McGarigal et al. 2002). Additional metrics could also have been used in this study, but initial evaluation of several others showed them to be highly correlated with each other.

Determination of an appropriate landscape extent for metric calculation

As the fragmentation metrics are calculated using data extracted from a specified area, it was necessary to determine an appropriate spatial extent that represented the variability of landscape patterns throughout the study region of eastern

Ontario. Non-appropriate scales may produce very different, and often meaningless results (McGarigal et al. 2002). In many studies, it has been common to calculate landscape metrics at many extents and then see which provide the strongest relations with the dependent variable. Alternatively, a set of extents may be selected logically if the scales of fragmentation effects are known. In this study, the spatial extent at which the selected fragmentation characteristics may be related to forest ice storm damage was unknown and an effort was made to avoid the arbitrary nature of processing metrics at many scales. Instead, a more deterministic methodology was implemented to select the most appropriate extents. The goal was to determine the spatial extent(s) that provided the largest variability of fragmentation over the study region for effective implementation of statistical modelling procedures.

Two methods were employed using the forest/non-forest map of eastern Ontario.

1. The variability (standard deviation) in the number of patches vs. spatial extent was analysed. As the number of patches continuously increased with increasing spatial extent, the standard deviation of the log-number of patches was used. The extent with the largest variation was selected to represent the range of landscape fragmentation in the study region.
2. Lacunarity analysis was used to determine the extent that displayed the greatest number of distinct forest/non-forest pattern scales (Plotnick et al. 1993; Butson and King 2005). The patterns of forest patches in the binary forest/non-forest map were processed using a common 'gliding box' algorithm as implemented by Butson and King (2005) from the formulation of Allain and Cloitre (1991). The slopes (first derivative) of the resulting lacunarity curves were plotted against spatial extent (i.e. the size of moving window) as recommended by Dale (2000). The break points or dips in these curves showed the extents at which given pattern scales were dominant in the map (Butson and King 2005). The optimal extent for processing the fragmentation metrics was taken as that with the most number of distinct pattern scales.

In the above analysis, a sampling approach was adopted as processing was very slow. Ten evenly spaced subsets were clipped from the map, each being 20 km $\times$ 20 km (667 $\times$ 667 pixels). Further subsets were then extracted representing square extents of 10, 5, 4, 3, 2, 1, 0.5, 0.27 km (9 $\times$ 9 pixels), 0.15 km (5 $\times$ 5 pixels), and 0.09 km (3 $\times$ 3 pixels), each centred within the previous subset.

Statistical modelling

In statistical modelling of fragmentation against damage, the average of the metric values within the 3 $\times$ 3 pixel area centered on each study site was used in order to account for any positional errors of the plots, as well as errors in the basemap. Each variable was checked for normality, and those that showed non-normal distributions were log-transformed. Correlation analyses were conducted to examine relations between metrics, as well as their relations with damage. Parametric and non-parametric methods were used where appropriate.

A Generalized Linear Model (GLM) was used to determine if combinations of fragmentation metrics were associated with damage, if any variability could be attributed to differences between the two datasets (highly expected due to differences in their acquisition), and if interactions between the dataset and metrics were significant. The *F*-to-enter value was 0.05 and the *F*-to-exit was 0.10. Model residuals were checked for normality.

Results and discussion

Extents used for calculating fragmentation metrics

The extents with the largest (log) standard deviation in number of patches were found to be 1 km $\times$ 1 km and 4 km $\times$ 4 km (Table 1).

The 10 lacunarity slope plots, produced for each of the 10 landscape subsets, showed forest pattern scales as break points, or dips in the curves. Each curve revealed at least one pattern scale but the curves for the 4 km $\times$ 4 km extent most consistently contained two (Figure 2). Both of these extents were used for calculating the fragmentation metrics.

Table 1. Standard deviation of the number of patches and of the log-number of patches for each extent.

Extent	St. Dev.	St. Dev. (log-nr patches)
20 km × 20 km (667 × 667 pixels)	172.18	0.12
10 km × 10 km (333 × 333 pixels)	54.88	0.17
5 km × 5 km (167 × 167 pixels)	17.86	0.22
4 km × 4 km (133 × 133 pixels)	18.82	**0.35**
3 km × 3 km (100 × 100 pixels)	6.28	0.25
2 km × 2 km (67 × 67 pixels)	3.95	0.25
1 km × 1 km (33 × 33 pixels)	3.35	**0.35**
0.5 km × 0.5 km (17 × 17 pixels)	1.40	0.28
0.27 km × 0.27 km (9 × 9 pixels)	0.82	0.19
0.15 km × 0.15 km (5 × 5 pixels)	0.57	0.13
0.09 km × 0.09 km (3 × 3 pixels)	0.42	0.00

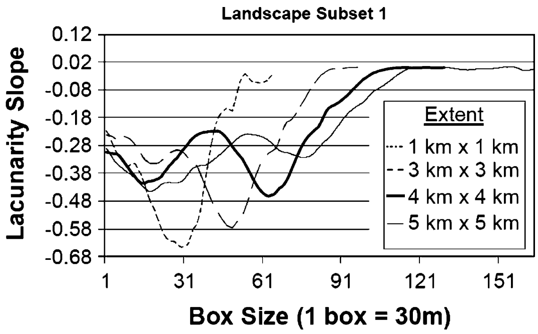

Figure 2. Example lacunarity slope plot for one of the 10 subset areas. A selection of extents from all those tested is shown to illustrate the pattern scales detected.

Correlation and GLM analysis

Correlations between metrics ranged from 0.06 to 0.77 for the 1 km × 1 km extent, while they ranged from 0.26 to 0.75 for the 4 km × 4 km extent. Both datasets showed that ENN at the 4 km × 4 km extent was significantly correlated with percent crown loss, and Dataset 2 revealed an additional but weaker relation with ED for this extent (Table 2). No significant relations were found using the 1 km × 1 km metrics for either of the datasets. For the 4 km × 4 km extent, the GLM analysis (Table 3) showed significant effects caused by the two datasets (p = 0.000). Once this was removed ENN showed significant explanation for the remaining variation in damage (p = 0.002). This GLM had an adjusted R^2 of 0.338, and the residuals were found to be normally distributed.

Figure 3 shows the independent relations between ENN and damage for each of the datasets. The relations are quite scattered and dependent on a few sites that were within the upper 5% of inter-patch distances in eastern Ontario. Removal of these points from the two datasets produced insignificant relations with damage. More samples of patches with such separations would be required to adequately confirm the relations.

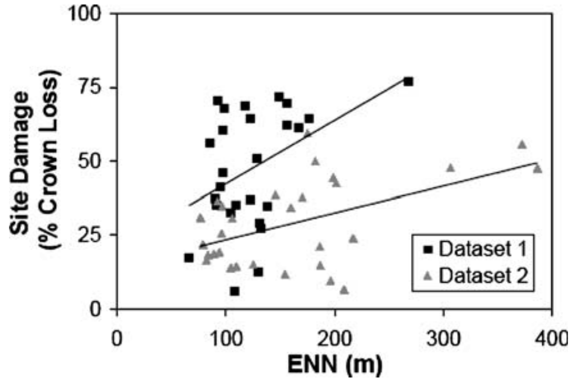

Figure 3. Relationship between ENN (4 km × 4 km extent) and damage for the two datasets. Note: The number of samples for Dataset 1 was reduced from 27 to 26 since one study block was too close to the study area boundary, making it impossible to calculate metric values for a 4 km × 4 km extent. Dataset 2 had 29 samples.

Other factors that may confound the ENN-damage relation

It was hypothesized that the ENN-damage relations found above may simply be surrogates for relations of other environmental and site variables with damage. The most plausible included elevation, distance to forest edge, ice accumulation, and wind. If any of these was also related to ENN, it could be the driving factor affecting damage instead of ENN. The first three of these were available for Dataset 1 and described in more detail in Olthof et al. (2004). Wind was not measured reliably across the large region of eastern Ontario due to icing of anemometers.

Elevation has been shown to be a factor in several studies. There was very little variation in elevation in Dataset 1, with all but six plots on an essentially flat plain with elevation variation of less than 100 m over an area of more than 15,000 km^2. Stepwise regression including elevation and ENN produced a model with elevation entered as the second variable without significant multicollinearity (R^2 = 0.41,

Table 2. Correlations between damage and metrics (calculated using 1 km and 4 km extents) for Dataset 1 and Dataset 2.

	1 km×1 km Extent		4 km×4 km Extent	
	r	*p*	*r*	*p*
Dataset 1				
ENN	– 0.29	0.17	**0.43**	**0.03**
ED	– 0.14	0.48	– 0.19	0.35
DIVISION	– 0.06	0.76	–0.21[a]	0.92
SPLITTING	0.06[b]	0.77	0.07[b]	0.75
Dataset 2				
ENN	0.22[b]	0.29	**0.52**	**0.00**
ED	– 0.12	0.39	– 0.40	**0.03**
DIVISION	0.35	0.06	0.23	0.24
SPLITTING	0.14[b]	0.47	0.31[b]	0.10

[a]indicates the use of non-parametric Spearman's Rank correlation.
[b]indicates log transformed independent variables.

Table 3. Generalized Linear Model (GLM) results.

Source	Type I sum of squares	df	Mean square	*F*	Significance
Corrected model	7583.562	2	3791.781	14.767	0.000
Intercept	78426.729	1	78426.729	305.421	0.000
Dataset	4705.437	1	4705.437	18.325	0.000
ENN4KM	2878.125	1	2878.125	11.208	0.002
Error	13352.677	52	256.782		
Total	99362.967	55			
Corrected total	20936.238	54			

$p = 0.00$). These results show that the ENN-damage relation found here is independent of elevation effects.

Distance to the nearest forest edge of the central point of the OMNR study blocks used here was not related to damage ($r = 0.02$; $p = 0.94$), nor to ENN ($r = -0.11$, $p = 0.59$). Similarly, for ice accumulation, the relations with damage ($r = 0.22$, $p = 0.28$) and ENN ($r = 0.13$, $p = 0.51$) were insignificant. Therefore, it was concluded that the relation between patch isolation and damage was not a surrogate for some other relation.

Conclusions

Landscape fragmentation relations with forest ice storm damage in eastern Ontario were investigated using a set of four complementary fragmentation metrics. They were calculated for spatial extents of 1 km×1 km and 4 km×4 km, which had been determined as most appropriate from forest map analysis of the variation in number of patches and of lacunarity slope curves. Significant relations between damage and patch isolation were found using a General Linear Model analysis. Further work is needed to confirm the association of isolation with damage using more samples of highly isolated patches. Conversely, it can be inferred that if patch isolation continues to increase in the region, a stronger association with ice damage from future storms may become evident.

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