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Timber harvesting as ongoing disturbance in a landscape of diverse ownership

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Abstract

Although the northeastern US includes extensive areas of aggrading forest, uncertainty regarding the intensity and pattern of forest harvesting hampers an understanding of important ecological processes and characteristics such as carbon and nitrogen storage, habitat quality, and forest dynamics, and impedes regional conservation and management planning. Due to the complex ownership pattern dominated by thousands of non-industrial private forest (NIPF) owners and the difficulty of detecting selective logging using remote sensing, details of the harvesting regime remain largely unknown to the scientific and policy communities. To examine the value of statewide regulatory data for Massachusetts as a unique source of this critical information, we analyzed 17 years of timber harvest data gathered for regulatory purposes for a 168,000 ha forested landscape in Massachusetts that is the focus of concerted conservation planning and intensive study of landscape and ecosystem pattern and process. The North Quabbin Region is heavily wooded with a complicated ownership pattern dominated by over 2500 NIPF owners, three state agencies, and diverse conservation and municipal holdings.

The extent and intensity of harvesting were surprising, with an annual disturbance rate of 1.5% and a mean intensity of 44.7 $m^3\ ha^{-1}$ (approximately one-fourth of average stand volume). The predominant form of harvesting was selective removal of commercially valuable tree sizes, grades and species (e.g., *Quercus rubra* and *Pinus strobus*). The spatial pattern of logging was random with regards to major physical, biological, or cultural factors. However, logging was strongly related to landowner class. NIPF owners control 60% of the forest area and were responsible for 64.1% of harvest area, but the highest logging intensity (volume per area harvested; 69.3 $m^3\ ha^{-1}$) among major landowners was conducted by the state agency responsible for managing southern New England's largest conservation property, the watershed of Boston's drinking reservoir.

This regime of chronic disturbance is occurring over the entire landscape and exerting a major influence on forest composition, dynamics, and habitat quality. However, dispersed selective harvesting is largely unnoticed by residents, is routinely overlooked by ecologists and conservationists, and would remain unrecognized in the absence of this previously unused regulatory data. These results identify the value of regional regulatory spatial information to estimate ecological trends and to assist in conservation planning. Given similarities among ownership and forest patterns for much of the northeastern US, we expect that the broad findings of this study to have regional application.

Keywords: Timber harvest; Disturbance; Non-industrial private forest owners; Spatial pattern; Northeastern United States

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1. Introduction

Much of the eastern US has undergone a remarkable transformation over the past 150 years as vast expanses of farmland and intensively logged or burned-over forestland have, through a great decline in management activity in the last 100 years, reforested through natural succession (Whitney, 1994; Irland, 1999; Foster and O'Keefe, 2000). Substantial legacies of past land use remain in the soils, structure, composition, and function of these redeveloping forest ecosystems (cf. Motzkin et al., 1996, 1999; Compton et al., 1998; Foster et al., in press). In most eastern states current forest growth exceeds removals through harvest or mortality, and forests are increasing in age and the accumulation of woody biomass (Irland, 1999). This significant regional return of forest has many important ecological and social ramifications: US temperate forests are a carbon sink of large but uncertain proportions (Wofsy et al., 1993; Dixon et al., 1994; Goulden et al., 1996), the re-growing forests store excess nitrogen produced by anthropogenic sources (Aber et al., 1998; Ollinger et al., 2002; Driscoll et al., 2001), woodland wildlife is increasing at a prolific rate (Foster and Motzkin, 1998), the impacts of natural disturbance processes including windstorms, ice-storms and fire that are mediated by forest structure are increasing in severity (Boose et al., 2001), and bold proposals for wilderness preservation are being made for areas with a lengthy history of intensive human impact (RESTORE, 2000; Klyza, 2001).

The future status of broad forest areas and the trajectories of many important ecological processes will be largely determined by one major, though complex set of factors: the extent, intensity, and landscape pattern of ongoing human influences on these re-growing forests. Although reliable information on forest conversion to other land covers is readily available and detectable through remote sensing (e.g., MacConnell et al., 1991; Vogelmann, 1995), forest harvesting, the most important ongoing anthropogenic disturbance to the largest area of forestland, remains difficult to quantify (especially on NIPF lands). Nonetheless, regional analysis of the rate and pattern of forest harvesting is critical for estimating carbon budgets and forest productivity (Wofsy et al., 1993; Ollinger et al., 2002; Dixon et al., 1994), ecological recovery from historical land use (Foster et al., 1998; Fuller et al., 1998), temporal changes in wildlife habitat (DeGraaf and Yamasaki, 2001; Askins, 2000), low-level effects on first-order streams (Schuler and Briggs, 2000), and the trajectory of recovery from natural and human-imposed disturbances (Foster and Boose, 1992; Foster et al., 1997).

Throughout the US, reliable spatial information on harvesting is hampered by limited data from private ownerships (Spies and Turner, 1999). This issue is accentuated in the eastern US where most forest ownership is private and often in small parcels. Compounding this problem is the fact that the prevalent form of forest harvesting across this region—selective or partial tree removal (not in the silvicultural sense of harvesting in a selection system)—is difficult to assess remotely with airborne sensors. Although regional forest statistics are available through the USDA Forest Service Forest Inventory Analysis (FIA), there are many shortcomings in these data for ecological applications (Ohmann and Spies, 1998). In particular, samples have been collected at approximately decadal intervals with no specific spatial content and no information regarding harvesting pattern. Net growth and removals can be estimated from FIA forest samples for broad ownership categories (e.g., "other public", "forest industry", and "other private"), but these estimates are only in the form of overall volumes statewide, and provide no information on harvest intensity per unit area, more specific ownership class, or temporal variation. While harvest patterns have been studied on landscapes dominated by federal or large-scale industrial ownerships in which clearcutting is often the principle silvicultural tool (cf. Spies et al., 1994; Wallin et al., 1994; Green et al., 1993), there has been virtually no regional spatial analysis of harvesting regimes on landscapes characterized by selective or partial harvesting and non-industrial private forest (NIPF) ownerships. Gansner et al. (1990) reviewed inventory plot data and forest owner attitudes towards harvest-based on survey work in New England, but this was not spatially explicit. Since this is the largest single ownership category nationally (58%, Birch, 1996a,b), it is important to understand the temporal and spatial pattern of logging.

Specific questions addressed by this work include:

1. To what extent is harvesting occurring as a form of disturbance in this region dominated by NIPF ownership?

2. Is there any temporal or spatial pattern to the occurrence of harvesting, especially with respect to ownership type, conservation status, or physical and biological characteristics of forestland?
3. If there are any patterns of harvest, are they unique to the study area, or may they be possibly applicable to a larger area?
4. Does an improved knowledge of harvest occurrence have any implications for regional ecological processes and conservation planning?

2. Study area

The North Quabbin Region (NQR) includes portions of 19 towns in three counties in the Central Upland region of Massachusetts and is delineated by the Connecticut River Valley to the west, the New Hampshire border to the north, and township boundaries to the east and south (Fig. 1; Foster et al., 1998). The area totals 168,312 ha at elevations ranging from 75 to 486 m a.s.l., has an average population density of 42 persons per square kilometer (ranging from 8 to 134; MISER, 2001), and includes small town centers, minor agricultural land, and extensive forestland held by many private landowners and diverse public agencies, municipalities, and non-profit organizations. Although only 120 km west of Boston, the largest metropolitan area in New England, 81% of the 19 town region is forested. Approximately 2,500 NIPF owners in the region collectively own 60% of the forest, but the largest landowners are state agencies collectively responsible for 31.2% of all forest: the Metropolitan District Commission (MDC 23,421 ha), which manages the Quabbin Reservoir and watershed, source of metropolitan Boston's drinking water; the Department of Environmental Management (DEM, 12,309 ha); and Department of Fisheries and Wildlife (DFW, 6,506 ha). The NQR is the focus of intensive research by the Harvard Forest Long Term Ecological Research Program and National Institutes of Global Environmental Change Program, which investigate carbon dynamics (Wofsy et al., 1993), nitrogen saturation and regional forest productivity (Aber et al., 1998; Ollinger et al., 2002), forest and wildlife dynamics (Foster, 2000), and disturbance (Boose et al., 2001). The region is also the focus of long-term conservation planning by regional, state, and national organizations and agencies (Golodetz and Foster, 1997).

The NQR is primarily composed of uplands of granite, schist, and gneiss and are topographically rough with southward-trending valleys (Motts and O'Brien, 1981). Well-drained sandy-loam soils derived from glacial till predominate, but sandy and gravelly soils are common on glacial outwash and alluvial deposits (Mott and Fuller, 1967). The climate is humid continental and temperatures average 9 °C, rainfall 56 cm and snowfall 165 cm per year (Taylor and Holtz, 1985).

By the mid-nineteenth century, European settlers had cleared much of this forested region for agriculture and had heavily cut the uncleared woodlands. Farmland was widely abandoned and reforested naturally between 1850 and 1900 as the rural population migrated into urban industrial areas and to the midwest (Foster and O'Keefe, 2000). Second-growth hardwoods-white pine-hemlock forests now cover 81% of the region (Foster et al., 1998).

2.1. Historical context on logging in Massachusetts

Massachusetts and adjoining New England states have undergone considerable change in logging and lumber production over the past 150 years (Fig. 2; Steer, 1948; Bond, 1962; Bond and Loud, 1992; DEM, 1997; Berlik et al., 2002). Following agricultural decline and regional development of old-field stands of *Pinus strobus* and second-growth hardwoods (e.g., *Acer rubrum*, *Quercus rubra*, *Betula lenta*) in the mid-nineteenth century, logging was widespread and predominantly included clearcutting of white pine for boxboards and containers, and hardwoods for charcoal and fuelwood (Foster, 1998, 1999). Peak pine production occurred from 1900 to 1920 and gradually declined through the end of World War II. Logging increased in the 1940s when the predominantly even-aged hardwoods resulting from earlier clearcutting reached a small but merchantable size. The average size and amount of timber harvested has increased greatly since that time. The statewide harvest of sawtimber was estimated to be approximately 80 million board feet in 1952, and 132 million board feet in 1998 (Dickson and McAfee, 1988; Peters and Bowers, 1977; Alerich, 2000). Massachusetts is a state in which forest area has approximately doubled in the

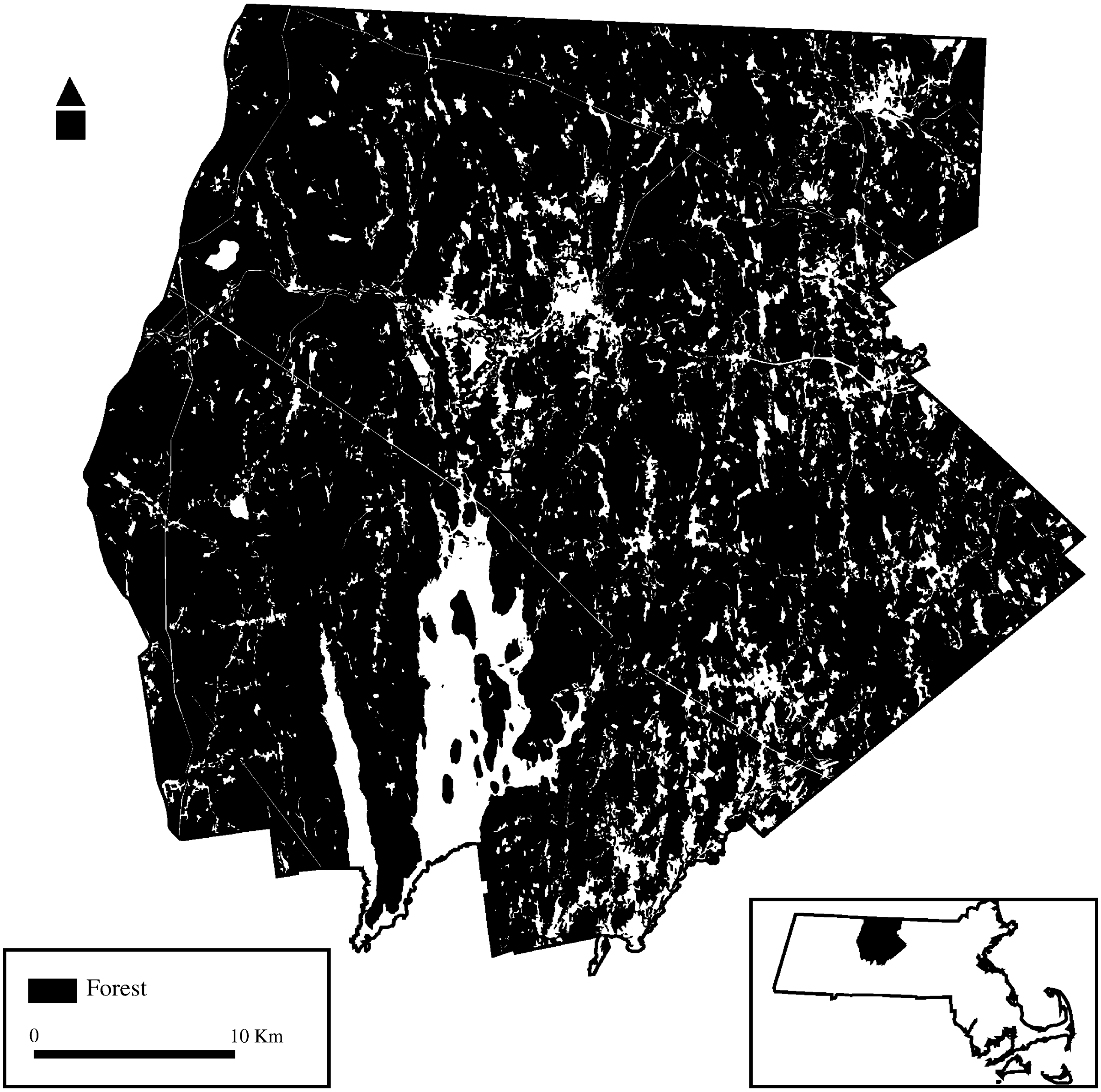

Fig. 1. Forest area (black) and non-forested fields, residential, water, and urban areas (white) in the North Quabbin Region, central Massachusetts. The northern portion of the Quabbin Reservoir, Boston's water supply is located in the southwestern portion of the study area.

last 150 years to 63% of all land (Irland, 1999; Alerich, 2000) and wood volumes have increased approximately 700% between 1953 and 1998 (Ferguson and Howard, 1956; Peters and Bowers, 1977; Alerich, 2000).

The ecological and cultural context for harvesting has also changed fundamentally over 150 years. Importantly: (1) rural farm-based land owners have been replaced by diverse owners who do not work on or derive substantial income from the land, and are not necessarily interested in timber products from their land (Rickenbach et al., 1998; MacConnell and Archey, 1982; Alexander, 1986; Birch, 1996a,b); (2) the number of forest owners statewide has increased

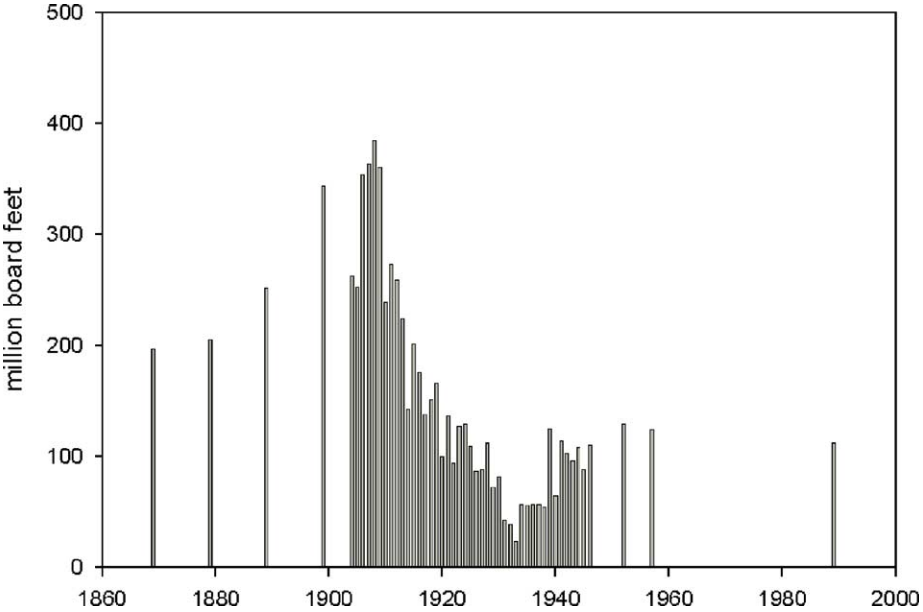

Fig. 2. Reported lumber production in Massachusetts, 1869–1996 (Steer, 1948; Bond, 1962; Bond and Loud, 1992; DEM, 1997).

with a corresponding decrease in average parcel size, e.g. from 125,000 NIPF owners in 1972 (mean parcel of 7.8 ha) to 235,000 in 1985 (mean parcel of 4.2 ha; Dickson and McAfee, 1988); (3) wood products are largely imported, used less for fuel, construction or packaging, and have a low market value as raw logs, relative to household income; (4) harvesting is predominantly selective (often due to concern for aesthetics) for commercially valuable species (e.g., *Q. rubra*, *P. strobus*), sizes, and grades, allowing for repeated operations in shorter time intervals; (5) exotic pests, including hemlock woolly adelgid are increasing (Orwig and Foster, 1998); (6) forests are compositionally more homogenous on a regional basis than prior to European settlement (Foster et al., 1998).

3. Methods

3.1. Harvesting

We analyzed long-term spatial information on timber harvesting throughout a forested region of diverse ownership. The 1983 Massachusetts Forest Cutting Practices Act requires submission of a Forest Cutting Plan (FCP) to the state forestry agency (Massachusetts Department of Environmental Management, DEM) prior to any harvest greater than 87 m^3 on all public or private land (Kittredge, 1996). FCPs are not required for harvesting that results in land use conversion. Thus, they characterize the amount of harvesting that is happening on forestland, but cannot be used as an indicator of the extent of ‘‘liquidation’’ or ‘‘terminal’’ harvests leading to some other land use. FCPs include quantitative descriptions and cartographic information on each harvesting operation in terms of location, spatial characteristics, silvicultural approach, wood volumes removed, owner motivation, and measures to mediate potential impacts to water quality and rare species habitat. Importantly, these statewide data have been maintained annually for 17 years, and cover all ownerships.

FCPs were obtained from the DEM (Massachusetts' forest and parks agency) for all regulated harvests in the NQR from 1984 to 2000. Each harvest was spatially captured by either tracing the areas onto a USGS topographic map and then digitizing these polygons, or by delineating harvest areas directly on-screen on digital topographic maps using ArcView (ESRI, 1992). For each harvest operation, we recorded: volume harvested, date, and landowner category (e.g., private, state, industry, conservation organization).

Spatial delineation of harvest areas varies in precision and accuracy because source data in FCPs are recorded for regulatory and not research purposes. Harvest maps represent the best estimates of the loggers and foresters who prepare FCPs, and the DEM foresters who review and approve them, and hence provide a good depiction of logging at a broad scale. Likewise, harvest volumes are estimated prior to sale and are reviewed by DEM foresters but are not precisely measured. A comparison of the statewide average annual harvest removal volume derived from FCP data (322,098 m^3) with the estimate of statewide annual harvest removal based on USDA Forest Service Forest Inventory and Analysis (Alerich, 2000; 366,173 m^3) suggests that FCPs describe a comparable level of harvest activity. While there may be commercial harvests that occur without a FCP, due to the regulatory nature of the program and penalties for non-compliance, we believe overall that FCPs describe the vast majority of harvest activity, and for the purposes of this analysis, they provide an index of relative harvest intensity or degree of disturbance.

3.2. Additional GIS overlays

To compare the spatial distribution of harvests and overall NQR forest with physical, biological, and cultural factors, GIS data layers were developed or obtained from the Massachusetts Office of GIS (MassGIS, 2002). Forest distribution was derived from a land cover data layer interpreted from 1985 aerial photography (MassGIS; 1:25,000 scale color infrared photography, minimum mapping unit of 0.4 ha). Slope, aspect, and elevation layers were generated from a digital elevation model (1:24,000, 30 m resolution, MassGIS). Surficial geology and a coarse expression of covertype (i.e., based on 1992 Landsat Thematic Mapper satellite imagery) were obtained from MassGIS. A data layer of roads developed by the Massachusetts Department of Transportation (MassGIS) was used to generate a map of distances from roads. MassGIS road classes 1 (limited access highway) to 6 (minor street or road) were included in the analysis. Smaller roads categorized as ‘‘tracks’’ or ‘‘trails’’ were not included.

We used historical sources to develop an overlay depicting continuously forested areas and areas that have reforested following clearing for agriculture over the last 150 years (cf. Foster et al., 1998 for details). This distinction is important for conservation purposes and the interpretation of ecosystem processes since continuously forested areas retain a much higher percentage of native species and have undergone less change in soil characteristics and processes (Compton et al., 1998; Donohue et al., 2000; Aber et al., 1998; Motzkin et al., 1999). Although most continuously forested areas have undergone some level of partial harvest and are not old growth forests, they are less disturbed than former agricultural sites that are currently forested.

3.3. Spatial analysis

We used the mean shape index (MSI) to determine the extent to which harvest polygons are compact (McGarigal and Marks, 1995). MSI is the sum of polygon perimeters divided by the square root of polygon areas, adjusted for a circular standard, and divided by the number of polygons. MSI can range from 1 for perfect circular shapes, and can increase without limit, indicating polygons that are non-compact.

We used a nearest neighbor analysis (NNA; Clark and Evans, 1954) to provide a metric of timber harvest distribution across the NQR landscape using centroids of timber harvest polygon events. The NNA algorithm used includes a boundary strip to eliminate bias possibly introduced by centroids near the edge of the NQR study area. The NNA generates a nearest neighbor index (R), which describes the collective point entity distribution across the study area as clustered, random, or evenly distributed. R is the ratio of the observed mean distance between nearest neighbor points and a random mean distance between neighbor points (holding the number of points sampled and sample area constant). The observed point scatter represents a random distribution when $R = 1$, discrete clusters when $R < 1$, and an even or regular distribution when $R > 1$. A measure of R-value significance provides a level of confidence for those point distributions that tend towards either a cluster pattern or an even or regular pattern. Because this analysis provides a measure of significance to point distributions, which deviate from random, it is not appropriate to equate a lack of significance with the amount of randomness in the point scatter. However, we may infer randomness when the R-value is near 1 and the z-score is less than the pre-set alpha level indicating significance. The *z*-score is calculated by dividing the difference between the mean distance between the nearest pairs of observed points and the mean distance between the nearest pairs in a perfectly random point distribution of the same number of points and area, by the standard error of the random point distribution (Hammond and McCullagh, 1978). The significance of the resulting *z*-score can be checked by referring to a table of critical values of a standard normal deviate with a pre-set significance level.

We used ArcView Spatial Analyst to compare the percent of grid cells of NQ forest and harvest areas across varying degrees or categories of biological, geographic, and cultural features.

3.4. Statistical analysis

A general linear model (GLM) analysis of variance was used to test for significant differences in harvest area and harvest intensity for six ownership categories. Duncan multiple-range tests ($P = 0.05$) were performed for both datasets (SAS Institute Inc., 2000).

Logistic regression coefficients, odds ratios, and corresponding confidence limits were used to assess the relative probability of timber harvesting on each ofthe NQs forest ownership categories (SAS Institute Inc., 2000). The response variable in the logistic regression is a dichotomous measure recorded as 1 = harvested or 0 = not harvested in the past 17 years. This presence or absence of harvest event was recorded for each $30\,\text{m} \times 30\,\text{m}$ forest pixel in the NQ study area. The explanatory variables are seven dummy variables each corresponding to one of the ownership types (DEM, DFW, federal land, private forest industry, municipal, MDC, and non-governmental agencies). The eighth ownership type (NIPF) was set as the reference variable in the analysis. In this manner harvest occurrence probability is estimated for each of the seven ownership types in relation to harvest activity on NIPF land (the dominant ownership type).

Chi-square analysis was used to test for significant differences between the percentages of overall NQ forest and NQ harvest areas, by geographic, biological, and cultural features. The goal was to determine whether or not harvest occurred in the same proportion as overall NQ forest, or in some disproportionate way, suggesting a pattern or tendency of harvest with respect to certain landscape features.

4. Results

4.1. Extent of harvest

Timber harvesting occurred frequently and consistently in the North Quabbin Region between 1984 and 2000. There were 2158 harvest events over this period, for an average of 126.9 per year (S.D. = 25.4). Approximately 26% of the forest was harvested at least once (35,626 ha; Fig. 3, Table 1) and nearly 3% (3,786 ha) was harvested more than once. The average harvest was 16.5 ha (S.D. = 18.8). Approximately 1.5% (2,000 ha) of the region's forest is disturbed by harvesting annually.

There was little annual variation or trend in the number of harvests or area harvested (Fig. 4). However, there was considerable variation among landowner categories. NIPF, industry, local agencies, and the MDC operated on 28–70% of their collective ownership, whereas the DEM, DFW, non-governmental organizations, and federal agencies operated on less than 14% of theirs (Table 1). The majority of harvests (64.1% by area, 64.8% by number) occurred on NIPF land, in approximate proportion to the extent of ownership (i.e., 60%, Table 1, Golodetz and Foster, 1997).

Harvesting intensity (HI: $\text{m}^3\,\text{ha}^{-1}$ removed in a harvest operation) varied among ownership types and within a given type, as reflected in the relatively large standard deviation around means (Table 1). Among major landowner groups, the MDC harvested at the highest mean intensity ($69.3\,\text{m}^3\,\text{ha}^{-1}$) followed by DEM ($44.8\,\text{m}^3\,\text{ha}^{-1}$), NIPF ($37\,\text{m}^3\,\text{ha}^{-1}$), and industry ($26.6\,\text{m}^3\,\text{ha}^{-1}$). The mean HI is $44.7\,\text{m}^3\,\text{ha}^{-1}$ (S.D. = 39.5) and overall median HI is $28.5\,\text{m}^3\,\text{ha}^{-1}$.

To put HI into perspective, the volume in sawtimber stands, which are most likely to support timber harvests covered by the Forest Cutting Practices Act was $153.2\,\text{m}^3\,\text{ha}^{-1}$ in 1985 and $181.8\,\text{m}^3\,\text{ha}^{-1}$ in 1998 (Alerich, 2000). Between 1985 and 1998, the average sawtimber volume was $167.5\,\text{m}^3\,\text{ha}^{-1}$. Based on this average, a mean NQR harvest intensity (HI) of $44.7\,\text{m}^3\,\text{ha}^{-1}$ represents an estimated reduction of 26.7% of volume from sawtimber stands.

A GLM analysis of variance was performed on harvest area ($F = 18.97$; d.f. = 5, 2148; $P = 0.0001$) and HI ($F = 23.06$; d.f. = 5, 2148; $P = 0.0001$) for six ownership categories. MDFW and

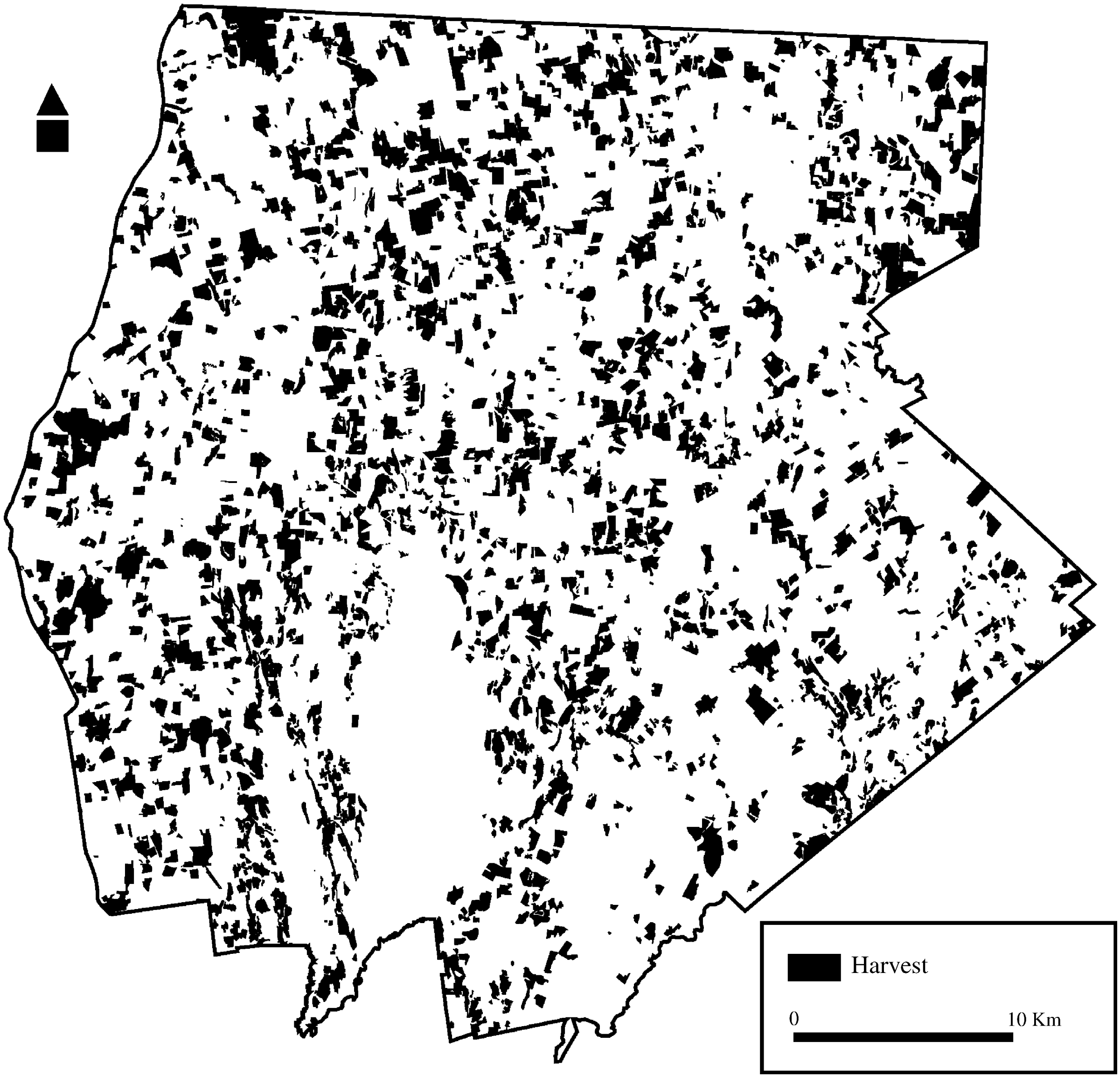

Fig. 3. Harvest operations (in black) in the North Quabbin Region, 1984–2000.

federal agency harvests were not included in the analysis because of insufficient observations. Duncan multiple-range tests ($P = 0.05$) were performed for both datasets to identify significant differences between ownership categories. There were significant differences in harvest area and intensity by ownership class (Table 1).

On a regional basis, approximately 1.053×10^6 m^3 of wood was harvested during the study period, with NIPF lands and MDC accounting for nearly 90% of all volume (Table 1). Collectively, NIPF lands represent 60% of forest area, and 53.6% of volume harvested, whereas MDC owns 17.3% of the forest area, and produced 30.3% of the volume. In contrast, DEM owns 9.1% of the forest area, and produced only 5.9% of the volume. There are clear differences in harvest by ownership category, with most volume coming from a disproportionate amount of forest area.

Table 1
Descriptive statistics of harvest area, by ownership category in the North Quabbin Region study area, 1984–2000

	Owner type[a]								
	DEM	MDC	DFW	Local agencies	NGO	NIPF	Industry	Federal agency	Grand total
Total forest area (ha) (% of total)	12,308.5 (9.1)	23,421.2 (17.3)	6506.2 (4.8)	2,667.8 (1.9)	2780.8 (2.1)	81,113.3 (60)	4,643.5 (3.4)	1853.1 (1.4)	135,294.3
Total harvest area (ha) (% of total)	1,329.5 (3.7)	6,877.1 (19.3)	15.6 (<.01)	874.9 (2.5)	397.9 (1.1)	22,835.8 (64.1)	3,263.3 (9.2)	31.9 (<.01)	35,626
Percentage of forest ownership harvested	10.8	29.4	0.2	32.8	14.3	28.2	70.3	1.7	26.3
Mean[b] harvest area (S.D.) (ha)	13.3 c (8.6)	14 bc (11.8)	7.8 (3.9)	19.9 b (26.6)	17.3 bc (14)	16.3 bc (19.4)	33.3 a (31.7)	15.9 (11.2)	16.5 (18.8)
Number of harvest operations (% of total)	100 (4.6)	491 (22.8)	2 (<.01)	44 (2)	23 (1.1)	1,398 (64.8)	98 (4.5)	2 (<.01)	2,158
Mean[b] HI (S.D.) ($\mathrm{m}^3\,\mathrm{ha}^{-1}$)	44.8 bc (41.8)	69.3 a (98.8)	19.7 (16.2)	41.1 bc (39.6)	56.2 ab (102.8)	37 bc (41.3)	26.6 c (25.3)	175.1 (116.1)	44.7 (61.6)
Total harvest volume (m^3) (% of total)	62,104 (5.9)	318,807 (30.3)	244 (<.01)	22,182 (2.1)	9003 (0.9)	564,081 (53.6)	69,813 (6.6)	6874 (0.7)	1,053,108

[a] DEM: Massachusetts Department of Environmental Management; MDC: Metropolitan District Commission (i.e., surface water supply for metropolitan Boston); DFW: Massachusetts Division of Fisheries and Wildlife; local agencies: municipal conservation lands; NGO: non-governmental organizations, e.g., The Trustees of Reservations, New England Forestry Foundation; NIPF: non-industrial private forests owned by families and individuals; industry: lands owned by sawmills or other wood products industries; federal agency: Army Corps of Engineers for flood control purposes.

[b] Means with different letters are significantly different at 0.05 level as determined by a Duncan multiple-range test.

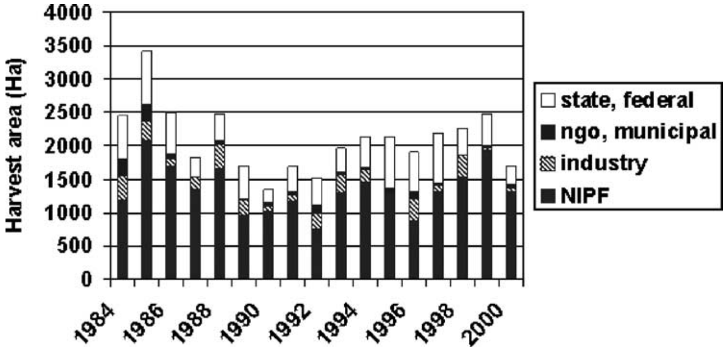

Fig. 4. Area of harvest (ha) by ownership type in the North Quabbin Region, 1984–2000.

Logistic regression was used to investigate the relationship between forest ownership type and probability of past timber harvest. At a 30 m × 30 m resolution the NQ study area contains over 1.5 million forested pixels. The dichotomous dependent variable in the logistic model consists of 326,420 pixels of past harvest and 1,176,846 pixels of non-harvested forest. With the forest ownership variables entered, the model chi-square fit statistic is highly significant with a chi-square value of 28,976.39, 7 degrees of freedom, and corresponding P-value of <0.0001.

The regression estimates the odds of harvest occurrence for ownership type. To understand the odds of harvest occurrence on a given ownership relative to the reference variable (i.e., NIPF), divide a given ownership's odds by the odds calculated for the model intercept (Table 2, odds ratio column). The odds ratios are a measure of harvest occurrence to non-occurrence (Hosmer and Lemeshow, 1989). For example, relative to NIPF ownerships, a given pixel on DEM land is about half as likely to experience a timber harvest, whereas, a given pixel on private industry land is over twice as likely to experience a timber harvest. A 95% confidence limit was calculated for each odds ratio. With the exception of the MDC and municipal ownership, the confidence intervals do not overlap and we can infer that most of the ownerships hold statistically unique probabilities of harvest events.

4.2. Spatial distribution of harvest

For each of the data layers characterizing the NQR landscape (cover type, roads, surficial geology, aspect, slope, elevation, estimate of original woods), the percentages of overall forest and harvested area were calculated by varying categories (Tables 3 and 4). For example, 63.2% of all forest in the NQR is on slopes of 0–5°, and 63.5% of all harvesting happened on slopes of 0–5°. Similarly, 11.3% of all NQR forest occurs on slopes with a southeast aspect, and 11.3% of all harvesting occurs on slopes with a southeast aspect. The occurrence of harvest exhibited no skewed rela-

Table 2
Logistic regression parameter estimates and related statistics for harvest occurrence by ownership type relative to NIPF lands (reference variable)

Parameters	Estimate	S.E.	Chi-square probability	Odds ratio	95% confidence limit
Intercept	−1.25	0.003	<0.0001		
DEM	−0.65	0.008	<0.0001	0.522	0.514–0.531
DFW	−0.85	0.012	<0.0001	0.429	0.419–0.439
Federal land	−1.86	0.035	<0.0001	0.156	0.146–0.167
Private industry	0.86	0.009	<0.0001	2.363	2.320–2.407
Municipal	0.15	0.014	<0.0001	1.167	1.136–1.199
MDC	0.14	0.005	<0.0001	1.154	1.142–1.165
NGO	−0.31	0.015	<0.0001	0.736	0.714–0.758

Table 3
Comparison of physical factors by percent of North Quabbin Region total forested area and the harvested area

	Percentage of total NQR forest area	Percentage of harvested NQR forest area	Chi-square statistic (d.f.) probability
Slope (°)			
0–5	63.2	63.5	0.2075 (2, 200) 0.9015
6–10	26.5	27.9	
>11	10.4	8.6	
Aspect			
Flat	1.6	1.3	0.1166 (8, 200) 1
N	6.4	5.9	
NE	10	9.9	
E	17.5	17.3	
SE	11.3	11.3	
S	7.7	8.2	
SW	12.7	13.5	
W	21.3	21.6	
NW	11.4	11.1	
Elevation (m)			
0–225	17.5	18.5	0.5512 (4, 200) 0.9683
226–275	18.6	21.5	
276–325	30.3	26.7	
326–375	27.5	26.1	
≥376	6.2	7.1	
Surficial geology[a]			
Sand, gravel	14.7	14.2	0.0157 (1, 200) 0.9002
Till, bedrock	83.7	84.8	

[a] Fine-grained and flood plain alluvium occurred too infrequently to include in the test, e.g. <1%.

Table 4
Comparison of biological and social factors, by percent of North Quabbin Region total forested area and the harvested area

	Percentage of total NQR forest area	Percentage of harvested NQR forest area	Chi-square statistic (d.f.) probability
Covertype			
Deciduous	41.4	39.4	0.1152 (3, 200) 0.9900
Coniferous	21.9	23.4	
Mixed conifer-hardwood	30.9	31.7	
Wooded wetland	5.8	5.5	
Land use history			
Continual forest	26	24	0.0008 (1, 200) 0.9772
Second, third-growth forest	74	76	
Distance from roads (m)			
0–210	40.7	38	0.2328 (4, 200) 0.9937
211–420	27.6	28.9	
421–630	15.1	16.7	
631–840	7.7	8.2	
≥841	8.9	8.3	

tionship with major physical, biological, cultural, or historical factors. Harvests were distributed evenly across forested areas with respect to slope, aspect, elevation, surficial geology, and cover type (Tables 3 and 4). Chi-square analysis indicates no significant differences between the proportions of forest and harvest area by category. Harvesting was also independent of broad patterns in historical land use as continuously forested areas were subject to similar rates of harvest as reforested agricultural lands (Table 4; total forest land in this analysis is less than other comparisons due to the lack of historical data for one township). There was also no apparent pattern of preferential harvest closer to roads (Table 4). The percentage of NQR forest area categorized by distance from roads is remarkably similar to, and not statistically different from, the percentage of harvest area categorized by distance from roads.

The overall MSI for harvest polygons was 1.537. When compared with a theoretical minimum of 1 for perfectly circular polygons and an infinitely large possible maximum for non-compact shapes, we believe harvest polygons in the study area to be relatively compact. In an overall landscape of over 168,000 ha, with the mean polygon area of 16.5 ha, we believe the use of centroids to represent harvest events in the NNA is a legitimate application.

NNA results (Table 5) show that for 13 of the 17 years of timber harvest data and for the cumulative timber harvest occurrence, harvest polygons were distributed randomly with respect to one another throughout the region.

Table 5
Results of NNA, indicating degree of randomness of harvest locations

Year	n	R	z-value	Arrangement
1984	117	1.07	1.55	Random
1985	165	0.94	−1.57	Random
1986	119	0.96	−0.82	Random
1987	98	0.92	−1.48	Random
1988	111	0.99	−1.90	Random
1989	89	0.99	−0.19	Random
1990	81	0.90	−1.81	Random
1991	79	0.96	−0.62	Random
1992	88	0.97	−0.51	Random
1993	109	0.95	−1.01	Random
1994	127	0.92	−1.62	Random
1995	144	0.97	−0.69	Random
1996	116	0.90	−2	Cluster*
1997	145	0.91	−2.10	Cluster*
1998	139	1.15	3.37	Dispersed*
1999	150	0.99	−0.16	Random
2000	126	0.87	−2.71	Cluster*
Total (1984–2000)	2022	1.01	1.20	Random

* Significance at $\alpha = 0.05$.

Table 6
Comparison of harvest activity at the regional level of the North Quabbin Region compared with Massachusetts as a whole (MA data from: Dickson and McAfee, 1988; DEM, 1999)

	NQR	Massachusetts
Forest area (ha)	136,585	1,254,526
Total land area (ha)	168,312	2,023,430
Forested (%)	81	62
Area harvested (ha per year)	2,090.9	12,416
Forest area harvested per year (%)	1.53	0.98
Average number harvest operations per year	137	771
No. of annual harvests/forest area (no./km^2)	0.96	0.61
Mean area/harvest occurrence (ha)	16.5	16.1
Population (2000 census)	71,374	6,349,097
Population density (persons/km^2)	42.4	313.8

4.3. How representative is the North Quabbin Region?

Is this logging pattern and intensity typical of activity across the greater forested region of the northeastern United States? Using statewide statistics from 1993 to 1998 as a basis of comparison (Table 6), it appears that the NQR is broadly representative of harvesting activity across much of Massachusetts. The NQR is more heavily forested than the state average, and is logged at a greater rate (i.e., 1.53% of forest area annually vs. 0.98% statewide), but given the fact that the population density statewide is more than seven times that of the NQR, it is remarkable that the rates of harvest disturbance are even comparable. For example, Wear et al. (1999) found that in Virginia population density is significantly and negatively related to harvest activity. By the time population density in their study area reached 388 km^{-2}, the probability of forest management approached zero. Barlow et al. (1998) noted a significant negative effect on the probability of harvest in Mississippi and Ala-

Table 7
Removals and percentage of NIPF forestland ownership by state in the NE[a]

	Year	Forest area (ha)	Mean annual statewide removals (m^3)[b]	Mean annual statewide removals per forestland area (m^3 ha^{-1})	Percentage of forestland in NIPF ownership	2001 Population density (persons/km^2)
MA	1998	1,254,526	1,526,343	1.217	66	314.2
VT	1997	1,873,291	2,317,463	1.237	71	25.6
NH	1997	1,952,205	3,782,302	1.937	70	54.2
CT	1985	738,957	692,181	0.937	64	272.9
RI	1985	163,898	118,875	0.725	80	391.3
NY	1993	7,543,752	5,513,461	0.731	67	155.4
PA	1989	6,856,595	8,187,294	1.194	62	105.8
NJ	1987	812,205	251,228	0.309	53	441.6

[a] http://www.fs.fed.us/ne/fia. Birch, 1996a,b. http://www.census.gov/.

[b] The net growing stock volume harvested or killed in logging, cultural operations such as timber stand improvement, or land clearing, and also the net growing stock volume neither harvested nor killed but growing on land that reclassified from timberland to non-commercial forestland during the period between surveys. This volume is divided by the number of growing seasons.

bama in areas of higher population density (130 km^{-2}). Harvest rates are significantly lower in densely populated urban/suburban areas that do not have a sufficient critical mass of forest areas large enough to support a commercial forest industry (Kittredge et al., 1996). The North Quabbin Region is probably typical of other parts of rural, heavily forested areas of western Massachusetts, and the rest of central and northern New England, excluding areas of considerable federal and industry ownership (Irland, 1999). More fragmented and densely populated parts of eastern Massachusetts, Connecticut, and Rhode Island probably experience far less disturbance from harvesting. USDA Forest Service Inventory and Analysis results from eight northeastern states show that removals per hectare of forestland compare more or less favorably with Massachusetts (Table 7). These northeastern states have a relatively high proportion of NIPF land, and hence a high likelihood of small, relatively light harvest-based disturbances occurring in a pattern similar to the one we document.

5. Discussion

Our results indicate that a representative sample of the central New England region supports a remarkable level of chronic, moderate intensity logging (average harvest removal of approximately 27% of timber volume) at an annual rate of 1.5% of forest area. Interestingly, this harvesting is spatially random, and exhibits little variation with major physical, historical, cultural, or biological factors, but varies strongly by ownership class. This form of disturbance is largely undetected by casual observation or even through detailed remote sensing. In particular, harvesting operates in a distinctly different manner compared to the typical wind-based natural disturbance processes of the region, since it occurs irrespective of elevation, slope, or aspect. We believe this form of light-to-moderate harvesting works to homogenize forest composition (in terms of species and diameter distribution) and landscape pattern, and delays the maturation of forests (Hall et al., 2002). A comparison with Massachusetts and other northeastern states suggests that these results can be broadly extrapolated and underscore the value of comprehensive, long-term spatial information on cutting patterns.

We believe our analysis of FCPs represents the vast majority of commercial logging activity in the region. There may have been some harvests that were not regulated since they fell below the threshold of 87 m^3, but we estimate these to be small, and few in number. The threshold of regulation represents a volume below which it is generally not commercially feasible to operate (Kittredge et al., 1996). However, some harvests below the threshold had FCPs voluntarily submitted, since an approved FCP creates an exemption from state wetland protection regulations.

Environmental factors such as slope, aspect, elevation, surficial geology, or coarse cover type appear to exert little influence on the occurrence of harvesting across the NQ region. Harvesting does vary strongly in extent and intensity according to ownership type. In particular, the principle driver of this disturbance regime is the non-industrial private ownership category, which represents 60% of forest ownership and has the largest potential cumulative effect on harvesting pattern across the region (Table 1, Fig. 4). NIPF harvest activity represents 64.1% of harvested hectares and 64.8% of harvest operations. Between 1984 and 2000, 28.2% of the NIPF lands were harvested, representing 53.6 of all volume from the region. In spite of landowner attitude surveys indicating disinterest in harvesting (Birch, 1996a,b; Alexander, 1986; MacConnell and Archey, 1982; Rickenbach et al., 1998), there appears to be a difference between attitudes and behaviors of this important landowner category.

The influence of state agencies on harvest disturbance in this landscape varied considerably. The MDC is responsible for 17.3% of the forest, and was involved in 19.3% of the harvest activities by area (22.8% of operations, covering 29.4% of its holdings), resulting in 30.3% of removed volume. In contrast, the state's forest and parks agency, the DEM is responsible for 9.1% of the forest area, but was involved in less than 4% of harvest activity (covering 10.8% of its holdings) resulting in 5.9% of regional harvest volume. The state's Department of Fisheries and Wildlife is responsible for only 4.8% of forest in the area, and during this study period engaged in negligible amounts of harvest.

Municipal conservation lands, and those owned by conservation-oriented non-governmental organizations represent a small portion of total forest ownership. Notably they do engage in harvesting on their lands, but it collectively does not amount to a significant form of disturbance. Unlike many forest-dominated regions, including northern New England, industrial ownership in the NQR is relatively uncommon (3.4% of total forest area), and harvesting patterns on those lands do not differ greatly from those on other ownerships.

5.1. Harvest implications

Timber harvesting disturbance in the NQR is undoubtedly selective in terms of species. For example, regionally, *Q. rubra* harvest exceeds *A. rubrum*, due to a nearly sixfold difference in stumpage price (e.g., $ 290/Mbf vs. $ 50/Mbf respectively). Statewide for 1984–1997, removals of *Q. rubra* sawtimber (i.e., trees greater than 11 in. dbh) exceeded those of *A. rubrum* by more than a factor of 4, in spite of the fact that *A. rubrum* stem density is more than four times that of *Q. rubra*, and *A. rubrum* sawtimber volume exceeds *Q. rubra* by 8% (Alerich, 2000).

Timber harvest in the NQR also selectively affects canopy structure. Since harvesting is conducted for commercial purposes, larger trees are preferentially removed, resulting in canopy openings of varying sizes, and retention of smaller trees undamaged by logging. Estimates of HI vary, indicating that the effect on the canopy ranges considerably from small, individual tree gaps, to areas in which large portions of the canopy are removed. HI ($m^3\ ha^{-1}$) or disturbance intensity may be considered a surrogate for basal area reduction of overstory trees. In general, approximately 27% of a stand's basal area is removed through this means of disturbance. A common structure in these second-growth hardwood and mixed stands is a multi-tiered canopy structure, with *Q. rubra* dominating the uppermost stratum, and *A. rubrum*, *B. lenta*, *Tsuga canadensis*, and other species prevailing in lower strata (Oliver, 1978). Market preferences for *Q. rubra* result in openings in this uppermost stratum, rather than uniformly throughout the vertical structure of the stands.

5.2. Comparison with other disturbance regimes

As a form of disturbance, timber harvesting is unique. Although its effects on canopies are most closely analogous to wind, harvesting removes biomass and in the NQR operates independently of topography or surficial geology. Natural disturbance in New England forests is primarily initiated by varying degrees of wind. While little is known about actual wind-based disturbance rates in second-growth forest, the probability of natural gap-based disturbance in eastern old growth forests (i.e., 1% annually; Runkle, 1981) is less than the rate of harvesting we observed (1.5% of the NQR influenced by harvest annually). Runkle (1982) reported mean gap sizes in eastern old growth mesic forests of 200 m^2 (ranging from 28 to 2009 m^2). Krasny and Whitmore (1992) made a distinction between gradual gaps (formed by individual tree death over time) and sudden gaps (caused by trees blowing over or snapping off). They observed mean gap areas of between 42.8 and 209.1 m^2 in "old" northern hardwood forests in New York that had not been disturbed for 60 years. Sipe (1990) reported that 80–90% of all gaps in temperate mature broadleaved forests are smaller than 300 m^2 in area. He furthermore reported that median areas of single-tree gaps in these forests range from 75 to 130 m^2, and median multiple tree gaps run from 240 to 290 m^2. The structure of eastern old growth or mature forests may make them more susceptible to gap-forming disturbances than even-aged second-growth forests that predominate in the NQR. Nevertheless, the same disturbance agents (e.g., wind, ice, insects) are acting on this younger forest, and one may expect roughly similar response.

Our data do not provide an estimate of gap size, and harvest treatment can vary significantly based on silvicultural prescription. Nevertheless, varying intensities of selection harvesting can mimic the results of disturbance regimes in this forest type (Engstrom et al., 1999). The relatively low HI compared to overall density suggests that harvesting may mimic this natural gap patchiness. Harvest also bears some similarity to disturbance by species-specific insect or disease (e.g., gypsy moth) due to the preferential focus on oaks. However it differs from all natural disturbances in that large woody biomass is exported from the site, and considerable edaphic disturbance can occur.

Many wind-based disturbances come from a prevailing direction, and hence can differentially impact the landscape based on slope, aspect, or elevation (Foster and Boose, 1992). In contrast, harvest activity in the NQR shows no relationship to these landscape characteristics. Some natural disturbance may preferentially occur on different parent materials, based on drainage (e.g., poorly drained soils are more susceptible to root rots; fire on excessively drained, sandy soils). This is not the case for harvests in the NQR.

5.3. Ecological implications

The pattern and intensity of harvesting has major ecological implications. Importantly, we believe one long-term consequence of this chronic disturbance will be a shift from large broad scale, coarse-grained even-aged forests that were the product of previous land use to smaller fine-grained two-aged and multi-aged forests (Hall et al., 2002). Second-growth even-aged stands would be trending towards an uneven-aged structure over time on the basis of natural disturbance and succession. The pattern of harvesting that we document most likely accelerates this shift, and also causes it to occur randomly throughout the landscape, rather than in patterns, as would be the case if natural disturbance regimes (e.g., wind of varying degrees, insect infestation) were the driver. There is also potential for a shift in regional species composition, as harvest preferentially focuses on *Q. rubra* and *P. strobus*, and generates conditions that favor *Acer rubrum* (already established in the understory; Abrams, 1999; Abrams and Nowacki, 1992) and *B. lenta* (Kizlinski et al., 2001). Harvest-based disturbance checks structural forest maturation and maintains an aggrading condition characterized by rapid biomass accumulation and carbon storage. Fuller et al. (1998) suggest that New England forests have been slow to recover from earlier landscape-level disturbances and evolve towards later seral stages due to "continuing low-levels of disturbance and perhaps insufficient time". Results reported here more specifically identify the extent to which these low-levels of disturbance occur spatially and temporally. The haphazard or random spatial distribution of harvests is likely to reinforce the homogenous composition and structure of forests that have developed in the past 300 years (Foster et al., 1998; Fuller et al., 1998; Hall et al., 2002). A forest landscape allowed to evolve through natural disturbance and response would tend to revert towards greater heterogeneity, since disturbances occur with varying frequency and wind-based disturbance is not random, but occurs to greater or lesser degrees according to topography (Lorimer, 2001).

5.4. Conservation and policy implications

Harvesting occurs randomly across the NQR landscape and represents an important form of disturbance in terms of local and even global environmental considerations. Because harvesting on a regional scale is the result of the cumulative actions of hundreds of individuals and dozens of organizations operating independently and with different objectives, the resulting pattern is haphazard, uncoordinated, and not varying with major biophysical, historical, or cultural factors. The only apparent pattern or consistent influence is related to ownership.

However, there exists potential to alter the ecological consequences of logging by coordinating the disturbance pattern, or consciously deviating from the established norm to achieve specific goals, including landscape diversity. For example, this and earlier work indicate that extensive forest areas can be interrupted by land conversion or harvesting (Kittredge and Kittredge, 1999). Recognizing this, it would be possible to develop areas of intensive harvesting on one hand, or to delineate continuous areas of no harvest, to develop natural structure, species composition, and support natural processes with interior forest taxa. Holders of larger pieces of land (e.g., state agencies) could consider these possibilities, since they are in a position to implement different management strategies and intensities than the plethora of different owners of small, private parcels that dominate the region.

The aggregation of harvest and non-harvest areas regionally would generate a very different landscape, as identified in similar work from Pacific northwestern landscapes (Franklin and Forman, 1987; Spies et al., 1994; Tang et al., 1997; Wallin et al., 1994). Even if it is neither possible nor practical to coordinate harvest activities on numerous small, non-industrial properties, larger public owners could use this information to guide their actions, or to seek ways to cooperate between agencies on adjoining parcels. In addition, incentives could be developed to inspire desired harvest effects on private lands.

5.5. Conclusion

This study has identified the extent of harvesting that occurs on a regional scale with potential ecological implications most likely unrecognized by scientists, conservationists, and planners. These results underscore the value of regional spatial information that spans ownerships, and the important potential for using environmental information gained as a byproduct of regulatory processes to generate ecological insights, assist in regional conservation planning, and identify new research directions.

Beyond these specific conclusions, these results have broader policy applications. An improved understanding of this chronic or continuous form of disturbance in a forested landscape contributes to further efforts to model carbon flux and other ecosystem processes. Likewise, the future of wildlife habitat at a regional scale can be better projected if we know how forests continue to be influenced. Policies and incentives can be better crafted to appeal to private landowners who hold the future of such a landscape in their collective hands. Similarly, understanding this harvest phenomenon allows for a more informed discussion of future policy alternatives for the management of public lands and regulatory or incentive programs for private lands.

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References

Aber, J., McDowell, W., Nadelhoffer, K., Magill, A., Berntson, G., Kamakea, M., McNulty, S., Currie, W., Rustad, L., Fernandez, I., 1998. Nitrogen saturation in temperate forest ecosystems. BioScience 48, 921–934.

Abrams, M.D., 1999. Red maple taking over eastern forests. J. For. 97 (5), 6.

Abrams, M.D., Nowacki, G.J., 1992. Historical variation in fire, oak recruitment, and post-logging accelerated succession in central Pennsylvania. Bull. Torrey Bot. Club 119 (12), 19–28.

Alerich, C.L., 2000. Forest Statistics for Massachusetts: 1985 and 1998. USDA Forest Service Resource, Bulletin NE-148, 104 pp.

Alexander, L., 1986. Nonindustrial private forest landowner relations to wildlife in New England. Dissertation. Yale University, New Haven, CT, 213 pp.

Askins, R., 2000. Restoring North America's Birds. Yale University Press, New Haven.

Barlow, S.A., Munn, I.A., Cleaves, D.A., Evans, D.L., 1998. The effect of urban sprawl on timber harvesting. J. For. 96 (12), 10–14.

Berlik, M.M., Kittredge Jr., D.B., Foster, D.R., 2002. The illusion of preservation: a global argument for the local production of natural resources. J. Biogeogr. 29 (10/11), 1557–1568.

Birch, T.W., 1996a. Private forest-land owners of the United States, 1994. USDA Forest Service Resource, Bulletin NE-134, 183 pp.

Birch, T.W., 1996b. Private forest-land owners of the northern United States, 1994. USDA Forest Service Resource, Bulletin NE-136, 293 pp.

Bond, R.S., 1962. Marketing lumber from Massachusetts sawmills. Massachusetts Agricultural Experiment Station, Bulletin No. 526. University of Massachusetts, Amherst, MA, 58 pp.

Bond, R.S., Loud, A.M., 1992. Lumber production and marketing changes by sawmills in Massachusetts, 1957–1989. Northern J. Appl. For. 9, 67–69.

Boose, E.R., Chamberlin, K.E., Foster, D.R., 2001. Landscape and regional impacts of hurricanes in New England. Ecol. Monogr. 71 (1), 27–48.

Clark, P.J., Evans, F.C., 1954. Distance to nearest neighbor as a measure of spatial relationships in populations. Ecology 35, 445–453.

Compton, J.E., Boone, R.D., Motzkin, G., Foster, D.R., 1998. Soil carbon and nitrogen in a pine-oak sand plain in central Massachusetts: role of vegetation and land-use history. Oecologia 116, 536–542.

DeGraaf, R.M., Yamasaki, M., 2001. New England Wildlife: Habitat, Natural History, and Distribution. University Press of New England, Hanover, 482 pp.

Massachusetts Department of Environmental Management (DEM), 1997. Directory of sawmills, dry kilns, and lumber treaters in Massachusetts, Boston, MA, 32 pp.

Massachusetts Department of Environmental Management (DEM), 1999. Personal communication, Boston, MA.

Dickson, D.R., McAfee, C.L., 1988. Forest statistics for Massachusetts—1972 and 1985. USDA Forest Service Resource, Bulletin NE-106.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., Wisniewski, J., 1994. Carbon pools and flux of global forest ecosystems. Science 263, 185–190.

Donohue, K., Foster, D.R., Motzkin, G., 2000. Effects of the past and the present on species distribution: land-use history and demography of wintergreen. J. Ecol. 88, 303–316.

Driscoll, C.T., Lawrence, G.B., Bulger, A.J., Butler, T.J., Cronan, C.S., Eagar, C., Fallon Lambert, K., Likens, G.E., Stoddard, J.L., Weathers, K.C., 2001. Acidic deposition in the northeastern United States: sources and inputs, ecosystem effects, and management strategies. BioScience 51, 180–198.

Engstrom, R.T., Gilbert, S., Hunter Jr., M.L., Merriwether, D., Nowacki, G.J., Spencer, P., 1999. Practical applications of disturbance ecology to natural resource management. In: Johnson, N.C., Malik, A.J., Sexton, W.T., Szabo, R.C. (Eds.), Ecological Stewardship: A Common Reference for Ecosystem Management, vol. 2. Elsevier, Oxford.

Environmental Systems Research Institute Inc. (ESRI), 1992. ArcView GIS 3.2. Redlands, CA.

Ferguson, R.H., Howard, M.C., 1956. The timber resource in Massachusetts. USDA Forest Service Northeast Forest Experiment Station, 45 pp.

Foster, C.H.W. (Ed.), 1998. Stepping Back to Look Forward: A History of the Massachusetts Forest. Harvard University Press, Harvard Forest, Petersham, MA, 339 pp.

Foster, D.R., 1999. Thoreau's Country: Journey Through a Transformed Landscape. Harvard University Press, Cambridge, MA.

Foster, D.R., 2000. From bobolinks to bears: interjecting geographical history into ecological studies, environmental interpretation, and conservation planning. J. Biogeogr. 27, 27–30.

Foster, D.R., Boose, E.R., 1992. Patterns of forest damage resulting from catastrophic wind in central New England, USA. J. Ecol. 80, 79–98.

Foster, D.R., Motzkin, G., 1998. Ecology and conservation in the cultural landscape of New England: lessons from nature's history. Northeastern Nat. 5, 111–126.

Foster, D.R., O'Keefe, J., 2000. New England Forests Through Time: Insights from the Harvard Forest Dioramas. Harvard University Press, Harvard Forest, Petersham, Cambridge.

Foster, D.R., Aber, J.D., Melillo, J.M., Bowden, R.D., Bazzaz, F.A., 1997. Forest response to disturbance and anthropogenic stress. BioScience 47, 437–445.

Foster, D.R., Motzkin, G., Slater, B., 1998. Land-use history as a long-term broad scale disturbance: regional forest dynamics in central New England. Ecosystems 1, 96–119.

Foster, D.R., Swanson, F., Aber, J., Burke, I., Brokaw, N., Tilman, D., Knapp, A., in press. The importance of land use and its legacies to ecology and environmental management. BioScience.

Franklin, J.F., Forman, R.T.T., 1987. Creating landscape patterns by forest cutting: ecological consequences and principles. Landscape Ecol. 1, 19–28.

Fuller, J.L., Foster, D.R., McLachlan, J.S., Drake, N., 1998. Impact of human activity on regional forest composition and dynamics in central New England. Ecosystems 1, 76–95.

Gansner, D.A., Birch, T.W., Arner, S.L., Zarnoch, S.J., 1990. Cutting disturbance on New England timberlands. Northern J. Appl. For. 7, 118–120.

Golodetz, A.D., Foster, D.R., 1997. History and importance of land use and protection in the North Quabbin Region of Massachusetts (USA). Conserv. Biol. 11 (1), 227–235.

Goulden, M.L., Munger, J.W., Fan, S.-M., Daube, B.C., Wofsy, S.C., 1996. Exchange of carbon dioxide by a deciduous forest: response to interannual climate variability. Science 271, 1576–1578.

Green, K., Bernath, S., Lackey, L., Brunengo, M., Smith, S., 1993. Analyzing the cumulative effects of forest practices: Where do we start? Geo Info Syst. (February).

Hall, B., Motzkin, G., Foster, D., Syfert, M., Burk, J., 2002. Three hundred years of forest and land-use change in Massachusetts, USA. J. Biogeogr. 29 (10/11), 1319–1336.

Hammond, R., McCullagh, P., 1978. Quantitative Techniques in Geography: An Introduction, 2nd ed. Clarendon Press, Oxford.

Hosmer, D.W., Lemeshow, S., 1989. Applied Logistic Regression. Wiley, New York, 307 pp.

Irland, L.C., 1999. The Northeast's Changing Forest. Harvard University Press, Harvard Forest, Petersham, MA, 401 pp.

Kittredge Jr., D.B., 1996. Protection of habitat for rare wetland fauna during timber harvesting in Massachusetts (USA). Nat. Areas J. 16 (4), 310–317.

Kittredge Jr., D.B., Kittredge, A.M., 1999. Interior and edge: the forest in Massachusetts. Massachusetts Wildlife, No. 3, pp. 22–28.

Kittredge Jr., D.B., Mauri, M.J., McGuire, E.J., 1996. Decreasing woodlot size and the future of timber sales in Massachusetts: When is an operation too small? Northern J. Appl. For. 13 (2), 96–101.

Kizlinski, M., Foster, D.R., Orwig, D.A., Kelty, M.J., Cobb, R., 2001. Ecosystem and vegetation response to hemlock logging. In: Pallant, J.S., Recos-Smith, D. (Eds.), Proceedings of the 12th Annual Harvard Forest Ecology Symposium. Long Term Ecological Research, Harvard Forest, Petersham, MA.

Klyza, C.M., 2001. An Eastern Turn for Wilderness. Wild Earth, Spring, pp. 10–14.

Krasny, M.E., Whitmore, M.C., 1992. Gradual and sudden forest canopy gaps in Allegheny northern hardwood forests. Can. J. For. Res. 22, 139–143.

Lorimer, C.G., 2001. Historical and ecological roles of disturbance in eastern North American forests: 9000 years of change. Wildlife Soc. Bull. 29 (2), 425–439.

MacConnell, W.P., Archey, W.E., 1982. Forest landowner characteristics and attitudes in Berkshire County, Massachusetts. Massachusetts Agricultural Experiment Station Research, Bulletin No. 679, Amherst, MA, 52 pp.

MacConnell, W.P., Goodwin, D.W., Jones, K.M.L., 1991. Land-use update for Massachusetts with area statistics for 1971 and 1984/1985. Massachusetts Agricultural Experiment Station Research, Bulletin No. 740, Amherst, MA, 976 pp.

MassGIS, 2002. http://www.state.ma.us/mgis/massgis.htm.

McGarigal, K., Marks, B.J., 1995. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. USDA For. Serv. Gen. Tech. Rep. PNW-351.

MISER, 2001. Massachusetts Institute for Social and Economic Research. University of Massachusetts, Amherst. http://www.umass.edu/miser/.

Mott, J.R., Fuller, D.C., 1967. Soil survey of Franklin County, Massachusetts. US Department of Agriculture in Cooperation with Massachusetts Agricultural Experiment Station, Washington, DC.

Motts, W.S., O'Brien, A.L., 1981. Geology and hydrology of wetlands in Massachusetts. University of Massachusetts Water Resources Center, Amherst.

Motzkin, G., Foster, D., Allen, A., Harrod, J., Boone, R., 1996. Controlling site to evaluate history: vegetation patterns of a New England sand plain. Ecol. Monogr. 66, 345–365.

Motzkin, G., Wilson, G.P., Foster, D.R., Allen, A., 1999. Vegetation patterns in heterogeneous landscapes: the importance of history and environment. J. Veg. Sci. 10, 903–920.

Ohmann, J.L., Spies, T.A., 1998. Regional gradient analysis and spatial pattern of woody plant communities of Oregon forests. Ecol. Monogr. 68, 151–182.

Oliver, C.D., 1978. The development of northern red oak in mixed stands in central New England. School of Forestry, Yale University, Bulletin No. 91, 63 pp.

Ollinger, S.V., Aber, J.D., Reich, P.B., Freuder, R., 2002. Interactive effects of nitrogen deposition, tropospheric ozone, elevated CO^2, and land use history on the carbon dynamics of northern hardwood forests. Glob. Change Biol. 8, 545–562.

Orwig, D.A., Foster, D.R., 1998. Forest response to the introduced hemlock wooly adelgid in southern New England, USA. J. Torrey Bot. Soc. 125, 59–72.

Peters, J.R., Bowers, T.M., 1977. Forest statistics for Massachusetts. USDA Forest Service Northeast Forest Experiment Station Resource, Bulletin NE-48, 43 pp.

RESTORE, 2000. Proposed: Maine Woods National Park and Preserve. The Northern Forest Forum 8A, pp. 1–16.

Rickenbach, M.G., Kittredge Jr., D.B., Dennis, D., Stevens, T., 1998. Ecosystem management: capturing the concept for woodland owners. J. For. 96 (4), 18–24.

Runkle, J.R., 1981. Gap regeneration in some old-growth forests of the eastern United States. Ecology 62 (4), 1041–1051.

Runkle, J.R., 1982. Patterns of disturbance in some old-growth mesic forests of eastern North America. Ecology 63 (5), 1533–1546.

SAS Institute Inc., 2000. SAS OnlineDoc®, Version 8. Cary, NC.

Schuler, J.L., Briggs, R.D., 2000. Assessing application and effectiveness of forestry best management practices in New York. Northern J. Appl. For. 17 (4), 125–134.

Sipe, T.W., 1990. Gap partitioning among maples (Acer) in the forests of central New England. Thesis. Harvard University, Cambridge, MA.

Spies, T.A., Turner, M.G., 1999. Dynamic forest mosaics. In: Hunter Jr., M.L. (Ed.), Maintaining Biodiversity in Forest Ecosystems. Cambridge University Press, Cambridge, pp. 95–160.

Spies, T.A., Ripple, W.J., Bradshaw, G.A., 1994. Dynamics and pattern of a managed coniferous forest landscape in Oregon. Ecol. Appl. 4 (3), 555–568.

Steer, H.B., 1948. Lumber Production in the United States: 1799–1946. USDA Miscellaneous Publication No. 669, 233 pp.

Tang, S.M., Franklin, J.F., Montgomery, D.R., 1997. Forest harvest patterns and landscape disturbance processes. Landscape Ecol. 12, 349–363.

Taylor, W.H., Holtz, C.F., 1985. Soil survey of Worcester County, Massachusetts, northeastern part. USDA in Cooperation with the Massachusetts Agricultural Experiment Station, Washington, DC.

Vogelmann, J.E., 1995. Assessment of forest fragmentation in southern New England using remote sensing and geographic information systems technology. Conserv. Biol. 9 (2), 439–449.

Wallin, D.O., Swanson, F.J., Marks, B., 1994. Landscape pattern response to changes in pattern generation rules: land-use legacies in forestry. Ecol. Appl. 4 (3), 569–580.

Wear, D.N., Liu, R., Foreman, J.M., Sheffield, R.M., 1999. The effects of population growth on timber management inventories in Virginia. For. Ecol. Manage. 118, 107–115.

Whitney, G., 1994. From Coastal Wilderness to Fruited Plain. Cambridge University Press, Cambridge.

Wofsy, S.C., Goulden, M.L., Munger, J.W., Fan, S.-M., Bakwin, P.S., Daube, B.C., Bassow, S.L., Bazzaz, F.A., 1993. Net exchange of CO^2 in a mid-latitude forest. Science 260, 1314–1317.