Patterns of Forest Damage Resulting from Catastrophic Wind in Central New England, USA

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Summary

1. The effect of catastrophic winds on a forested landscape in central Massachusetts was examined to investigate the factors controlling the geographic pattern of damage. The study area, Tom Swamp Tract, Harvard Forest, comprises a valley and adjoining hillslopes supporting second-growth hardwood and conifer stands. Much of the study used records and maps that were analysed cartographically with a geographic information system (GIS).

2. Areally, forest damage was distributed fairly evenly among different damage classes ranging from no damage to more than 75% of stems broken or uprooted. However, there was a negative exponential size distribution of contiguous areas of the same damage intensity, with a preponderance less than 2 ha; These areas ranged from less than 0·04 ha to more than 35 ha; hurricane damage exhibited a continuum ranging from minor damage of individual trees to extensive blow-down of broad areas of forest.

3. The spatial pattern of wind damage was controlled by vegetation height and composition and by site exposure, which is predominantly determined by slope orientation and angle. Approximately 3% of the stands in the study site occupied protected sites, 31% intermediate sites, and 66% exposed sites.

4. Forest type susceptibility followed the ranking: *Pinus strobus* > conifer plantations > *Pinus strobus*–hardwood = *Tsuga canadensis*–hardwood–*Pinus strobus* > hardwood–*Pinus strobus* > hardwood. Damage increased with increasing site exposure to wind and increased approximately linearly with stand height.

5. An empirical GIS model of landscape-level response to wind was constructed based on other stands in the same township (not including the Tom Swamp Tract). Hurricane damage in these stands was analysed as a function of site factors (exposure) and vegetational factors (height and composition). Model predictions for the study area agreed well with observed effects, suggesting that a relatively small number of variables can be used to explain the damage in this topographically simple area. Significant variation in the predicted damage under different vegetational scenarios suggests that the landscape-level response to catastrophic wind may be highly sensitive to historical changes in vegetation.

Key-words: geographic information system, landscape patterns, spatial analysis, wind damage

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Introduction

One major conclusion of the numerous studies of natural disturbance in forested ecosystems is that repeated episodes of disturbance within a region may diversify vegetation on a landscape scale by creating a mosaic of patches of different age and successional status (Heinselman 1973; Johnson 1983; Pickett & White 1985). However, another component of the disturbance regime, namely the differential intensity of disturbance across the landscape, may be equally important in contributing to landscape diversity. Spatial variation in disturbance intensity may enhance vegetation diversity in the following ways: (i) the immediate aftermath of the disturbance may be a structural and compositional mosaic of patches, (ii) variation in environmental conditions, surviving vegetation, and availability of propagules in these patches may result in substantial differences in the pattern of vegetation development between patches, and (iii) recurrent effects of disturbance in a consistent manner across the landscape may produce gradients of vegetation and ecosystem characteristics that interact with inherent site conditions.

In the present study we examine some effects of catastrophic wind at a landscape scale in central New England. We seek to describe the consequences of a single disturbance, to find the underlying factors that control forest response to this disturbance, and to explore the ecological implications of these results. The research builds on studies of the disturbance history of the region (Foster 1988a) and species and stand-level response to wind (Foster 1988b). The focus of our investigation is the 1938 hurricane, the last catastrophic storm to affect this region.

RATIONALE FOR THE STUDY

There are three compelling reasons for investigating the landscape-level effects of the 1938 hurricane. First, hurricane damage has been an important factor influencing forest structure, composition and dynamics in this region (Smith 1946; Stephens 1955; Henry & Swan 1974; Foster 1988a). Storms of catastrophic magnitude struck southern and central New England in 1635, 1788, 1815 and 1938 (Perley 1891; Smith 1946). Secondly, although the effects of the storm on individual trees and forest stands have been described (Jensen 1941; Rowlands 1941; Foster 1988b) the way in which vegetation and site characteristics interact to control forest response to wind is very poorly understood. Finally, meteorological considerations suggest that the 1938 hurricane is representative of the major storms that have affected this region (Smith 1946). The geography of eastern North America and the meteorology of cyclonic storms constrain the pathway and wind distribution of the powerful hurricanes that enter New England. Therefore, results from the current study may have general implications for understanding the historical role of large disturbance processes in this area.

METEOROLOGY OF HURRICANES AFFECTING CENTRAL NEW ENGLAND

Tropical cyclonic storms travel one of four generalized paths across New England depending on their origin and the configuration of the North Atlantic high-pressure system (Fig. 1; Brooks 1939; Smith 1946):

1. from the Gulf of Mexico over the south-eastern United States and into the Atlantic off or north of Georgia;

2. inland between the Virginia capes and New York, and overland into New England;

3. over the Atlantic northward to the southern coast of Long Island and New England west of Cape Cod;

4. over the Atlantic but east of Cape Cod towards Maine or eastern Canada.

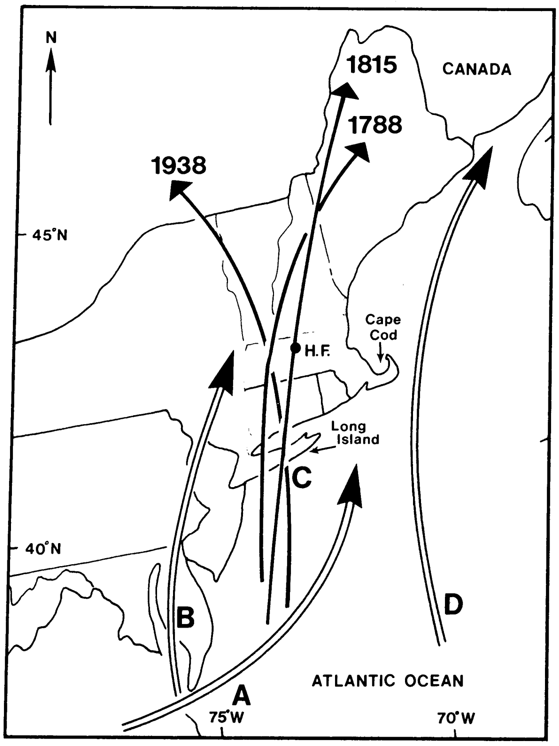

Fig. 1. North-eastern USA showing the four generalized pathways (A–D) that hurricanes follow into the region and the historical tracks of the hurricanes of 1788, 1815 and 1938 (pathway C). The location of the Harvard Forest (H.F.) is indicated by the circle. Modified from Smith (1946).

Of these storm systems, (3) is most likely to generate winds of catastrophic force in central New England. Storms travelling over land (1 and 2) tend to weaken rapidly because they are cut off from their primary energy source, warm ocean water, and because of increased surface friction. Storms travelling over water (3 and 4) may retain their full force at higher latitudes, especially if they move rapidly. In the Northern Hemisphere tropical cyclones rotate in an anticlockwise direction. Normally the highest winds are found on the right-hand side (with respect to the forward track), where the forward motion of the storm coincides with the rotational motion of the wind around the storm centre (Brooks 1939; Dunn & Miller 1964; Simpson & Riehl 1981). Consequently, the greatest wind damage to central New England should come from storms passing to the west (Fig. 1,C) with winds from the south to east, as verified in 1938 as well as in 1635, 1788 and 1815 (Smith 1946; Stephens 1955).

REGIONAL EFFECTS OF THE HURRICANE OF 1938

The hurricane travelled across central Connecticut and Massachusetts to the north-west corner of Vermont (Fig. 1), preceded by 15–35 cm of rain and including winds in excess of 200 km h^{-1} (Brooks 1939). Forest damage was concentrated east of the

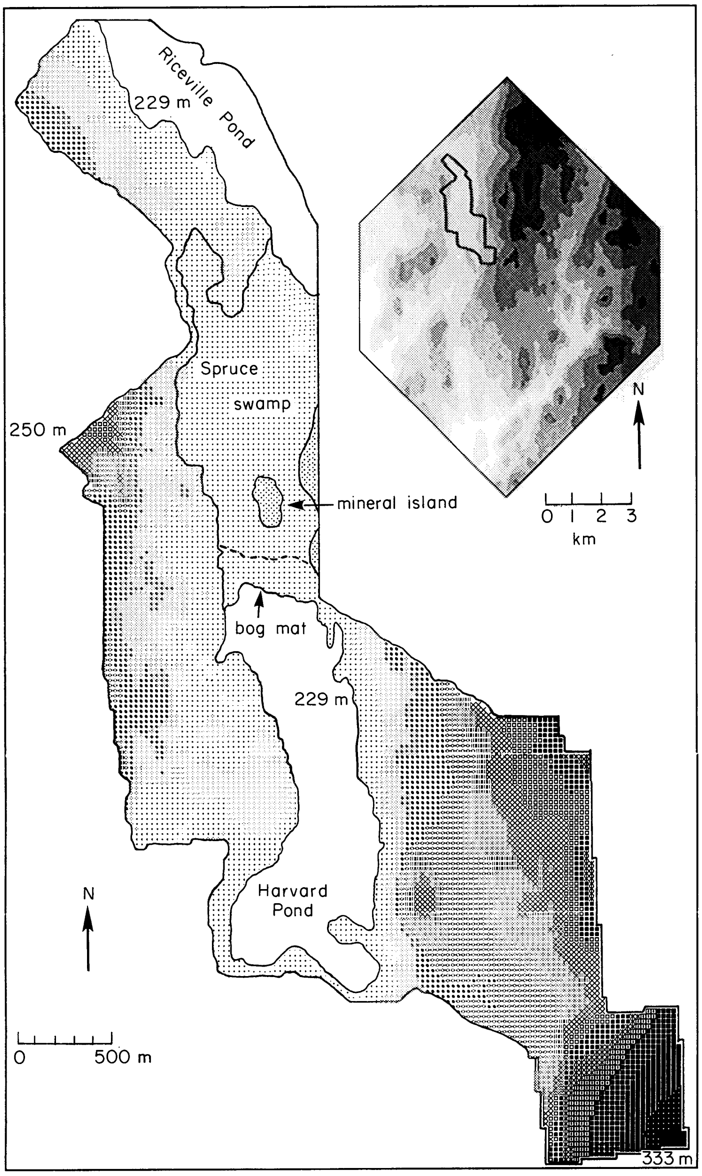

Fig. 2. Topographic map of the study area in the Tom Swamp Tract of the Harvard Forest showing the major physiographic features and altitude ranging from 229 m (white) to 333 m a.s.l. (black). On the inset map of the township of Petersham, Massachusetts altitude ranges from 180 m (white) to 420 m a.s.l. (black).

storm track, with the strongest winds coming from a south-easterly direction (Brooks 1939). The storm destroyed more than 4×10^9 board feet* of timber along a 150-km-wide path (NETSA 1943), including approximately 70% of the standing volume of timber at the Harvard Forest (Brake & Post 1941). The storm initiated even-aged stands that comprise a significant portion of the modern landscape (Spurr 1956a).

Methods

STUDY AREA

The study was conducted primarily in the Tom Swamp Tract of the Harvard Forest in Petersham, Massachusetts (42°30′N, 72°12′W; Fig. 2). Petersham occupies a highland area consisting of north–south trending ridges and valleys ranging from 180 to 420 m a.s.l.. The Tom Swamp Tract occupies one such valley and the adjoining hillslopes and is physiographically characteristic of the larger township. In the valley bottom, two ponds are separated by *Picea mariana* swamp and open wetland (Fig. 2; Davis 1958; Swan & Gill 1970). Limited areas of well-drained soils adjoin the ponds, whereas very poorly drained peat and muck soils characterize the wetlands (Fig. 3a). On the flanks and crests of the ridges the stony till is thin and moderately well drained (Simmons 1939; Harvard Forest (H.F.) Archives — unpublished material that is permanently stored and accessible in the Archives of the Harvard Forest, Harvard University). The forest cover is characteristic of the transition-hardwood–*Pinus strobus*–*Tsuga canadensis* vegetation zone (Stout 1952; Spurr 1956b; Westveld 1956). Principal

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* The board foot is a commonly employed measure of timber volume in the USA. Each unit is equal to a board 1 inch thick, 12 inches wide and 12 inches long (1 inch = 2·54 cm, 1 board foot = 0·00236 m^3).

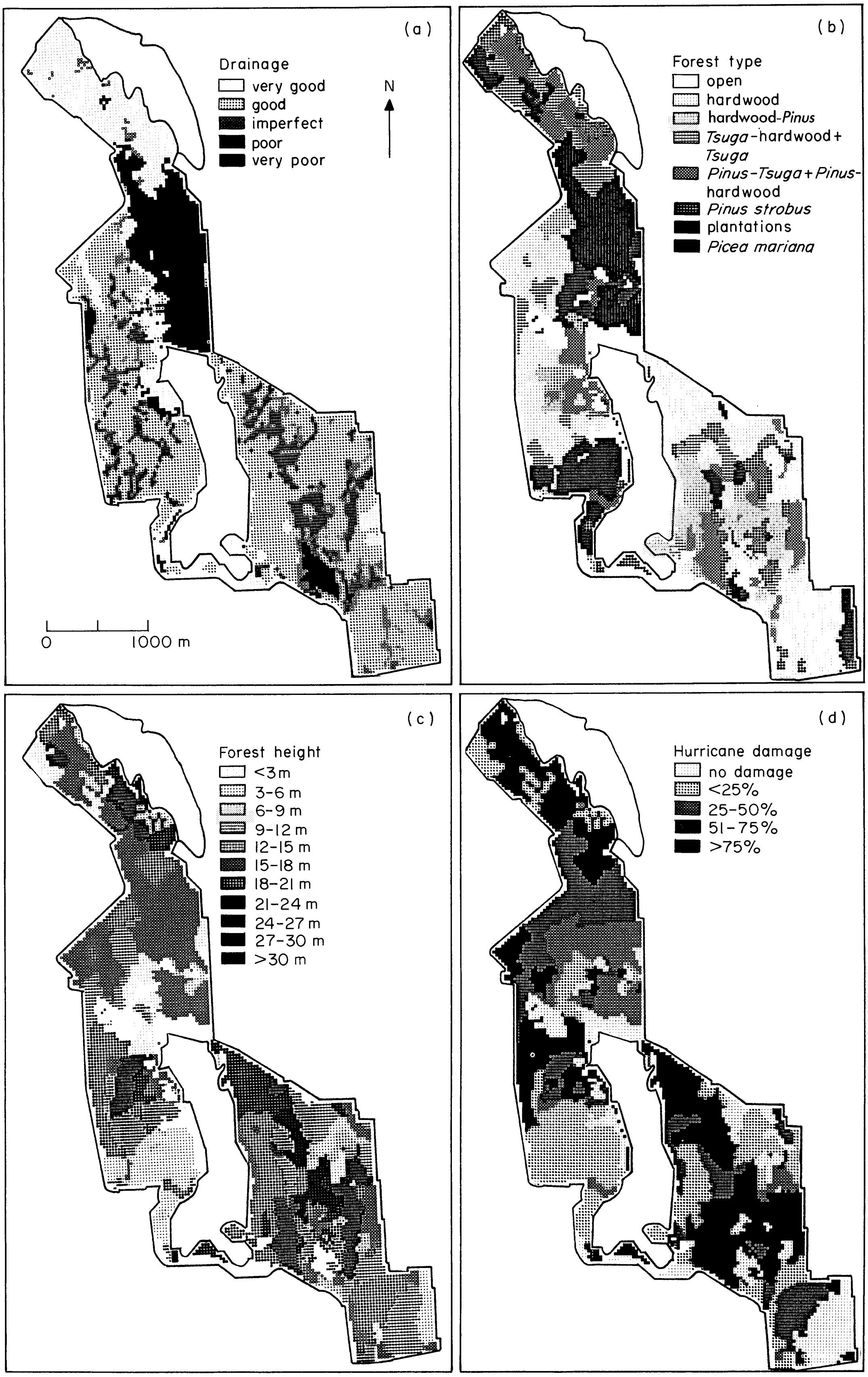

Fig. 3. Maps of the study area in the Tom Swamp Tract of the Harvard Forest showing (a) soil drainage, (b) 1938 forest type, (c) 1938 forest height, and (d) 1938 hurricane damage. See Fig. 2 for scale and detail of the study area.

tree species include *Quercus rubra*, *Acer rubrum*, *Betula lenta*, *Tsuga canadensis* and *Pinus strobus*. Nomenclature follows Fernald (1970). Other widely distributed species include *Fraxinus americana*, *Betula papyrifera*, *B. lutea*, *Fagus grandifolia*, *Quercus alba* and *Q. velutina*. At the time of the hurricane the second-growth forests were generally even-aged and in various stages of vegetation development (Fisher 1933; Raup & Carlson 1941). Conifer plantings and forestry operations added heterogeneity to the vegetation pattern.

VEGETATION MAPPING AND ANALYSIS

Stand maps and vegetation surveys undertaken in 1936–38 provide a detailed characterization of the forest destroyed in the hurricane. In the 1936–38 surveys, stands (minimum size 0·2 ha) were mapped at a scale of 1:2400, and sampled with a minimum of three circular plots (0·05–0·20 ha) per stand and a total of 239 stands in the study area. In each plot, trees were measured for diameter and canopy position. Herbs, shrubs and tree regeneration were estimated by species in three abundance classes, and stand age was determined. Stand height was measured to within 5 feet (*c.* 1·6 m).

In the present study, vegetation types were identified from the 1936–38 survey using detrended correspondence analysis (DECORANA; Hill 1979). Before the initial DECORANA analysis, all plantations and stands in which a single species comprised over 95% of the basal area were removed from the data set.

DAMAGE ASSESSMENT

Following the hurricane, detailed maps and field tallies were compiled of Harvard Forest property and large areas of Petersham (Rowlands 1941; H.F. Archives). Damaged areas were mapped by stand and classified into five categories (no damage, <25%, 25–50%, 51–75%, >75% damage) according to the percentage of canopy trees that were uprooted, snapped off or leaning so extensively that recovery was unlikely.

DATA ENCODING — GEOGRAPHIC INFORMATION SYSTEM

Spatial analysis was undertaken on a geographic information system (GIS; Tomlin 1983, 1986). The database consisted of separate overlays of physical and biological features of the study area ($3{\cdot}38\,\mathrm{km}^2$) in a 20-m raster grid. Overlays included altitude, forest stands, vegetation height, forest type and age, soils and hurricane damage. The GIS was used to derive new overlays from the encoded maps, including slope (in degrees of inclination), aspect (eight compass orientations and level), soil drainage, cover types (e.g. hardwood (i.e. non-conifer) forest, conifer forest and open areas) and composite overlays of two or more maps (e.g. exposure as a function of slope and aspect).

Initial analysis and comparison of maps were made using descriptive statistics, e.g. the percentage and absolute area occupied by different map regions or the percentage and absolute areal overlap of regions on two different overlays. The strength of the association between two regions on different overlays (e.g. *Pinus strobus* forest on the forest overlay vs. >75% damage on the damage overlay) was assessed using Cole's coefficient (Cole 1949; Grimm 1984). This technique compares the absence or presence of the two regions on a cell-by-cell basis. The value of the coefficient ranges from −1 (maximum disassociation) to +1 (maximum association).

SITE EXPOSURE TO WIND

A preliminary analysis of factors controlling hurricane damage in the Tom Swamp area concluded that site factors such as slope or soil drainage contributed little to explaining susceptibility to wind and that the major site factor governing damage is the degree of exposure to the wind (Fetherston 1987). Exposure is a complex characteristic controlled by slope orientation (aspect), slope inclination, topographic position, and landscape placement relative to obstructing barriers in the upwind direction (Somerville 1980).

In the present study, exposure in Tom Swamp was calculated cartographically using the GIS based on reported studies and empirical results (Gloyne 1968; Neustein 1971; Fetherston 1987; D.R. Foster, unpublished data) and defined as follows:

1. Exposed: nearly level sites ($\text{slope} < 5°$) or slopes orientated in a windward direction (S, SE, E).

2. Intermediate: mild leeward slopes ($5° \leq \text{slope} \leq 10°$ and W, NW, N) or intermediate orientation (NE, SW, $\text{slope} \geq 5°$).

3. Protected: moderate to steep leeward slopes ($\text{slope} > 10°$ and W, NW, N).

Exposure was calculated on a cell-by-cell basis, and stands were classified as exposed, intermediate or protected according to the most common exposure value for the cells comprising the stand.

ANALYSIS OF HURRICANE DAMAGE

Forest types identified with DECORANA were analysed in terms of site and vegetation characteristics and hurricane damage. A simpler classification of forest types was used to analyse stands on the basis of cover type (hardwood, conifer, open), stand height (3-m classes), site exposure (protected, intermediate, exposed), and hurricane damage (no damage, <25%, 25–50%, 51–75%, >75%

damage). The average damage class was determined for all stands sharing the same cover type, stand height and site exposure.

TOWNSHIP-WIDE ANALYSIS OF HURRICANE DAMAGE

Surveys of selected forest lands comprising 1044 ha (803 stands) across Petersham but outside the study area enabled the comparison of the results from the Tom Swamp site to those from a much broader area (Fig. 4). These lands were surveyed before and after the hurricane by Harvard Forest personnel using the methods employed in the Tom Swamp survey (H.F. Archives). In the current study, these stands were analysed in terms of the factors described above: forest cover type, stand height, site exposure and hurricane damage. The average damage class was determined for all stands sharing the same cover type, stand height and site exposure.

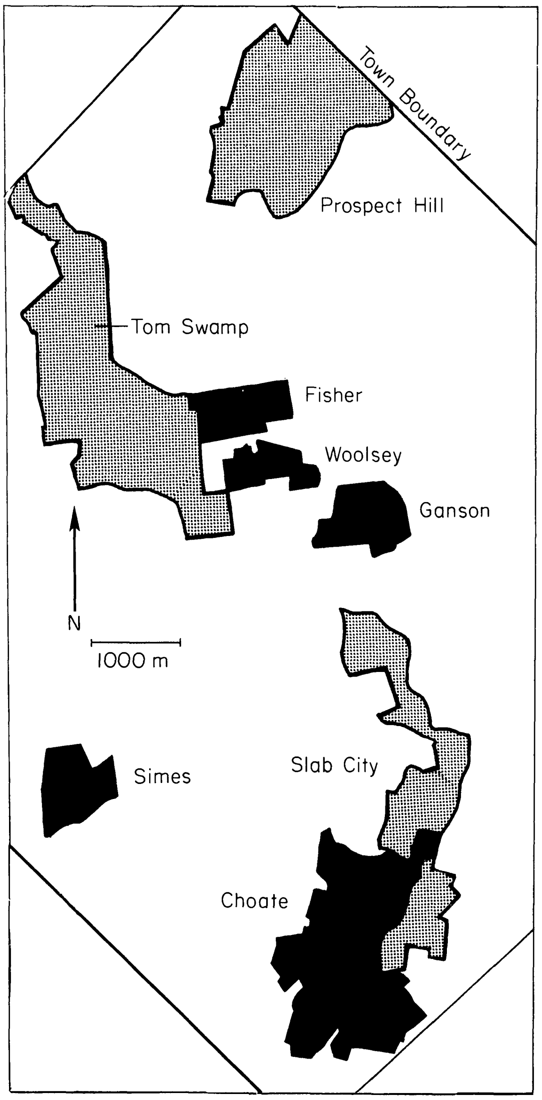

Fig. 4. Map of the central portion of Petersham township, Massachusetts showing the location of the private properties (black) and Harvard Forest tracts (stippled) investigated for the township-wide analysis of hurricane damage. The Tom Swamp Tract, although not included in the township-wide analysis, is also shown.

MODELLING OF LANDSCAPE RESPONSE TO WIND

The township-wide data (not including the Tom Swamp Tract) was used to construct a simple model of hurricane damage as a function of (i) vegetation type, (ii) vegetation height and (iii) site exposure to wind. The model was then used in two ways: (i) to check empirically our ability to explain the pattern of wind damage in the Tom Swamp study site and (ii) to explore variations in damage under different vegetational scenarios. In the first case, the map of actual damage was subtracted from the map of predicted damage derived from the model, and the resulting 'difference map' examined for its range of values and spatial distribution. In the second case, input values to the model were varied to simulate changes in forest composition or height, or both.

Results

VEGETATION DESCRIPTION

Seven forest types in the Tom Swamp Tract were recognized on the first two DECORANA axes: *Tsuga canadensis*; *Pinus strobus*; *P. strobus–T. canadensis*; *P. strobus*–hardwood; hardwood–*P. strobus*; *T. canadensis*–hardwood–*P. strobus*; and hardwood. These and both plantations and *Picea mariana* forest, dominated by a single species, are described briefly below (Fig. 5, Tables 1 and 2). In the simpler forest-type classification, open lands were regarded as open, hardwood and hardwood–*Pinus strobus* types as hardwood, and all other types as conifer.

1. Hardwood forest. Five distinct assemblages comprise the 105 ha designated as hardwood forest, including *Acer rubrum–Quercus rubra–Betula papyrifera*, *Quercus–Carya*, *Acer saccharum–Fraxinus americana*, *Acer rubrum* swamp, and *Betula populifolia–Populus–Prunus serotina*. These forests range from <3 m to 27 m in height and occupy well-drained soils with more than half of the stands situated on western to northern slopes. On average hardwood stands occur at higher altitudes and on steeper slopes than other forest types.

2. Hardwood–*Pinus strobus*. In this type, *Pinus strobus* is followed by *Acer rubrum*, *Quercus rubra*, *Q. alba*, *Tsuga canadensis* and *Betula lenta* in basal area. Most of the stands were established in old fields abandoned in the nineteenth century and exceed 18 m in height (Spurr 1956a). The 34 ha of hardwood–*Pinus strobus* are distributed at low to mid altitudes on mostly well-drained soils with nearly half of the stands on western to northern slopes.

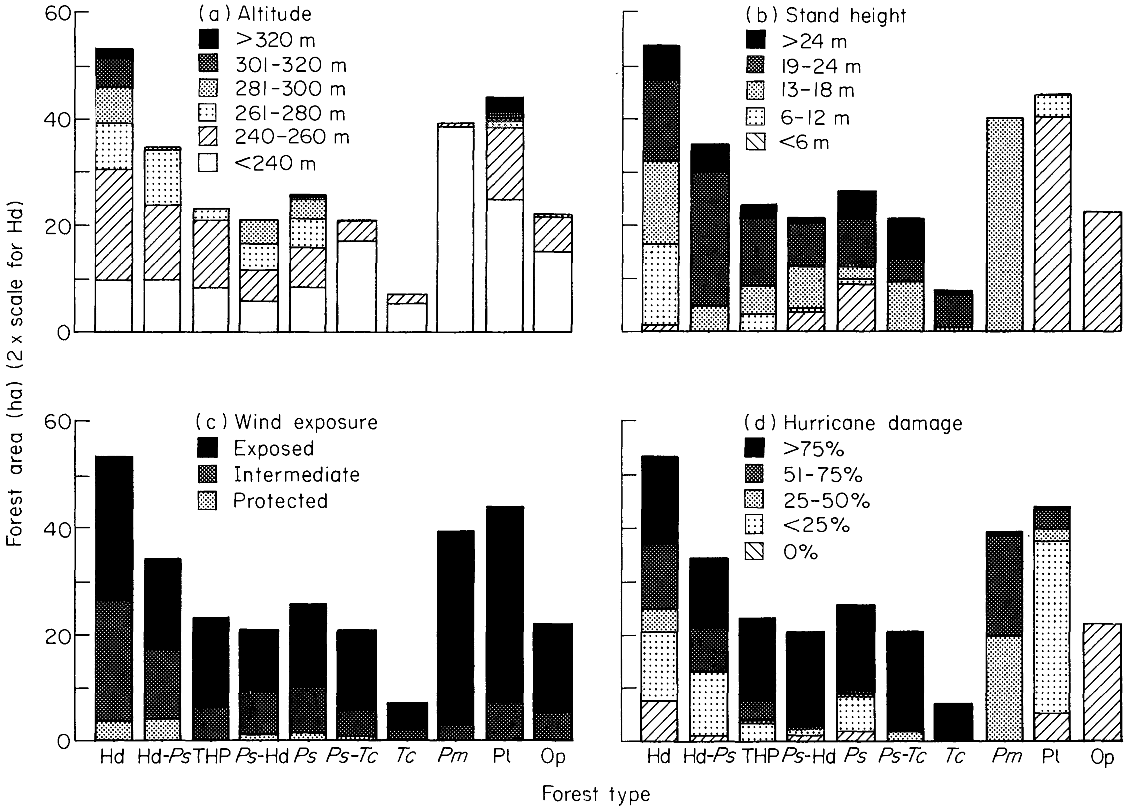

Fig. 5. Areal distribution of 1938 forest vegetation in the Tom Swamp Tract, Harvard Forest by (a) altitude, (b) stand height, (c) exposure to wind and (d) hurricane damage. Hd, hardwood; Hd–*Ps*, Hardwood–*Pinus strobus*; THP, *Tsuga*–hardwood–*Pinus*; *Ps*-Hd, *Pinus strobus*–hardwood; *Ps*, *Pinus strobus*; *Ps*–*Tc*, *Pinus strobus*–*Tsuga canadensis*; *Tc*, *Tsuga canadensis*; *Pm* — *Picea mariana*; Pl, Plantation; Op, Open. Values for the *y*-axis should be doubled for the hardwood (Hd) category.

3. *Tsuga canadensis*–hardwood–*Pinus strobus*. This assemblage is comprised of *Tsuga*, *Pinus strobus*, *Acer rubrum*, *Quercus rubra* and *Betula lenta* with some *Betula lutea* and *Fagus grandifolia*, and covers 23 ha. The forests are relatively old with more than half exceeding 18 m in height. Sites are primarily on well- to very-well-drained soils at low to mid altitudes. Aspect is rather evenly distributed.

4. *Pinus strobus*–hardwood. *Pinus strobus* comprises nearly half of the basal area of this forest type with *Quercus rubra*, *Acer rubrum*, *Fraxinus americana* and *Betula lenta*. The forests range from <3 m to 34 m tall. Sites are well drained to very well drained and occupy western to southwestern slopes at low to mid altitudes.

5. *Pinus strobus*. Nearly pure *Pinus strobus* with some *Acer rubrum*, *Quercus rubra* and *Prunus serotina* occurs on 25 ha. These stands include plantations and old-field *Pinus strobus* and range from <3 m to 30 m in height. Sites include low- to mid-level slopes with a south-westerly to westerly orientation and well-drained to very-well-drained soils.

6. *Pinus strobus*–*Tsuga canadensis*. Large *Tsuga canadensis* and *Pinus strobus* comprise older stands ranging from 15 to 34 m in height. Other species include *Acer rubrum*, *Betula lenta* and *B. lutea*. This type occurs with *Tsuga* forest at lower altitudes on the well- to very-well-drained soils in the valley bottoms.

7. *Tsuga canadensis*. These forests contain older *Tsuga*, *Pinus strobus* and *Acer rubrum* ranging from 15 to 27 m in height. The average altitude is low with large stands in the valley bottom.

8. *Picea mariana*. *Picea mariana* with *Larix laricina* and *Picea rubens* with *Acer rubrum*, *Tsuga* and *Pinus strobus* dominate the 39-ha swamp.

9. Plantations. *Pinus resinosa* occupies 36 ha with the remainder (6 ha) largely in *Picea glauca*, *P. abies*, *Larix* spp. and *Pinus sylvestris*. Plantings were made between 1912 and 1938 on well-drained, level of rolling terrain generally at lower altitudes. Most were less than 6 m in height in 1938.

10. Open land. Marsh (5 ha) largely adjacent to Harvard Pond and old fields (17 ha) along the valley bottom comprised the open land in 1938.

VEGETATION PATTERN

Spatial variation in site factors, natural disturbance history, and about 200 years of human land-use,

Table 1. Forest vegetation of the Tom Swamp Tract, Harvard Forest, in 1938 interpreted from DECORANA analysis. Composition is described by basal area (BA) ($m^2 ha^{-1}$) and frequency (F) of occurrence of each species in plots sampled in a forest type. The number of plots sampled, the areal extent and the basal area ha^{-1} for each forest type are given

	Forest type																	
	hardwood ($n = 52$)		hardwood–*Pinus strobus* ($n = 22$)		*Tsuga canadensis*–hardwood–*Pinus strobus* ($n = 15$)		*Pinus strobus*–hardwood ($n = 19$)		*Pinus strobus* ($n = 53$)		*Pinus strobus*–*Tsuga canadensis* ($n = 13$)		*Tsuga canadensis* ($n = 14$)		*Picea* spp. ($n = 6$)		*Pinus resinosa* ($n = 14$)	
Species	BA	F	BA	F	BA	F	BA	F	BA	F	BA	F	BA	F	BA	F	BA	F
Carya spp.	0·21	0·14	0·07	0·05														
Acer saccharum	0·65	0·44	0·27	0·18			0·33	0·22										
Ostrya virginiana	0·34	0·23	0·27	0·18			0·08	0·06										
Ulmus americana	0·44	0·30	0·27	0·18			0·16	0·11	0·04	0·03								
Tilia americana	0·51	0·30	0·20	0·18	0·11	0·15												
Amelanchier sp.	0·21	0·14	0·13	0·09	0·11	0·15												
Quercus velutina	0·10	0·07	0·34	0·23	0·11	0·07	0·08	0·06										
Populus spp.	0·82	0·51	0·34	0·23	0·32	0·30	0·25	0·17										
Fraxinus americana	1·13	0·69	0·60	0·41	0·32	0·22	0·49	0·33	0·27	0·18								
Castanea dentata	0·10	0·07	0·07	0·05	0·11	0·07	0·08	0·06	0·04	0·03								
Quercus alba	0·68	0·46	0·94	0·64	0·42	0·37	0·57	0·44	0·18	0·12	0·34	0·23						
Betula lenta	0·75	0·51	0·81	0·55	1·06	0·74	0·49	0·33	0·45	0·30	0·45	0·31						
Betula populifolia	0·86	0·58	0·54	0·36	0·21	0·22	0·25	0·22	0·13	0·09	0·23	0·15			0·11	0·13	0·07	0·03
Prunus serotina	0·86	0·58	0·47	0·36	0·21	0·22	0·33	0·22	0·45	0·27	0·34	0·23						
Quercus rubra	1·64	0·90	1·88	0·86	1·48	0·89	1·56	0·72	0·54	0·36	0·34	0·23	0·21	0·14				
Fagus grandifolia	0·48	0·35	0·47	0·32	0·53	0·37	0·08	0·06			0·11	0·08						
Betula papyrifera	1·57	0·58	0·47	0·32	0·74	0·52	0·25	0·22	0·04	0·03	0·11	0·08	0·21	0·14				
Betula lutea	0·79	0·53	0·54	0·36	0·84	0·59	0·33	0·22	0·18	0·15	0·45	0·31	0·21	0·14				
Acer rubrum	1·95	0·97	1·95	1·00	1·79	1·00	1·97	0·89	1·03	0·70	0·91	0·62	0·63	0·43	0·61	0·86	0·37	0·13
Pinus strobus	0·89	0·60	2·49	0·95	2·22	0·96	6·08	1·00	9·18	1·00	6·48	1·00	1·27	0·71	0·62	0·50	0·37	0·25
Tsuga canadensis	0·72	0·46	1·08	0·68	4·43	1·00	0·33	0·22	0·08	0·12	7·16	1·00	8·87	1·00	0·74	0·86		
Picea spp.					0·11	0·07	0·08	0·06			0·11	0·08	0·21	0·14	3·55	1·00		
Larix laricina									0·13	0·03					1·16	0·78		
Pinus resinosa																	5·17	1·00
Basal area ($m^2 ha^{-1}$)	15·70		14·20		15·12		13·79		12·74		17·03		11·61		7·79		5·98	
Total area (ha)	105		34		23		20		25		21		7		39		36	

Table 2. Site characteristics and hurricane damage of the forest types at Tom Swamp in 1938. Values given are Cole's coefficient for positive association

	Forest type*									
	Hd	Hd–*Ps*	*Tc*–Hd–*Ps*	*Ps*–Hd	*Ps*	*Ps*–*Tc*	*Tc*	*Pm*	Pl	Open
Altitude (m a.s.l.)										
<240						0·66	0·51	0·96	0·22	0·43
240–260	0·11	0·13	0·35							
261–280	0·13	0·21		0·15	0·11					
281–300	0·47			0·14	0·09					
301–320	0·83									
>320	0·29								0·33	
Slope (degrees)										
level								0·60		0·09
<5			0·08		0·27	0·24	0·40		0·51	0·01
5–10	0·16	0·10	0·02	0·13						
11–15	0·28	0·09		0·04						
16–20	0·30	0·08	0·06							
>20	0·41	0·01	0·13							
Aspect										
level								0·60		0·09
north-east					0·06	0·18	0·36		0·05	0·05
east			0·10	0·02		0·05			0·05	0·05
south-east			0·03	0·01		0·09			0·06	
south	0·02			0·04	0·03				0·08	
south-west	0·07	0·05		0·13	0·06					
west	0·20	0·17	0·01	0·04	0·07					
north-west	0·25								0·04	0·03
north						0·03	0·06		0·15	0·01
Exposure										
protected	0·27	0·20			0·02					
intermediate	0·20	0·11		0·14	0·05					
exposed			0·23			0·22	0·14	0·80	0·53	0·34
Drainage										
very poor								0·92		0·17
poor	0·19	0·12	0·01							
intermediate	0·25	0·04		0·01	0·01		0·01			
good	0·43	0·20		0·27	0·15				0·11	
very good			0·13	0·05	0·12	0·63	0·89		0·05	0·06
Forest height (m)										
<6					0·13				0·88	1·00
6–12	0·68									
13–18				0·10		0·19		1·00		
19–24	0·02	0·62	0·36	0·15	0·10		0·85			
>24	0·09	0·05	0·01		0·11	0·30				
Hurricane damage (%)										
no damage	0·04									1·00
<25		0·16			0·03				0·67	
25–50								0·53		
51–75	0·14	0·08						0·36		
>75		0·04	0·48	0·84	0·42	0·90	1·00			

* Hd = hardwood; Hd–*Ps* = hardwood–*Pinus strobus*; *Tc*–Hd–*Ps* = *Tsuga canadensis*–hardwood–*Pinus strobus*; *Ps*–Hd = *Pinus strobus*–hardwood; *Ps* = *Pinus strobus*; *Ps*–*Tc* = *Pinus strobus*–*Tsuga canadensis*; *Tc* = *Tsuga canadensis*; *Pm* = *Picea*; Pl = Plantation.

have created a mosaic of forest types and structure (Fig. 3b,c). In the northern section of the tract, conifer forest dominates, primarily *Picea mariana* in the swamp, taller *Tsuga canadensis* and *Pinus strobus* on outwash soils, and interspersed plantations. Larger plantations occur west and south-east of Harvard Pond. Conifer forests on the slope east of the pond include older-growth stands of *Tsuga* and *Pinus strobus*. Hardwood forests are of varying second-growth origins. Two areas of old-growth hardwood forest intermixed with *Pinus strobus* and *Tsuga* occur to the north-west and south-east of Harvard Pond.

ANALYSIS OF WIND DAMAGE

Damage to the forest in 1938 may be described by: (i) the spatial pattern and size distribution of contiguous areas sharing the same damage class, (ii) stratification of damage intensity by physiographic position and site factors and (iii) stratification of damage intensity by structure and composition of the original vegetation. Ideally, relationships emerging from the comparison of stand damage with site and biotic factors may be used to explain the spatial pattern.

Spatial patterns of hurricane damage

Wind damage created an intricate landscape pattern of vegetation structure, in terms of the spatial arrangement, shape and size of damaged areas (Fig. 3d). The area of land in each of the five damage classes is fairly evenly distributed, and ranges from 10% in the 25–50% damage class to 36% in the >75% damage class.

Distinct geographic patterns of damage distribution are apparent. The greatest extent of severe damage occurred on the western edge of the study area, the east side of Harvard Pond and the west side of Riceville Pond. Sites receiving little damage include the broad shrub wetland north of Harvard Pond, and valley-bottom sites with young plantations or early-successional vegetation.

The damage map (Fig. 3d) was analysed with the GIS to identify damage patches, i.e. contiguous areas sharing the same damage class. The size-class frequency of these areas exhibits a negative exponential distribution with a predominance of areas <2 ha and few large areas (Fig. 6). The smallest area is 0·04 ha and the largest area approximately 37 ha. The latter consisted of mature forest to the south-east of Harvard Pond and sustained more than 75% damage.

Site exposure and relationship to wind damage

Less than 3% of the stands in Tom Swamp were protected from southerly to easterly winds, approximately 31% had an intermediate level of exposure and 66% were fully exposed (Fig. 5). Protected and intermediate sites occur predominantly on the west-facing slopes east of Harvard Pond, whereas exposed and some intermediate sites occupy the level area north of the pond and gentle slopes to the west. One large exposed site occupies the crest and eastern slope of a hill in the middle of the slope on the eastern side of the pond. To the north of the pond the exposed swamp is interrupted by small islands that provide locally intermediate sites.

Analysis of hurricane damage in Tom Swamp shows that, for both hardwood and conifer stands, and for all stand heights, the general ranking of damage by site exposure was exposed > intermediate > protected (Fig. 7). The number of stands averaged for each combination of cover type, site exposure and stand height ranged from 1 to 17 (average 5·3); exceptional damage-class values for exposed hardwoods 24–27 m tall and intermediate conifers <3 m tall are based on single stands.

EFFECT OF FOREST STRUCTURE AND COMPOSITION ON HURRICANE DAMAGE

The role that forest structure plays in controlling wind damage can also be seen clearly in the Tom Swamp data (Figs 7 and 8). Damage increased approximately linearly with increasing height. Severe

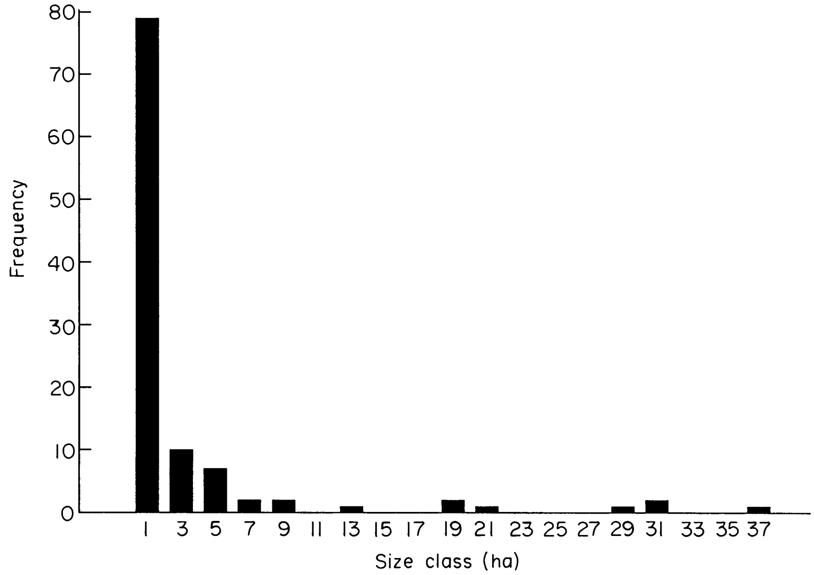

Fig. 6. Size-class distribution of contiguous areas sharing the same damage class, derived from the 1938 hurricane damage map (Fig. 3d) for the Tom Swamp Tract, Harvard Forest. Mid-points of 2-ha size classes are labelled.

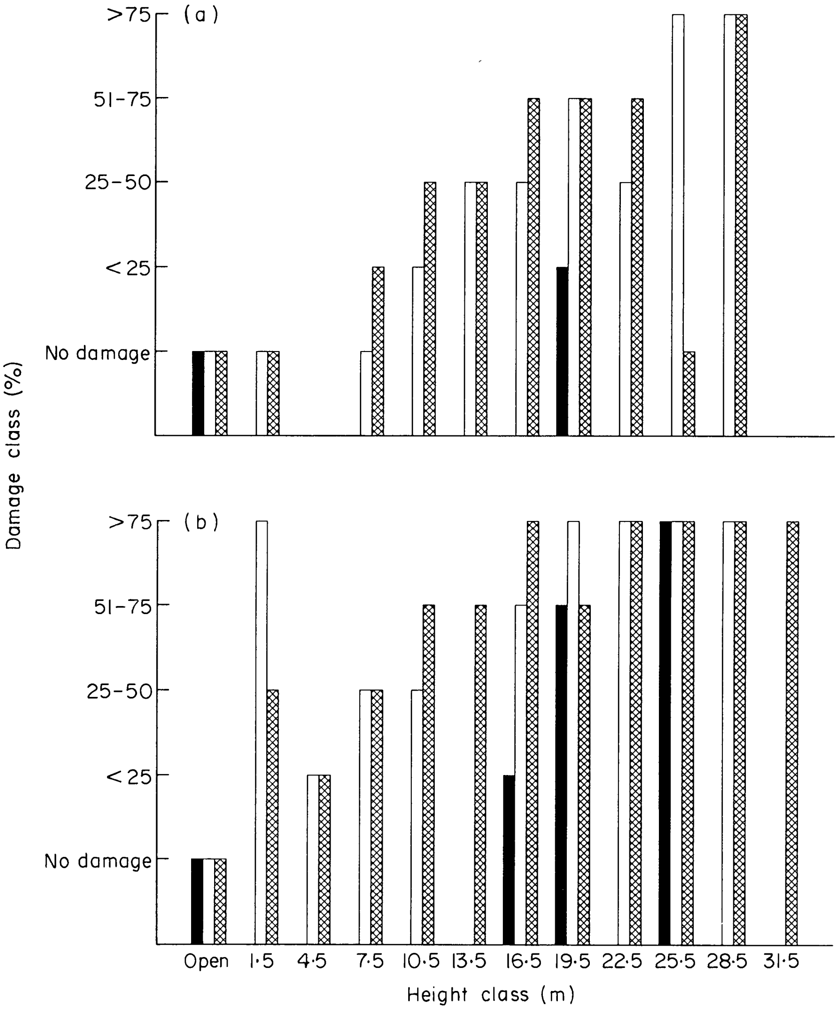

Fig. 7. Damage following the 1938 hurricane in the Tom Swamp Tract, Harvard Forest. Stands are divided into two cover types: (a) hardwood and (b) conifer; three site-exposure classes: protected (■), intermediate (□) and exposed (▨); and twelve 3-m height classes. Mid-points of height classes are labelled. Each bar represents the average damage class for all stands sharing the same cover type, site exposure and height class.

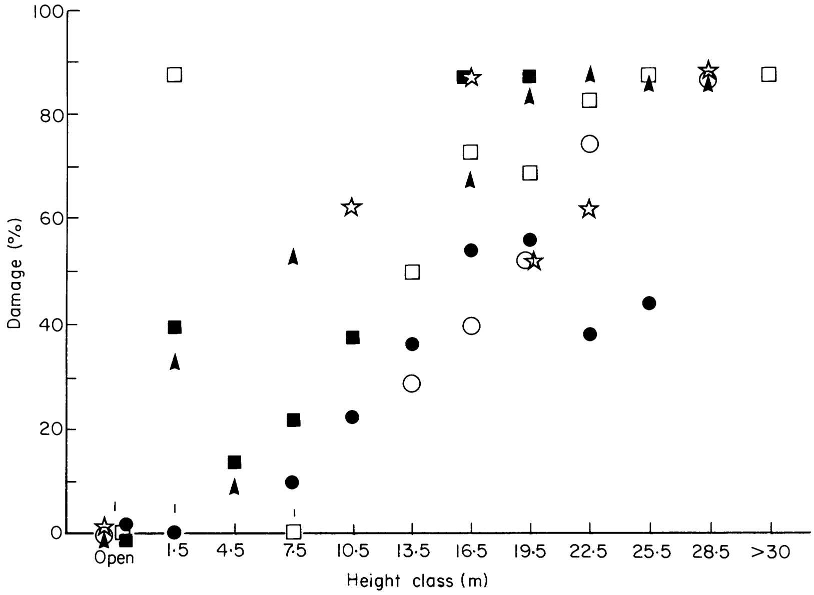

Fig. 8. 1938 hurricane damage for the major forest types in the Tom Swamp Tract, Harvard Forest. Each point represents the average percentage damage for all stands sharing the same forest type and height class: (□) *Pinus strobus*–hardwood; (☆) *Tsuga canadensis–Pinus strobus*; (■) plantations; (▲) *Pinus strobus*; (○) hardwood–*Pinus strobus*; (●) hardwood. Mid-points of 3-m height classes are labelled.

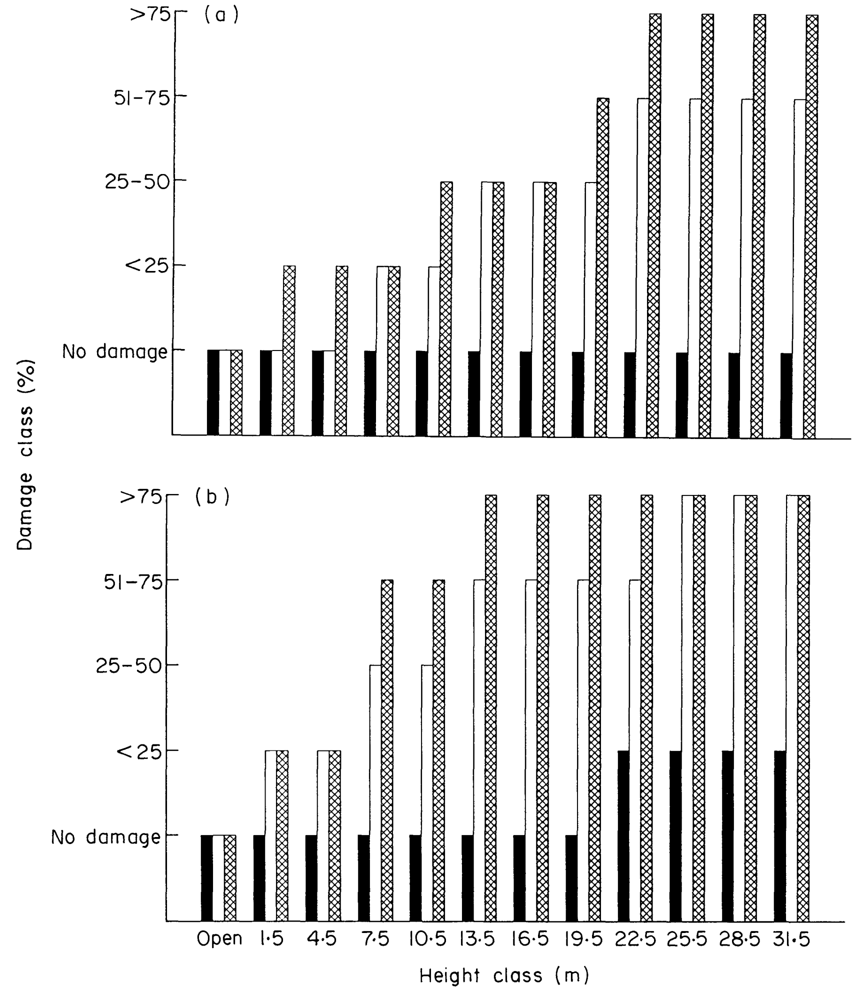

Fig. 9. Damage following the 1938 hurricane in the township-wide analysis of Petersham, Massachusetts (excluding the Tom Swamp Tract). Stands are divided into two cover types: (a) hardwood and (b) conifer; three site-exposure classes: protected (■), intermediate (□), and exposed (▨); and twelve 3-m height classes. Mid-points of height classes are labelled. Each bar represents the average damage class for all stands sharing the same cover type, site exposure and height class. These values are used by the model to predict hurricane damage as a function of cover type, site exposure and height class.

windthrow of more than 75% of the trees was reached in most stands by a height of 25 m. However, the response recorded across all stands was less than that reported in a previous study (Foster 1988b) due to the averaging of stand response from across the range of site exposure.

DISTRIBUTION OF DAMAGE AMONG FOREST TYPES

Differences in susceptibility and site distribution among forest types resulted in highly uneven distribution of damage among the different types (Fig. 5d, Table 2). Forest types dominated by *Pinus strobus* or *Tsuga canadensis* comprise the bulk of the severely damaged area. All of the *Tsuga* stands and 63–94% of the stands dominated by *Pinus* or *Tsuga* sustained >75% damage.

In contrast, hardwood forests, *Picea mariana* swamp, and plantations are more represented in the lower damage classes. More than 85% of the plantations experienced <25% damage and *Picea* stands were evenly distributed between 25–50% and 51–75% damage. Only 31% of the hardwood stands and 39% of the hardwood–*Pinus strobus* stands sustained >75% damage.

Average damage was plotted as a function of stand height for each forest type to obtain an approximate ranking of damage susceptibility: *Pinus strobus* > conifer plantations > *P. strobus*–hardwood = *Tsuga canadensis*–hardwood–*P. strobus* > hardwood–*P. strobus* > hardwood (Fig. 8).

ANALYSIS OF TOWNSHIP-WIDE HURRICANE DAMAGE

The analysis of over 800 stands from seven other tracts of land throughout Petersham reveals that the relationships between forest type, forest height, site exposure and wind damage described for the Tom Swamp Tract may be generalized across the landscape (Fig. 9). The seven tracts are quite varied in

Table 3. Hurricane damage to forest properties in Petersham, Massachusetts (with number of stands in parentheses). The area of land affected and estimated amount of salvageable timber are given by damage class. Area (A) is given in hectares and timber volume (V) in thousands of board feet (MBF) (1 board foot = 0·00236 m^3)

	Private ownership										Harvard Forest							
	Woolsey (n = 19)		Ganson (n = 13)		Simes (n = 30)		Fisher (n = 38)		Choate (n = 252)		Tom Swamp (n = 222)		Prospect Hill (n = 243)		Slab City (n = 208)		Total (n = 1025)	
Damage class	A	V	A	V	A	V	A	V	A	V	A	V	A	V	A	V	A	V
No damage	2	—	1	—	—	—	1	—	50	—	23	—	50	—	27	—	154	—
<25%	13	29	13	22	15	25	18	18	57	31	85	28	128	82	59	33	388	268
25–50%	1	5	3	10	14	167	5	15	34	57	34	69	41	62	12	38	144	423
51–75%	1	24	4	35	11	190	10	50	35	148	57	146	50	212	18	79	186	884
>75%	11	429	10	312	13	772	19	250	91	1589	117	1858	28	596	91	2058	380	7864
Open land	13	—	10	—	1	—	—	—	35	—	22	—	47	—	2	—	130	—
Total	41	487	41	379	54	1154	53	333	302	1825	338	2101	344	952	209	2208	1382	9438
Mean damage (MBF ha^{-1})		11·9		9·2		21.4		6·3		6·0		6·2		2·8		10·6		6·8

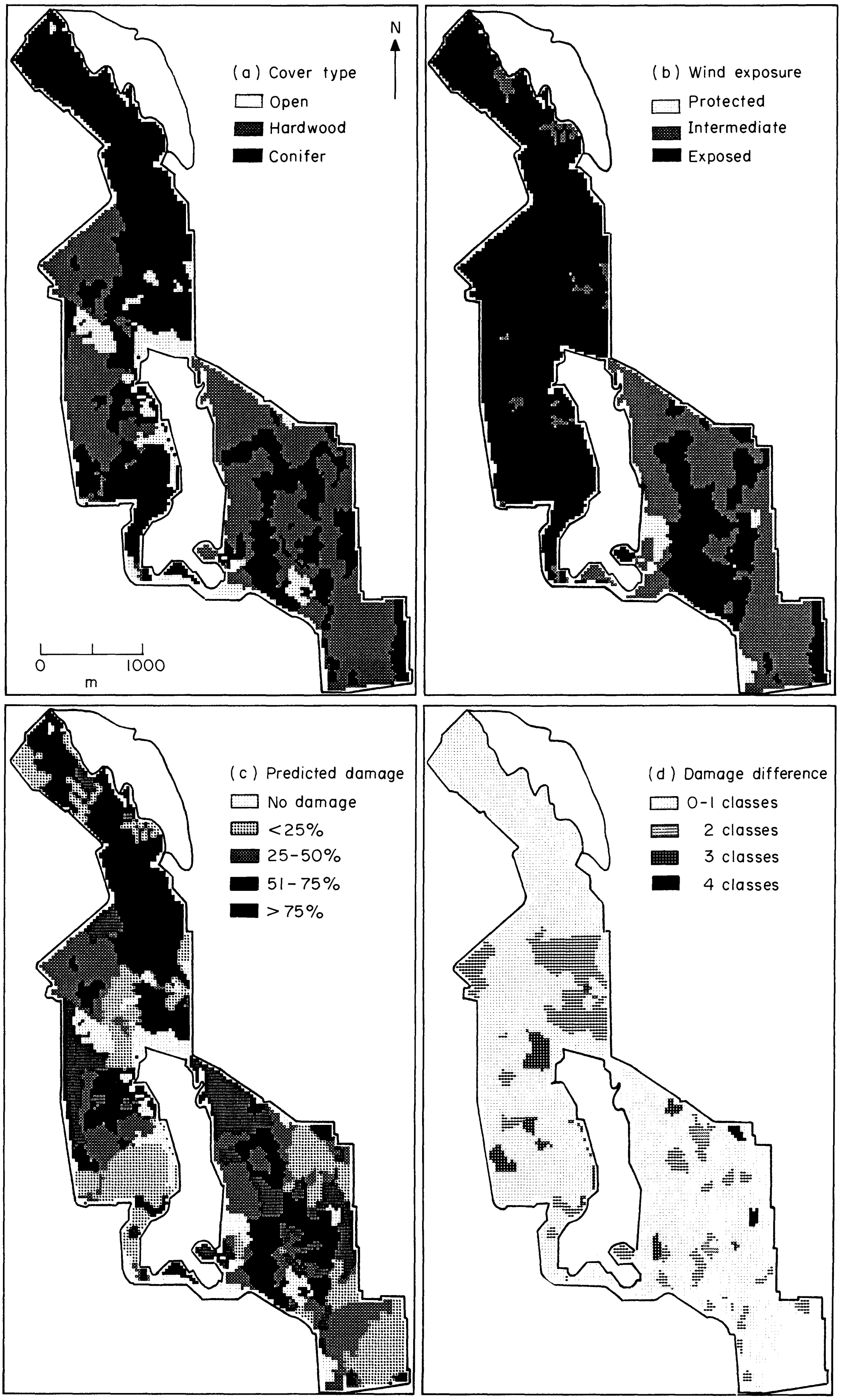

Fig. 10. Cartographic modelling of landscape response to the 1938 hurricane in the Tom Swamp Tract, Harvard Forest. Input for the model includes (a) 1938 cover type, (b) site exposure to wind, and 1938 forest height (Fig. 3c). Model output is a map of predicted damage (c). The observed damage map (Fig. 3d) is subtracted from the predicted damage map to create a difference map whose absolute values (d) highlight areas where the predicted damage is too high or too low.

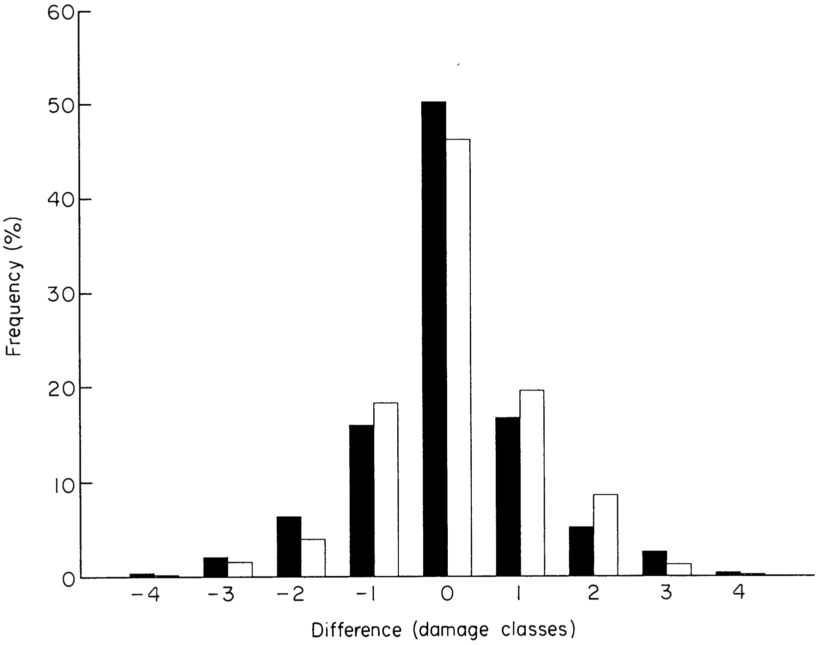

Fig. 11. Frequency distribution of the difference map created by subtracting the observed damage map (Fig. 3d) from the predicted damage map (Fig. 10c) for the 1938 hurricane in the Tom Swamp Tract, Harvard Forest. Values in the observed and predicted damage maps range from 1 (no damage) to 5 (>75% damage), while values in the difference map range from −4 (predicted value = 4 damage classes too low) to +4 (predicted value = 4 damage classes too high). Frequency is given by percentage of stands (■) and percentage of area (□).

size, forest cover and extent of damage (Table 3). The severity of damage, as indicated by the mean volume of salvageable timber per hectare, is primarily controlled by stand age and extent of conifer forests. For example, the Prospect Hill Tract, which suffered relatively low damage (2·8 MBF ha^{-1}) was nearly 14% open land in 1938 and had sizeable areas of very young forest and plantation (H.F. Archives). In contrast, the Simes lot was most severely damaged (21·4 MBF ha^{-1}) and had extensive older *Pinus strobus* forests and only 2% of the area in open land (Table 3). Across the stands, damage was consistently greater in conifer forests than in hardwood forests, and within a given cover type damage increased with stand age and with site exposure to wind in a consistent manner (Fig. 9).

MODEL OF LANDSCAPE RESPONSE TO WIND

Analysis of the difference map produced by subtracting actual damage from predicted damage shows a close fit between actual and modelled results (Fig. 10). On a stand-by-stand basis, the difference map has a normal distribution; mean ± SD = −0·0043 ± 1·1627 (Fig. 11). Model predictions were correct for 50% of the stands, within one damage class for 83% of the stands, and within two damage classes for 94% of the stands. Stands in which the difference was two or more damage classes appear to be distributed fairly evenly throughout the study site (Fig. 10d), suggesting that these differences were not the result of an undetermined factor separate from cover type, stand height and site exposure and concentrated in particular areas of the map.

This observation was confirmed by testing the difference map with Moran's coefficient for spatial autocorrelation (Ebdon 1985). Under a null hypothesis of random spatial distribution, the value of Moran's coefficient is 0·0231, the expected value and standard deviation are −0·0043 and 0·0400, respectively, and the significance level for a two-tailed test is 0·49, indicating a high probability that the spatial distribution is random.

Analysis of the difference map highlights situations in which our understanding of forest response is weak (Fig. 10d). Damage in protected sites was consistently underestimated and accounts for two of the six stands with a difference value less than −2. Apparently the protected areas in the study site were too small (i.e. the protecting slope was too short) to provide real protection. The other four stands were quite young (<3 m tall) and include two conifer plantations on the mineral island in the *Picea mariana* swamp and *Pinus strobus* and *P. strobus*–hardwood stands along the north-west shores of Harvard Pond (Fig. 10). The fact that these sites are extremely vulnerable to the south-east wind may help to explain why they sustained >75% damage. Seven stands where damage was greatly overestimated (difference >+2) include mostly mature conifer or hardwood stands, relatively small in area, on exposed sites, and are difficult to explain.

The largest contiguous area of misclassification is the *Picea mariana* swamp between the two ponds (Fig. 2) which was predicted to receive greater damage than observed. The forest on this site is a rare type, for which there are no empirical data available from the township-wide analysis. The results suggest that wetland *Picea* forest is more wind-firm than forests comprised of other conifer species.

Discussion

FACTORS CONTROLLING THE DISTRIBUTION OF HURRICANE DAMAGE

Across the range of spatial scales, from that of individual forest stands to regional landscapes, the pattern of forest damage resulting from hurricane winds is complex (Stoeckler & Arbogast 1955; Neustein 1971; Putz *et al.* 1983). The level of wind damage is determined by the interaction of biotic, edaphic and historical factors with meteorological and stochastic processes. However, in the present study of a single tract of land it is possible to identify explaining variables that reduce this complexity and allow for some generalization. Three pervasive classes of factor emerge: the local meteorology of the storm, physiographic characteristics of the landscape, and vegetation structure and composition.

Storm meteorology, primarily local wind speed and direction, interacts with topographic characteristics of the landscape to determine site susceptibility to a storm (Neustein 1971). The force exerted on an object by wind increases with the square of the velocity and consequently variation in wind speed is a dominant factor controlling the intensity of disturbance. For winds of a given velocity, wind direction will determine whether a particular physiographic setting is fully exposed, partially exposed or protected from the wind. During the storm of 1938 the winds responsible for breaking and uprooting trees at the Harvard Forest came from within 30° of south-east (Foster 1988b), which suggests that level sites ($<5°$ inclination) and slopes facing south to east would be fully exposed to the wind, whereas steeper slopes ($>10°$) facing west to north would be protected. Transitional sites on north-east or south-west slopes should face intermediate levels of wind. These site characterizations are borne out by the analysis of damage in both the Tom Swamp Tract and surrounding areas (Figs 7 and 9). The slope of regression lines relating damage to stand height increased from protected to intermediate to exposed sites.

Higher-order landscape-level effects were noted. Site position relative to open areas or physiographic wind breaks exerts an effect on susceptibility to wind. Although the small sample size precludes a quantitative analysis, the pattern of damage and contemporary observations indicate that trees within 10–100 m of open areas were more susceptible to blow-down than trees in continuous forest (Rowlands 1941). The only abrupt obstruction to wind movement in the study area is the small hill south-east of Harvard Pond (Fig. 2). Forests on the leeward slopes suffered little damage and were apparently shielded from the wind by the hill. However, other higher-order effects of physiography on wind structure reported in other studies were not noted in the current analysis. For example, there was no evidence of the 'lee-slope effect' created by winds curling down beyond the crest of a hill to damage forests on the lee slope. Savill (1983) has postulated that at hurricane force this effect may be reduced. Slope position also seemed to have a negligible effect on site susceptibility. Presumably, the gentle topography and approximately north–south orientation of the Tom Swamp valley allowed the strong winds to penetrate to the bottom of the valley. Slope position would be expected to be more important as the sharpness of the relief becomes more exaggerated (Gloyne 1968; Neustein 1971).

On a given site type the forest composition and structure were strongly associated with the level of damage. For each forest type the percentage of damaged trees increased progressively and approximately linearly with height. Conifer species are considerably more susceptible than hardwoods and the relative proportion of these groups may strongly influence overall forest susceptibility. Among the conifers, *Pinus strobus* and plantations of *P. strobus*, *P. resinosa* and *Picea abies* were apparently more susceptible than *Tsuga canadensis*. Natural forests of *Picea mariana* and *P. rubens* in wetlands were not particularly susceptible.

LANDSCAPE PATTERN OF HURRICANE DAMAGE

Results from the past study of individual stands on exposed sites show that surprisingly straightforward relationships between stand structure and damage provide the information necessary to interpret damage to a given stand (Foster 1988b). The present study indicates that for a relatively simple landscape setting such as the Tom Swamp valley in which relief varies gently, that the same relationships, modified by the degree of site exposure, may explain a considerable portion of the landscape-level pattern of damage.

The robustness of this statement was examined by a simple model of landscape-level wind damage constructed using one site variable (wind exposure) and two vegetational variables (forest type and height) to predict wind damage. Empirical values, derived from other stands in the Petersham area, were used as the basis for predicting expected wind damage, which was then compared to the damage observed in 1938. Across the study area there was close agreement between the prediction and the actual pattern of damage.

The rather close fit between the modelled damage pattern and the observed pattern suggests that a first approximation of landscape response to hurricanes can be generated using fairly simple, and easily obtained, measures of biotic and edaphic factors. It also suggests some general observations about the range of landscape patterns that may emerge from catastrophic wind.

Site susceptibility to the particular wind experienced in 1938 is apparently an inherent characteristic of each location, depending on its aspect, slope and placement relative to wind breaks. This susceptibility factor places a maximum range of response on the vegetation growing on the site — from zero in the absence of trees taller than 3 m to a maximum for the tallest pine stands. The maximum may range from less than 25% damage for a completely protected site to more than 75% for an exposed site.

Across a landscape the extent of damage should be sensitive to historical factors such as prior natural disturbance or human activity that altered the structure or composition of the vegetation. Using the simple model developed above, some aspects of this sensitivity have been explored. In 1938 the vegetation in the Tom Swamp valley was a mosaic of second-growth stands regenerating from agricultural abandonment and extensive cutting. Management emphasis was on conifer development on a 50–60-year cutting cycle (Gould 1960). The effect of wind on four vegetational scenarios related to this management plan was assessed for Tom Swamp: all conifers or all hardwoods with the same stand height as in 1938, and all conifers or all hardwoods 20 m in height (Fig. 12).

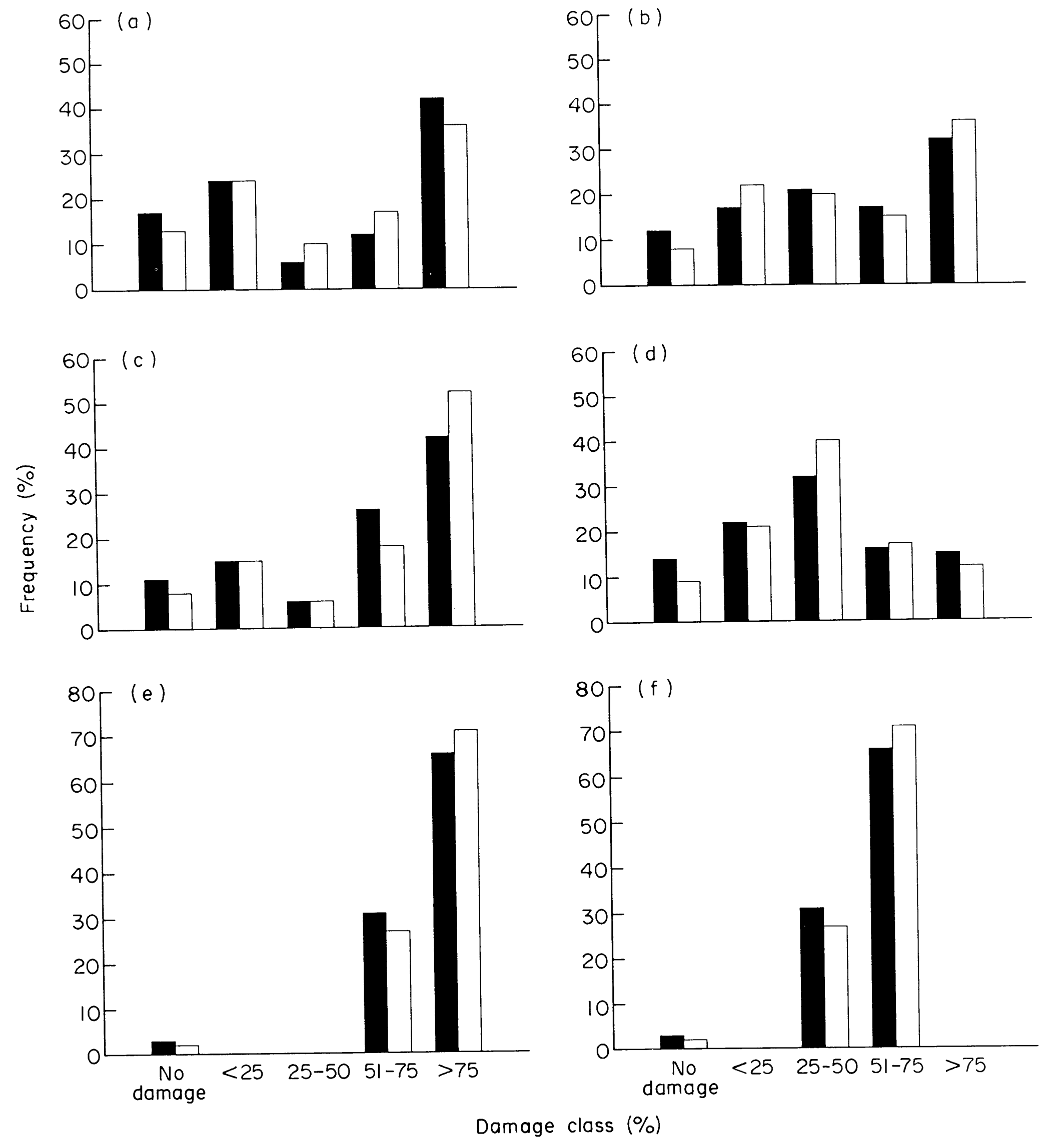

Fig. 12. Application of the wind-damage model to different vegetational scenarios for the 1938 hurricane in the Tom Swamp Tract, Harvard Forest: observed damage (a) and predicted damage for (b) actual 1938 stands, (c) all conifer stands with 1938 stand heights, (d) all hardwood stands with 1938 stand heights, (e) all conifer stands with a uniform 20-m height, (f) all hardwood stands with a uniform 20-m height. Frequency is given by percentage of stands (■) and percentage of area (□).

As expected, the outcomes in terms of forest damage under these different scenarios are vastly different. In 1938, 54% of the stands sustained more than 50% damage. If the same forest structure were converted to all conifers, this figure would increase to 69%; under a scenario of 20-m-tall conifers, it would increase to 97%. In contrast, if the 1938 forest structure were converted to all hardwoods, the figure would decrease to 32%; under a scenario of 20-m-tall hardwoods it would be 66%.

This simple exercise highlights the sensitivity of the landscape-level wind response vegetation pattern and underscores the importance of historical factors in controlling landscape susceptibility to wind damage. Interestingly, the pattern of vegetation in 1938 probably enhanced the susceptibility of the study area to disturbance relative to that of the naturally regenerating hardwood–conifer forest due to the management concentration on *Pinus* and successional history of old-field *Pinus strobus* establishment. In addition, the suceptible conifer stands tended to be situated on exposed sites, whereas hardwood stands, which are more resistant, were situated on protected and intermediate sites.

Alternative management schemes could greatly alter the damage experienced under a storm such as occurred in 1938. The results of the modelling exercise in the current study suggest that simple tools and guidelines may be used effectively to control landscape susceptibility to wind.

DISTURBANCE EFFECTS OF THE HURRICANE

Literature discussions of wind disturbance in forested ecosystems often make a distinction between 'gap dynamics' in which the mortality of an individual or a small group of trees creates a limited (e.g. 20–900-m^2) canopy opening and 'catastrophic disturbance' in which a broad-scale wind (e.g. hurricane) opens very large openings across a region (Bormann & Likens 1979; Oliver 1981; Pickett & White 1985). This dichotomy has been emphasized because different initiating factors are involved (e.g. ice-storm or wind-storm vs. hurricane), different-sized patches are thought to be produced (small vs. large), different successional processes may be initiated (release and ingrowth vs. seedling establishment and sprouting), and ecosystem consequences and landscape dynamics may be distinct.

The current study presents a more-complex picture in which the intensity of disturbance and effects on the forest vegetation by the 1938 hurricane fall along a gradient controlled by site position and vegetation.

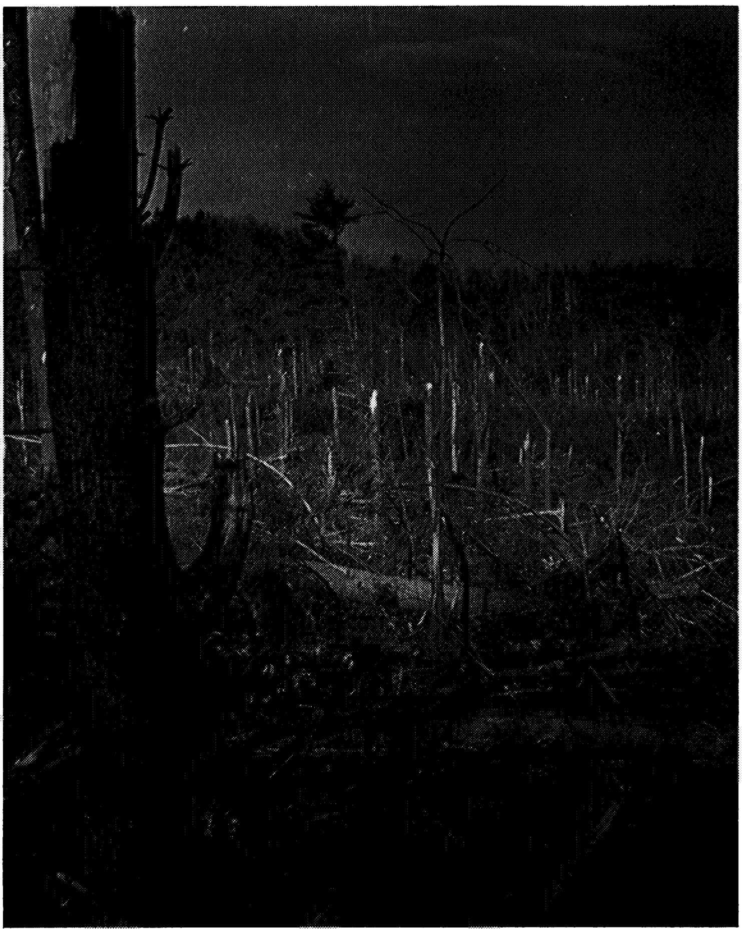

Fig. 13. Damage from the 1938 hurricane to forests on the Harvard Forest in Petersham, Massachusetts. Variability in site exposure and forest height and composition resulted in a complex landscape pattern of forest damage (photograph by W. Rowlands).

The results describe a continuum of effects ranging from damage to individual or scattered trees to uprooting of entire stands. Many trees suffered only branch-break or defoliation (Rowlands 1941); however, the spectacular sight of entire windthrown stands (Fig. 13) plus the regional extent of forest damage gave rise to the impression that the effect of the storm was primarily catastrophic. In reality the intensity of disturbance was spread rather evenly. blow-downs, is also incomplete. The size-class dis-

The other characterization of hurricanes, that they generate broad-scale destruction of very large tribution of contiguous areas of the same damage intensity exhibits a pronounced skewness towards the smallest size classes of 0·04 ha. Very few extremely large areas were formed; rather, a very heterogeneous mosaic of smaller areas was created (Rowlands 1941). Descriptions and photographs of the hurricane's effects emphasize this heterogeneity and the abrupt changes in damage intensity across short distances (Cline & Spurr 1942; Jensen 1941).

One limitation in defining size distribution of such areas in the present study is that the field workers arbitrarily chose a minimum size of 0·04 ha to map. There are therefore no quantitative data available to determine the frequency of openings that interest many ecologists who work with gaps 50–400 m^2 in area. However, photographs and field descriptions indicate that on a frequency basis there were increasing numbers of low-intensity events: moderate-sized gaps, small gaps, individual tree-throw, branch-break, and defoliation. This would be consistent with contemporaneous observations (H.M. Raup and E. Gould, personal communication) and observations from other hurricanes (D.R. Foster, unpublished data).

Conclusion

The results of this study emphasize the selective and variable effect of wind as a disturbance process in forested landscapes. Although the relationship between the site and biotic factors that control this effect are relatively simple to assess, spatial variation in these factors and interactions among them lead to the creation of a complex geographic pattern of disturbance. The disturbance effects fall along a continuum of severity and areal extent and add significant heterogeneity to the structural and compositional characteristics of the vegetation pattern. The initial post-disturbance heterogeneity provides a template for further changes through vegetation development.

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References

Bormann, F.H. & Likens, G.E. (1979) *Pattern and Process in a Forested Ecosystem*. Springer, New York.

Brake, R.W. & Post, H.A. (1941) *Natural restocking following hurricane damaged 'old field' white pine areas in north central Massachusetts*. MFS thesis, Harvard University.

Brooks, C.F. (1939) Hurricanes into New England: meteorology of the storm of September 21, 1938. *Smithsonian Institution Report*, **3563**, 241–251.

Carmean, W.H., Hahn, J.T. & Jacobs, R.D. (1989) Site index curves for forest tree species in the eastern United States. *USDA Forest Service General Technical Report*, **NE-128**.

Cline, A.C. & Spurr, S.H. (1942) The virgin upland forest of central New England: a study of old growth stands in the Pisgah mountain section of southwestern New Hampshire. *Harvard Forest Bulletin*, **21**, 1–58.

Cole, L.C. (1949) The measurement of interspecific association. *Ecology*, **30**, 411–424.

Curtis, J.D. (1943) Some observations on wind damage. *Journal of Forestry*, **41**, 877–882.

Davis, M.B. (1958) Three pollen diagrams from central Massachusetts. *American Journal of Science*, **256**, 540–570.

Dunn, G.E. & Miller, B.I. (1964) *Atlantic Hurricanes*. Louisiana State University Press, Baton Rouge.

Ebdon, D. (1985) *Statistics in Geography*, 2nd edn. Basil Blackwell, Oxford.

Fernald, M.L. (1970) *Gray's Manual of Botany*, 8th edn. Van Nostrand Reinhold, New York.

Fetherston, K.L. (1987) *A computer cartographic analysis of a forested landscape's response to hurricane force wind in central New England*. MFS thesis, Harvard University.

Fisher, R.T. (1933) New England's forests: biological factors. New England's Prospect. *American Geographical Society Special Publication*, **16**, 493–506.

Foster, D.R. (1988a) Disturbance history, community organization and vegetation dynamics of the old-growth Pisgah Forest, south-western New Hampshire, U.S.A. *Journal of Ecology*, **76**, 105–134.

Foster, D.R. (1988b) Species and stand response to catastrophic wind in central New England, U.S.A. *Journal of Ecology*, **76**, 135–151.

Gloyne, R.W. (1968) Wind Effects on the Forest — Report of the Eighth Discussion Meeting, Edinburgh, 22 to 24 March 1968. Society of Foresters of Great Britain. *Forestry*, **41**, 7–19.

Gould, E.M. (1960) Fifty years of management at the Harvard Forest. *Harvard Forest Bulletin*, **29**, 1–30.

Grimm, E.C. (1984) Fire and other factors controlling the Big Woods vegetation of Minnesota in the mid-nineteenth century. *Ecological Monographs*, **54**, 291–311.

Hawley, R.C. (1942) Growing of white pine on the Yale Forest near Keene, New Hampshire. *Yale University, School of Forestry Bulletin*, **48**, 1–44.

Heinselman, M.L. (1973) Fire in the virgin forests of the Boundary Water Canoe Area, Minnesota. *Quaternary Research*, **3**, 329–382.

Henry, J.D. & Swan, J.M.A. (1974) Reconstructing forest history from live and dead plant material — an approach to the study of forest succession in southwest New Hampshire. *Ecology*, **55**, 772–783.

Hill, M.O. (1979) *DECORANA: a* FORTRAN *Program for Detrended Correspondence Analysis and Reciprocal Averaging*. Section of Ecology and Systematics, Cornell University, Ithaca, NY.

Jensen, V.S. (1941) Hurricane damage on the Bartlett Experimental Forest. *USDA Northeast Forest Experiment Station Technical Note*, **42**.

Johnson, E.A. (1981) Vegetation organization and dynamics of lichen woodland communities in the Northwest Territories, Canada. *Ecology*, **62**, 200–215.

Lyford, W.H., Goodlet, J.C. & Coates, W.H. (1963) Landforms, soils with fragipans, and forest on a slope in the Harvard Forest. *Harvard Forest Bulletin*, **30**, 1–68.

NETSA (1943) *Report of the U.S. Forest Service Programs Resulting from the New England Hurricane of September 21, 1938*. Northeastern Timber Salvage Administration, Boston, MA.

Neustein, S.A. (1971) Intense windblow of Scottish forests in January 1968. *Forestry Commission Bulletin*, **45**.

Oliver, C.D. (1981) Forest development in North America following major disturbances. *Forest Ecology and Management*, **3**, 153–168.

Perley, S. (1891) *Historic Storms of New England*. Salem Press, Salem, MA.

Pickett, S.T.A. & White, P.S. (eds) (1985). *The Ecology of Natural Disturbance and Patch Dynamics*. Academic Press, New York.

Putz, F.E., Coley, D.D., Lu, K., Montalvo, A. & Aiello, A. (1983) Uprooting and snapping of trees: structural determinants and ecological consequences. *Canadian Journal of Forest Research*, **13**, 1004–1020.

Raup, H.M. & Carlson, R.E. (1941) The history of land use in the Harvard Forest. *Harvard Forest Bulletin*, **20**, 1–64.

Rowlands, W. (1941) *Damage to even-aged stands in Petersham, Massachusetts by the 1938 hurricane as influenced by stand condition*. MFS thesis, Harvard University.

Savill, P.S. (1983) Silviculture in windy climates. *Forestry Abstracts*, **44**, 473–488.

Simpson, R.H. & Riehl, H. (1981) *The Hurricane and Its Impact*. Louisiana State University Press, Baton Rouge.

Smith, D.M. (1946) *Storm damage in New England forests*. MF thesis, Yale University.

Somerville, A. (1980) Wind stability: forest layout and silviculture. *New Zealand Journal of Forestry Science*, **10**, 476–501.

Spurr, S.H. (1956a) *Stand composition in the Harvard Forest*. PhD thesis, Yale University.

Spurr, S.H. (1956b) Forest associations in the Harvard Forest. *Ecological Monographs*, **26**, 245–262.

Stephens, E.P. (1955) *The historical-development method of determining forest trends*. PhD thesis, Harvard University.

Stoeckler, J.H. & Arbogast, C. (1955) Forest management lessons from a 1949 windstorm in northern Wisconsin and upper Michigan. *USDA Forest Service, Lake States Forest Experiment Station Paper*, **34**.

Stout, B. (1952) Species distribution and soils in the Harvard Forest. *Harvard Forest Bulletin*, **24**, 1–29.

Swan, J.M.A. & Gill, A.M. (1970) The origins, spread, and consolidation of a floating bog in Harvard Pond, Petersham, Massachusetts. *Ecology*, **51**, 829–840.

Tomlin, C.D. (1983) *Digital cartographic modeling techniques in environmental planning*. PhD thesis, Yale University.

Tomlin, C.D. (1986) *The IBM Personal Computer Version of the Map Analysis Package*. Laboratory for Computer Graphics and Spatial Analysis, Harvard University Graduate School of Design, Harvard, Cambridge, MA.

Westveld, M. (1956) Natural forest vegetation zones of New England. *Journal of Forestry*, **54**, 332–338.

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