Preemptive and Salvage Harvesting of New England Forests: When Doing Nothing Is a Viable Alternative

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Abstract: *One unexpected consequence of natural disturbances in forested areas is that managers often initiate activities that may impose greater ecosystem impacts than the disturbances themselves. By salvage logging areas affected by windstorms or other impacts, by harvesting host trees in advance of insect infestation or disease, or by preemptively harvesting forests in an attempt to improve their resilience to future disturbances and stresses, managers initiate substantial changes in the ecosystem structure and function. Much of this activity is undertaken in the absence of information on the qualitative and quantitative differences between disturbance impacts and harvesting. To provide insight for such decisions we evaluated the ecosystem consequences of two major disturbance processes in New England (U.S.A.)—intense windstorms and invasive pests and pathogens—and contrasted them with impacts from preemptive and salvage harvesting. Despite dramatic physical changes in forest structure resulting from hurricane impacts and insect infestation, little disruption of biogeochemical processes or other ecosystem functions typically follows these disturbances. Indeed, the physical and organic structures produced by these disturbances are important natural features providing habitat and landscape heterogeneity that are often missing due to centuries of land use. From an ecosystem perspective there are strong arguments against preemptive and salvage logging or the attempt through silvicultural means to improve the resistance or resilience of forests to disturbance and stress. There are often valid motivations for salvage or preemptive logging including financial considerations, human safety, and a desire to shape the long-term composition and resource-production characteristics of forests. Nonetheless, there are many ecological benefits derived from leaving forests alone when they are affected or threatened by disturbances and pest and pathogen outbreaks.*

Keywords: disturbance, fire, forest restoration, hemlock, hurricane, pathogen, pest

Cosecha Preventiva y de Salvamento en Bosques de Nueva Inglaterra: Cuando Hacer Nada es una Alternativa Viable

Resumen: *Una consecuencia insospechada de las perturbaciones naturales en áreas boscosas es los gestores que a menudo inician actividades que causan mayor impacto en los ecosistemas que las perturbaciones mismas. Al salvar áreas afectadas por vendavales u otros impactos, al cosechar árboles hospederos antes de la infestación de insectos o enfermedades, o al cosechar bosques preventivamente como intento de mejorar su resiliencia a perturbaciones y estreses futuros, los gestores inician cambios sustanciales en la estructura y función de ecosistemas. Mucha de esta actividad se lleva a cabo en ausencia de información sobre las diferencias cualitativas y cuantitativas entre los impactos de las perturbaciones y de la cosecha. Para proporcionar información a tales decisiones, evaluamos las consecuencias sobre el ecosistema de dos procesos de perturbación severos en Nueva Inglaterra (E. U. A.)—vendavales intensos y plagas y patógenos invasores—y los contrastamos con los impactos de la cosecha preventiva y de salvamento. A pesar de los dramáticos cambios físicos en la estructura del bosque resultantes de los impactos de huracán y la infestación de insectos, típicamente hay poca disrupción de los procesos biogeoquímicos u otras funciones ecosistémicas después de estas perturbaciones. Ciertamente, las estructuras físicas y orgánicas producidas por estas perturbaciones son atributos naturales importantes que producen heterogeneidad de hábitat y de paisaje que a menudo no existen debido a siglos de uso de suelo. Desde una perspectiva de ecosistema hay argumentos sólidos contra la*

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Paper submitted October 13, 2004; revised manuscript accepted April 24, 2006.

Conservation Biology Volume 20, No. 4, 959–970

DOI: 10.1111/j.1523-1739.2006.00495.x

cosecha preventiva y de salvamento o el intento de mejorar la resistencia o resiliencia de los bosques a la perturbación y estrés por medios silviculturales. A menudo hay motivaciones válidas para la cosecha preventiva o de salvamento incluyendo consideraciones financieras, seguridad humana y un deseo de configurar, a largo plazo, la composición y las características de producción de recursos de los bosques. Sin embargo, hay muchos beneficios ecológicos derivados de dejar solos a los bosques cuando son afectados o amenazados por perturbaciones y el surgimiento de plagas y patógenos.

Palabras Clave: abeto, fuego, huracán, patógeno, perturbación, plaga, restauración de bosques

Introduction

Over the past century New England (U.S.A.) forests have experienced two major disturbance processes in addition to many direct human impacts: infrequent, intense windstorms (predominately hurricanes but also downbursts, tornadoes, and winter storms) and outbreaks of nonnative pests and pathogens (e.g., gypsy moth [*Lymantria dispar*], chestnut blight [*Cryphonectria parasitica*], Dutch elm disease [*Ophiostoma ulmi*], beech bark disease [*Nectria coccinea* var. *fraginata*], and more recently, the hemlock woolly adelgid [HWA; *Adelges tsugae*]) (Foster & Aber 2004). Management responses to these events have been varied, ranging from doing nothing to massive salvage harvesting and preemptive harvesting (i.e., harvesting of trees believed to be vulnerable to damage by disturbance or insects; Smith et al. 1997). Recently, a variant of the preemptive approach has been promoted: silviculture aimed at developing a "protection forest" that is hypothesized to be resistant or resilient to a broad range of disturbances and stresses (Kyker-Snowman 2000; Muzika & Liebhold 2000; Waring & O'Hara 2005). Although many motivations drive these harvesting approaches, including economics, public safety, access, and fire hazard, the perceived negative attributes of forests affected by disturbance or stress is often a major contributing factor (Maloney 2005).

We assessed the immediate and long-term consequences of disturbance by wind and insects on forests in terms of ecosystem structure, composition, and function. We contrasted these with the effects of salvage and preemptive harvesting. We considered studies of "natural" experiments as well as some large, long-term manipulative experiments in which disturbances and stresses have been evaluated based on applied treatments and controls (Foster & Aber 2004). We discuss the benefits of different management approaches to forest disturbance and stress and evaluate the hypothesis that active management can improve long-term ecosystem function by increasing ecosystem resilience and resistance.

Wind Disturbance and Management Response

Numerous meteorological disturbances affect New England forests including ice and snowstorms, thunderstorms and downbursts, tornadoes, and northeasterly winter storms (Lemon 1961; Seischab et al.1993; Foster & Aber 2004; Jenkins 2004). Nevertheless, hurricanes are most important in terms of total area affected and potential for initiating broad-scale salvage logging. Regionally, hurricanes exhibit a decreasing gradient in frequency and intensity from the southeast to northwest, with southern areas experiencing extremely damaging storms every 75–125 years. At a landscape scale southern and eastern slopes and level sites are fully exposed to the strongest winds (Boose et al. 1994, 2001).

Interpretations of hurricane dynamics have been strongly shaped by studies of the 1938 storm, which was the most destructive in the last 175 years. This storm passed across central Massachusetts to the northwest corner of Vermont with winds exceeding 220 km/hour. Forest damage included windthrow of over 3 billion board feet of timber along a 150-km-wide path (Fig. 1). Following the storm the federal government organized the largest timber salvage operation in U.S. history, salvaging more than 1.5 billion board feet of lumber on private, state, and federal land (Fig. 2; NETSA 1943). This effort sought to reduce the threat of wildfire and minimize financial loss, but it led to road construction, soil scarification, slash burning, and enduring effects on forest

Figure 1. The old-growth forest on the Harvard Forest Pisgah tract in southwestern New Hampshire after the 1938 hurricane. Photograph from the Harvard Forest Archives.

Figure 2. Salvage logging in central Massachusetts following the 1938 hurricane. Photograph from the Harvard Forest Archives.

structure and composition (H.I. Baldwin, unpublished manuscript [1940]). The storm also exerted a long-term influence on forest practices as managers sought to incorporate information on hurricane impacts (cf. Clapp 1938; Jensen 1941; Smith 1946; Foster 1988). Recently, such information has been used in the development of management plans for the largest conservation property in southern New England—the 100,000-acre (40,500 ha) Quabbin Reservoir Reservation (Kyker-Snowman 2000).

Studies by Patric (1974) and others documented major ecosystem changes after the 1938 hurricane, including 5 years of increased river flow due to decreased evapotranspiration. Patric's work, the observations of increased nutrient export associated with experimental logging at Hubbard Brook (Bormann & Likens 1979), and the increased nutrient fluxes following Hurricane Hugo (Foster et al. 1997) have raised many questions about the effects of hurricanes on hydrology, soil chemistry, and ecosystem dynamics.

Assessing Ecosystem Response and Resilience to Hurricanes

To address ecosystem response and resilience to hurricanes we established a large experiment in 1990 to simulate the effects of a hurricane by pulling down several hundred canopy trees in a NW direction (Cooper-Ellis et al. 1999). The goal of the experiment was to (1) mimic the impact of a severe hurricane on a common forest type (red oak-red maple), (2) identify changes in forest structure and environment, (3) document patterns of species damage, regeneration, and growth, and (4) explore the relationships between vegetation dynamics, environmental change, and ecosystem processes. The design was based on empirical studies of the 1938 hurricane, when approximately 80% of canopy trees on exposed sites were damaged (Cooper-Ellis et al. 1999).

The manipulation produced dramatic changes in forest structure, including a redistribution of biomass to a tangle of prostrate boles and branches a few meters above the forest floor and the development of pit and mound topography. The basal area and density of standing trees declined by more than 70%, and the ratio of uprooted to snapped trees (approximately 70:30) closely approximated the damage in 1938. Despite the impact, the vegetation exhibited a remarkable capacity for survival and growth, which in turn maintained the functional leaf area and many key biotic processes (Fig. 3). Mortality of damaged and uprooted trees occurred gradually but progressively; despite 90% survival the first season, more than 80% of damaged trees died within 6 years. Compositional changes in the understory and overstory were minor.

Although vegetation was dramatically rearranged, few ecosystem-level changes occurred (Bowden et al. 1993; Fig. 4). Average soil temperature and moisture were unchanged because of the continued shade of sprouting and releafing of damaged trees, the expansion of ferns, and the

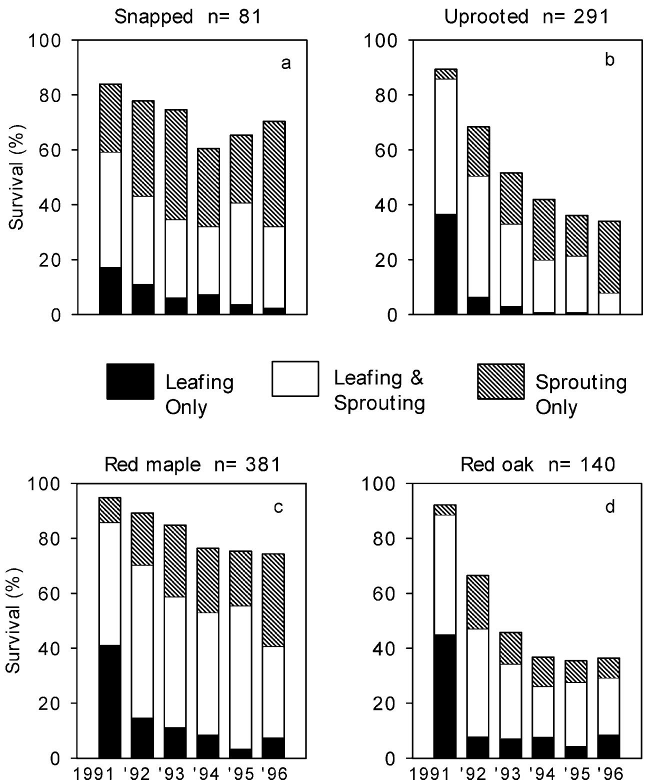

Figure 3. Survival (releafing and sprouting) of trees by (a, b) damage type and (c, d) species in the experimental hurricane area. Modified from Cooper-Ellis et al. (1999).

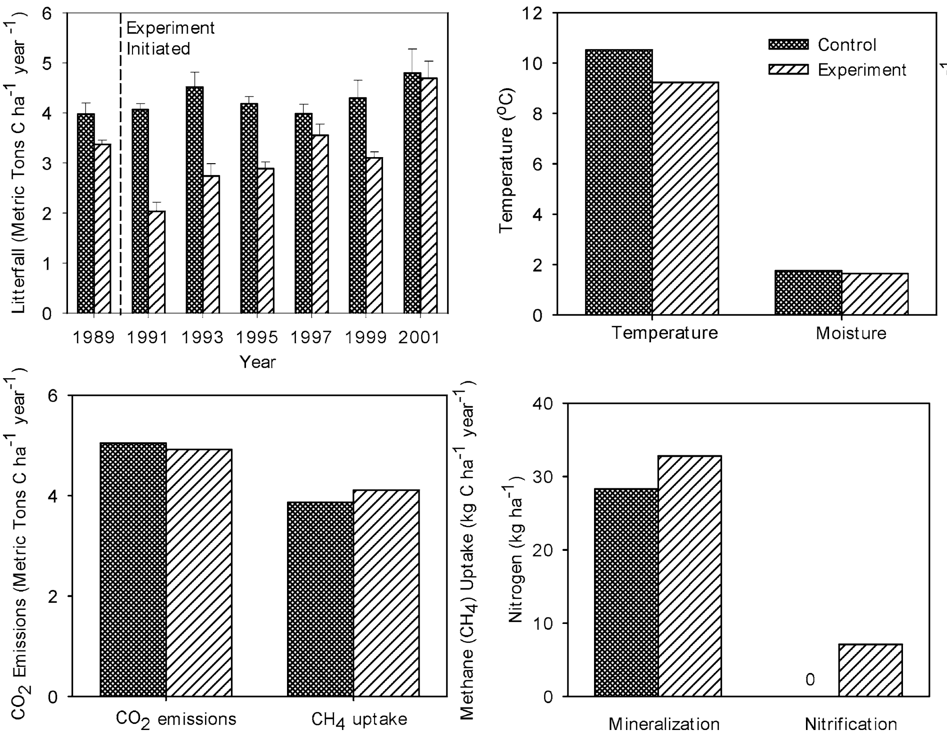

Figure 4. Summary of the major ecosystem and biogeochemical changes following the experimental hurricane blowdown. Modified from Foster et al. (1997). Unpublished litterfall data from A. Magill.

growth of saplings and seedlings, which increased from <6,000 to nearly 25,000/ha over 3 years. Modest changes in nitrogen (N) processing, especially nitrification, occurred, but these were minor relative to the N economy of the site. Net N mineralization was unchanged, soil nitrate remained low, and available ammonium increased. A strong indicator that the physical and biogeochemical environments were not severely altered was the stability in methane, carbon dioxide, and nitrous oxide levels.

Interpretation and Insights from the Experimental Hurricane

The results of this experiment led us to reevaluate the 1938 hurricane, the role of wind disturbance in our forests, and the impact of salvage logging (cf. Foster et al. 1997; Cooper-Ellis et al. 1999). Three results stand out: the initial high rate of tree survival; the early importance of vegetative reproduction; and the minor changes in composition. Nearly 15 years later the forest includes many growth forms and age cohorts: surviving trees; bent, misshapen, and sprouting stems; and seedlings on tip-up mounds and pit margins (Carlton & Bazzaz 1998). In contrast, after the 1938 hurricane windthrown areas were rapidly dominated by even-aged young stands of paper birch (*Betula papyrifera* Marsh.) and pin cherry (*Prunus pensylvanica* L.f.) (H.I. Baldwin, unpublished manuscript [1940]; Jensen 1941). The differences are largely attributable to salvage logging and the legacy of past land use, notably the extensive old-field white pine (*Pinus strobus* L.) stands in 1938. White pine, which had established on abandoned fields is highly susceptible to windthrow and comprised more than half of the timber damaged in 1938. Unlike hardwoods, pines do not sprout and die rapidly after uprooting. Consequently, in 1938 leaf-area continuity was interrupted as the pines died and were replaced by hardwoods. Salvage exacerbated environmental changes as damaged and sound trees were cut, slash was burned, and soils were scarified. Increased light altered the microenvironment and seed beds, favoring early successional and sprouting hardwoods (Foster et al. 1997).

The abrupt environmental and structural changes in 1938 were accompanied by soil and biogeochemical responses that differed from our experiment, including a great increase in soil moisture and river flow (Patric 1974) (Table 1). Although the decline in evapotranspiration was interpreted as a natural response it was certainly exacerbated by human activity. The dominance of white pine, the decrease in leaf area, and the soil disruption by logging and burning all reduced biotic control of soil and biogeochemical processes. Salvage logging produces substantial ecosystem response as biomass is removed, leaf area and canopy cover are further reduced, and changes in the soil environments increase metabolic and chemical processes. The consequences are reduced biotic control over hydrology and nutrient cycling and more abrupt and substantial changes in forest composition and structure. Salvage harvesting turns a natural event and process into a forest management operation.

Contrasting Impacts of Tree Species Decline and Mortality from Pests and Pathogens versus Harvesting

Tree decline from infestations of pathogens and pests is an important ecological and evolutionary process that alters ecosystems and natural resources (Castello et al. 1995; Everett 2000). These organisms may change forest composition, structure, and microenvironment; disrupt ecosystem processes such as nutrient cycling; and increase forest susceptibility to invasion by exotic plants and animals (Ramakrishnan & Vitousek 1989; Mack et al. 2000). Over the last century pest and pathogen outbreaks have occurred with increasing frequency in New England (Castello et al. 1995; Liebhold et al. 1995), including periodic outbreaks of spruce budworm (*Choristoneura fumiferana*) affecting red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* [L.] Mill.) in northern New England, a decline in white pine from white pine blister rust (*Cronartium ribicola*), and precipitous reductions in chestnut (*Castanea dentata* [Marshall] Borkh.), elm (*Ulmus americana* L.), and beech (*Fagus grandifolia* Ehrh.) from insects and diseases (Liebhold et al. 1995). Many of these episodes have involved introduced, exotic organisms.

Insect and disease outbreaks often lead to increased harvesting of the host species, including preemptive cutting before the arrival of the damaging organism and post-mortality salvage logging (Frothingham 1924; Irland et al. 1988; Muzika & Liebhold 2000; Radeloff et al. 2000). Although such harvesting is frequently ignored as an indirect impact of the outbreak, it oftentimes includes removal of nonhost species and may generate more profound ecosystem disruption than the pest or pathogen itself. The introduction of pests and pathogens is becoming an increasingly important ecological process with major economic, conservation, and social implications. Thus, it is critical to understand the ecological consequences of both the direct impact of these organisms on forest ecosystems and the indirect effects from human management responses.

The Hemlock Woolly Adelgid and Resulting Management Responses

Recent infestation by the exotic insect hemlock wooly adelgid (HWA) across the northeastern United States provides an opportunity to examine the ecological consequences of the removal of a dominant tree species, eastern hemlock (*Tsuga canadensis* [L.] Carrière), on forest composition, structure, and function. The HWA was introduced to the western and eastern United States in the 1920s and early 1950s, respectively (Annand 1924; Souto et al. 1996). It reached southern Massachusetts by the late 1980s (McClure & Cheah 1999). The HWA is a major threat due to its effective dispersal by birds, wind, and humans and the annual production of two parthenogenetic generations (McClure 1989, 1990). The absence of effective predators and the susceptibility of all age classes of hemlock to HWA present a major management concern across eastern North America (Orwig & Foster 1998).

Considerable effort has been expended on controlling HWA chemically (Steward & Horner 1994; Webb et al. 2003), but biological control is considered the only feasible broad-scale prospect (McClure & Cheah 1999). Over one million HWA-specific predatory beetles (*Sasajiscymnus tsugae*) from Japan have been released in 15 eastern states (Ward et al. 2004), and efforts are underway to release additional predators from China (Montgomery et al. 2000) and British Columbia (Zilahi-Balogh et al. 2003). To date there is no evidence that these predators will be effective (Cheah & McClure 2000; McClure et al. 2000).

Widespread hemlock decline over 4–12 years and subsequent mortality from HWA is gradually converting many forests to stands dominated by black birch (*Betula lenta* L.) (Orwig et al. 2002). The HWA has also prompted extensive salvage and preemptive logging of hemlock (Foster 2000; Brooks 2004), a species that otherwise has low commercial demand (Howard et al. 2000). For example, a single timber company cut >4 million board feet of hemlock in Connecticut and Massachusetts during 1998, and over 2400 ha of hemlock were harvested in central Connecticut in the late 1990s in response to HWA (Foster 2000; Orwig et al. 2002). In many cases valuable white pine and hardwood species are also removed to increase the economic return (Brooks 2004). Stated motivations for hemlock harvesting vary but include public safety, protection of drinking water supplies from excess nutrients and soil erosion, fire prevention, diversification of forest composition, and income. Land managers, owners, and policy makers seldom consider the ecological tradeoffs between harvesting and allowing trees to die from HWA (Cox & Mauri 2000; Orwig & Kittredge 2005).

Comparison of the Effects of HWA versus Harvesting

To provide a scientific background for hemlock management, we designed a study to compare the changes in microenvironment, vegetation, and ecosystem processes initiated by HWA, salvage logging and preemptive logging of hemlock (Kizlinski et al. 2002). At 10 sites in Connecticut and Massachusetts, 2 replicates of 5 different harvest ages (1, 2, 3, 7, and 13 years since harvest) were examined for immediate and long-term responses to logging. All sites had a minimum of 1 ha that was intensively logged (i.e., >65% basal area removed), were similar in soils and hemlock dominance (>65% basal area), and were adjoined by unlogged hemlock forest. Composition of the stands after logging included hemlock (68% of all uncut trees), smaller birch, and a few large oaks. Ecosystem analyses focused strongly on the microenvironment and N cycling,

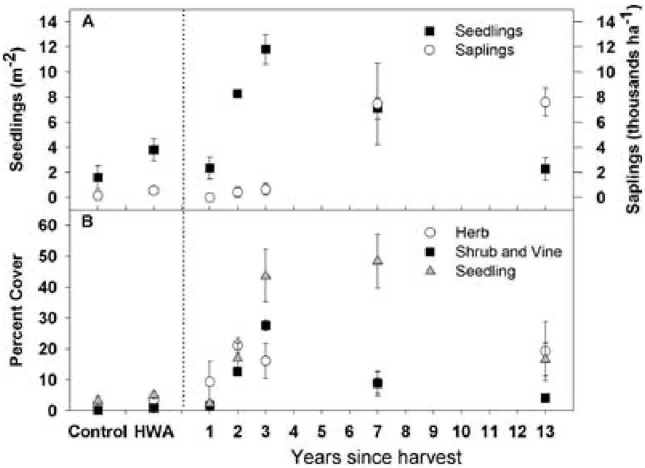

Figure 5. (a) Understory seedling and sapling densities and (b) understory vegetation cover of uninfested control, HWA(hemlock woolly adelgid)-damaged, and logged hemlock stands in southern New England (adopted from Kizlinksi et al. 2002). Each age is represented by two sites (mean 1 SE). The dashed line delineates unharvested and harvested stands.

especially net nitrification, net mineralization, and the availability of inorganic N in soil solution (see Kizlinksi et al. 2002 for details).

Results from this study and others (Brooks 2004) indicate that logging initiated stronger ecosystem changes than HWA-induced mortality due to abrupt and larger microenvironmental and vegetation changes, soil scarification, and the presence of extensive slash. Compositional changes accompanying logging or decline from HWA were similar overall but occurred at very different temporal and spatial scales. In each case, black birch and other hardwoods replaced hemlock. Following logging, however, there was a much greater increase in shade-intolerant seedlings, herbs, and shrubs (Fig. 5), red maple (*Acer rubrum* L.) sprouts, and invasive species (Brooks 2004).

Dramatic alterations in N cycling were initiated by harvesting and persisted for many years. In particular, although inorganic N pools increased only slightly in HWA-damaged sites relative to uninfested controls, they increased greatly with logging (Fig. 6). Net nitrification rates were 41 times higher in HWA-damaged sites, 72 times higher in recent harvests (1–3 years old), and over 200 times higher in old harvests (7–13 years old) when compared with near-zero rates in undamaged hemlock sites. The increased NO_3-N availability measured in recent harvests were lacking in older cuts. The large response on harvested sites may have resulted from a lack of vegetative uptake and an increase in microbial populations coupled with a rapid decomposition of organic layers under warm, moist conditions (cf. Vitousek et al. 1979; Ohtonen et al. 1992). In contrast, on sites undergoing decline due to HWA, understory vegetation replaces the gradually dying hemlocks and mitigates microenvironmental changes and losses of inorganic N (Bormann & Likens 1979; Vitousek et al. 1979). The large pools of N on harvest sites are a concern because N is highly mobile and frequently lost to groundwater and streams immediately following logging (Matson & Vitousek 1981; Krause 1982). Consequently, preemptive cutting appears to pose the greatest threat for nitrate leaching, followed by logging of declining sites and then by decline in the absence of logging.

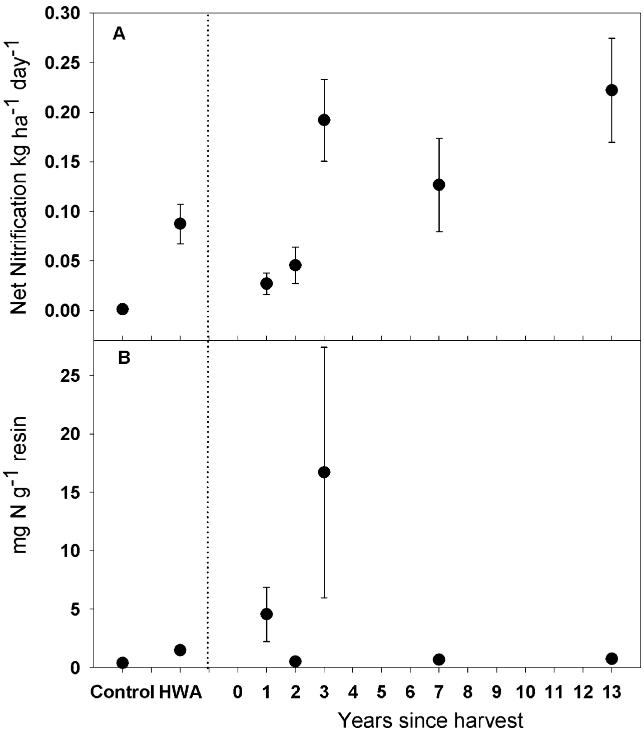

Figure 6. Soil nitrogen (N) dynamics expressed as (a) net nitrification rates and (b) nitrate capture on ion exchange resin bags in uninfested control, HWA (hemlock woolly adelgid)-damaged, and logged hemlock stands in southern New England (adopted from Kizlinksi et al. 2002). The dashed line delineates unharvested and harvested stands. Error bars are 1 SE of the mean.

Long-Term Management to Minimize Disturbance and Stress: the "Protection Forest" Approach

A variation on preemptive harvesting is the emerging silvicultural strategy to manage forests for structural and compositional characteristics believed to enhance resistance and/or resilience to potential disturbances and stresses (Kohm & Franklin 1997; NASF 2003; Waring & O'Hara 2005). This approach is based on the following untested rationale. First, forests are interpreted as being

Table 1. Increased river flow and decreased evaporative loss from hurricane-damaged watersheds (Connecticut and Merrimack) (inches per hydrologic year).*

	Flow increase		Evaporative decrease	
Year	Connecticut	Merrimack	Connecticut	Merrimack
1939	+4.8	+5.1	−5.8	−5.0
1940	+2.4	+2.9	−1.6	+1.6
1941	+2.5	+3.8	−3.4	−4.2

*Significant at the 0.05 level of probability.

increasingly subjected to disturbance and stresses from natural processes, introduced organisms, and industrial by-products such as N deposition (Banzhaf 1997; Aber et al. 1998; Billings 2000). Second, these stresses and disturbances are believed to alter forest ecosystem processes in ways that may decrease productivity or impair ecosystem services such as water quality (Barten et al. 1998; Maloney 2005). For example, it has been suggested that impacts from severe windstorms or insect infestations might increase erosional inputs or N leaching from forests that could impair stream, lake, and reservoir water quality or threaten human health. Third, it is proposed that long-term silvicultural programs might be able to develop forest structure and composition that minimize future impacts from these processes and thereby mitigate their deleterious environmental consequences (Kyker-Snowman 2000; Waring & O'Hara 2005). Finally, any negative consequences of harvesting on ecosystem processes are purported to be more than offset by the gains in resilience and resistance achieved by the harvesting (Kyker-Snowman 2000). Consequently, the long-term health of forest and aquatic ecosystems ostensibly will be greater under such proactive management than under the regime of natural disturbances, pests and pathogens, and anthropogenic stresses such as N deposition (Maloney 2005).

This logic has historical precedence in New England in the response of silviculturalists to the 1938 hurricane and a 1998 ice storm (Clapp 1938; Jensen 1941; Rowlands 1941; Smith 1946; Irland 1998). A variant of this approach is an attempt to reduce the vulnerability of forests to recurring insect outbreaks such as the spruce budworm and gypsy moth (Irland et al. 1988; Gottschalk 1993; Muzika & Liebhold 2000). Creating a mosaic of vegetation types is believed to lessen pest and pathogen impacts by lowering host abundance and potentially increasing the variety of parasitoids and predators (Muzika & Liebhold 2000).

A major implementation of the "protection forest" approach is occurring on state water-supply lands in Massachusetts, where the Department of Conservation and Recreation manages portions of three watersheds totaling 90,000 ha that produce over 250 million gallons of water daily for 2.5 million people or 40% of the state's population (Kyker-Snowman 2000; NASF 2003). These state lands are managed with a mandate to "protect the drinking water supply watersheds" and under the application of the protection-forest hypothesis they are among the most intensively harvested forests in southern New England (Kittredge et al. 2003; McDonald et al. 2006). The stated motivation for this intensive harvesting is "to improve natural filtration and improve water quality" by diversifying the age, size, and species structure of individual stands and the landscape (Barten et al. 1998; Kyker-Snowman 2000).

> "The working hypothesis of this approach is that frequent, endogenous [sic] disturbance of the scale of group-selection silviculture will lessen the amplitude of the disturbance wave represented by infrequent, exogenous disturbances, such as catastrophic hurricanes. The MDC-DWM made the commitment that any short-term negative effects of timber harvesting would not exceed the long-term negative effects of timber harvesting would not exceed the long-term benefits to drinking water derived from this deliberate forest structuring."

In the management plan for the largest area, the Quabbin Reservoir watershed, the creation of a "protection forest" is described as harvesting to produce a "diverse, stable, multi-layered forest. . .[that is] optimal with regard to watershed protection" (Kyker-Snowman 2000).

The cited ecological rationale underlying this application of the protection forest approach is that short, uneven-aged, and structurally varied forests of diverse composition are expected to be more resistant to physical disturbance (wind and ice storms), selective organisms (pests and pathogens), or chemical stresses (e.g., N deposition, ozone) than mature forests of simple structure and composition. This approach adopts the Vitousek–Reiners (1975) (see also, Bormann & Likens 1979) hypothesis regarding nutrient retention and suggests that aggrading, midsuccessional forests actively sequester carbon and nutrients, whereas maturing stands approaching a steady state of biomass are "leaky." It is suggested that in older forests nutrients such as N may leach into soils, streams, and water bodies to become pollutants.

Evaluation of the Protection-Forest Approach

Results from studies that implemented silvicultural strategies to reduce the impact of insect pests have had mixed success. In spruce-fir forests, altering the age and structure of regenerating stands reduced the susceptibility to spruce budworm defoliation in some but not all forests (Irland et al. 1988; Miller & Rusnock 1993). Similarly, thinning oak stands to reduce gypsy moth defoliation had variable success (Muzika et al. 1998). In both cases, there were situations where preemptive harvesting actually led to higher defoliation levels than in unthinned stands.

In terms of watershed protection, although a few large forest areas are currently managed with the belief that "forestry activities in source watersheds may maintain or improve the quality of drinking water," the protection-forest idea is an untested hypothesis (Kyker-Snowman 2000). A reasonable test would involve a large-scale experiment in which individual "control" watersheds would be maintained in a maturing and unharvested condition and allowed to be disturbed by natural disturbance or pests and pathogens, while similar "treatment" watersheds would be harvested according to the prescription for "forest protection." Forest and stream ecosystems in both watersheds would be monitored for nutrients and environmental characteristics over a lengthy period (cf. Hornbeck & Swank 1992). This experiment would explicitly test the protection-forest hypothesis and yield important data on both harvesting impacts and the function of unmanaged forests. Widespread application of protection prescriptions in the absence of true controls and monitoring precludes rigorous evaluation of the hypothesis (Barten et al. 1998; Kyker-Snowman 2000).

Nonetheless, many studies raise major doubts concerning the protection-forest hypothesis. First, although shorter statured forests may indeed be less susceptible to wind disturbance, no evidence exists that the stresses of wind and other disturbances pose a threat to water quality or ecosystem health. As shown above and in numerous other studies, these forests display great resilience to physical and chemical disturbances and stresses, recover quickly from impacts, and exhibit little disruption of processes that maintain water quality and forest health (Houlton et al. 2003). Even under extremely high (artificial) application rates of N deposition these forests show great control over biogeochemistry (Aber et al. 1993, 1998; Foster & Aber 2004). This ability is especially pronounced in forests such as those at Quabbin that have experienced a long history of cutting, burning, and grazing, which reduces N stocks (Compton & Boone 2000; Goodale et al. 2000; Goodale & Aber 2001). Indeed, New England forests exhibit an ability to immobilize N, a problematic nutrient in water supplies, in ways and at rates that greatly exceed the predictions of the Vitousek–Reiners model (Aber et al. 1998).

Second, in the case of many disturbances (e.g., wind, ice, or insects), the physical structures produced, such as uproot mounds and downed woody debris, are desirable natural features of forest and aquatic ecosystems that are missing from many forests due to their land-use history (Foster & O'Keefe 1998). One could argue that a management approach that allows trees to grow, age, and experience a range of disturbances will generate these missing features and thereby improve the health and diversity of forest ecosystems. Third, although the argument may appear reasonable, little evidence exists to suggest that it is possible to manage for increased resistance or resilience to the array of disturbances and stresses that temperate forests may experience (Aber et al. 2000). Many studies suggest that forests are oftentimes more vulnerable to exogenous impacts following management. Finally, although long-term management may not impair water quality, the notion that it will equal or improve on that from unmanaged forests has no support. All evidence suggests that harvesting exerts greater impacts on ecosystem processes than leaving disturbed or stressed forests intact. A conservative alternative hypothesis for the long-term management of watershed lands might be proposed: the elimination of harvesting and its associated impacts (e.g., soil compaction, road development and improvement) will yield forest and landscape conditions that maintain and improve water quality in the face of ongoing disturbances and stresses.

Discussion

Decisions on whether to salvage, cut preemptively, or leave forests after large natural disturbances depend on forest region, disturbance regimes, and landowner objectives. For example, New England forests do not commonly experience insect outbreaks that lead to large accumulations of hazardous fuels as the southern or western United States do (White et al. 1999). Many salvage decisions are made without the scientific background of management alternatives because landowners seldom have this information. Meanwhile, research and agency effort is largely geared at controlling the pests and pathogens or recouping financial losses and thwarting perceived risks to humans or property by damaged trees. By reviewing the relative ecological consequences of major types of disturbance that affect New England forests versus harvesting we seek to provide information to guide these decisions. We recognize that both the decision to leave damaged forests and the decision to harvest them are valid options in various settings (Orwig & Kittredge 2005).

One indirect consequence of natural disturbance and pest and pathogen outbreaks that is often overlooked is that salvage or preemptive harvesting may affect a larger area or create a greater impact on forest ecosystems than the disturbance itself (Frothingham 1924; Irland 1998; Radeloff et al. 2000). This is true for the recent infestation of HWA in New England. In areas affected by the insect in Connecticut, more than 50% of hemlock forests have been logged intensively (Orwig et al. 2002). Meanwhile, far to the north of the current distribution of the insect, landowners and foresters are cutting hemlocks extensively in anticipation of eventual impacts (Brooks 2004). In both cases the removal of many trees in addition to hemlock is turning what might have been the selective decline and mortality of a single species into a regional logging activity.

Many decisions to harvest before or after a disturbance or to attempt to increase forest resistance or resilience to disturbance and stress are based on the incorrect notion that forest ecosystems are damaged, destroyed, or impaired following major disturbance and that this situation should be avoided or remediated (Maloney 2005). From a functional perspective, however, substantial evidence indicates that northeastern forest ecosystems are extraordinarily resilient and that natural disturbances are inherent and essential processes for ecosystem function. Although novel disturbances and stresses are not inherent to these ecosystems, forests appear to cope with many them in a similar fashion (Aber et al. 2000).

Areas affected by extreme wind or insect outbreaks exhibit low to modest disruptions of nutrient cycling and little nutrient loss because of rapid regeneration, recovery of leaf area and vegetation cover, and effective biotic control of microenvironmental conditions (Bowden et al. 1993, D.O., unpublished data). In contrast, salvage and preemptive harvesting generate more rapid and extreme changes in microenvironment, forest cover, and soil litter and organic layer depth. For example, the efflux of nitrate measured in streams following such natural disturbances as soil freezing, insect defoliation, and ice storm damage were 2–10 times lower than nitrate fluxes associated with forest harvesting in New Hampshire (Houlton et al. 2003).

The unfolding situation with the woolly adelgid provides another good case study because many managers of conservation land, public water supplies, and private forests are concerned about the long-term health of their forests and the retention of nutrients by the ecosystem. In this situation preemptive and salvage logging may induce more profound ecosystem disruption than hemlock decline from HWA due to the more abrupt microenvironmental and vegetation changes (Kizlinski et al. 2002). Although both approaches led to forest dominated by black birch, logging resulted in greater regeneration of shade-intolerant species and an increase in stump sprouts, N availability, and net nitrification rates than unlogged sites. Whereas slow decline and the gradual development of a hardwood understory appear to result in the lowest loss of N, preemptive cutting poses the greatest threat, and logging of declining sites poses the second greatest threat for nitrate leaching due to reduced vegetative uptake.

The hurricane experiment is also highly instructive (Cooper-Ellis et al. 1999). Despite the dramatic appearance, the major ecological impact was a vertical reorganization of the canopy and foliage. The minimal change we observed in soil, microenvironment, and biogeochemical processes after the experiment suggests that natural hurricane disturbance is not functionally disruptive, at least where hardwood species are dominant. If the maintenance of biotic control over hydrology, soil environment, and nutrient fluxes is a priority of management and if rapid forest recovery is sought, then leaving the site intact may be a preferred approach. Because harvesting may also generate many undesirable impacts (compaction, erosion, scarification, residual tree damage) that alter ecosystem function, leaving the forest alone may be the approach taken, for example, in a municipal watershed where water quality is a primary objective or in conservation areas in which natural conditions and structures such as standing and dead trees are objectives (Foster et al. 1998; Lindenmeyer & Franklin 2002).

Rationale for Preemptive and Salvage Logging

Despite the potentially greater environmental and biogeochemical impacts of preemptive and salvage logging, both can be undertaken in a careful fashion that will not jeopardize long-term forest productivity or aquatic ecosystem health. There are benefits from harvesting, perhaps most importantly that it enables the manager to influence the future course of forest development. For example, at low infestation levels, light thinning of hemlock may increase vigor of remaining trees (cf. Waring & O'Hara 2005) and initiate understory vegetation establishment important for nutrient retention, especially if future salvage is planned (Orwig & Kittredge 2005). Salvage typically eliminates leaning, bent, and broken trees and promotes stump sprouts as opposed to stem sprouts. Although these structures are ecologically valuable they may reduce the future economic value of the stand for natural resource production. In addition, a desire to derive financial value from threatened or windthrown trees is a major motivation for many landowners, although care must be taken not to encourage invasive and equally undesirable early successional species by creating large forest openings and exposing mineral soil. Moreover, in many public landscapes there is a desire to remove damaged, dying, or dead trees that pose a direct hazard to people. In most cases this threat seldom warrants more than local removal along roads, trails, and vistas and need not be a motivation for stand-wide management.

Finally, many management decisions cite a concern about wildfire, both as a threat to the forest and to surrounding property. On this subject there is much speculation and strong opinions but few studies or real data for the northeastern U.S. temperate forests. Windstorms are frequently cited as one possible catalyst for forest fires in the New England landscape, and this was a major motivation for the massive salvage program following the 1938 hurricane. Nevertheless, no studies exist of the changes in fuel loading after windstorms from New England forests, and there is no good historical research that links windstorm events and fire. Most cutting is predicated on the intuitive notion that downed woody debris enhances long-term fire hazard. Although blowdowns in New England conifer stands may produce a short-lived increase in hazard (Patterson & Foster 1990), data from the hurricane experiment suggest that fine fuels, which are the main fire concern, are unevenly distributed and highly transient due to the rapid decay of fine material and the gradual mortality of the trees. The decomposition of fine fuels and the rapid growth of hardwood sprouts and understory plants quickly reduce the fire hazard. As a consequence, overall fire hazard was only slightly increased in the experimental study and for a relatively short time.

Conclusion

Whereas there are many reasons to harvest forests preemptively or following disturbances, there are equally viable and different arguments for a conservative approach of leaving the site and its dead and dying trees intact. From a biogeochemical, ecosystem function, and water-quality perspective there is strong evidence that a no-management policy is prudent. When other motivations, including economics, long-term natural resource production, and human safety prevail, harvesting can be conducted in a careful manner to minimize ecosystem disruption. Although intuitive support exists for the development of "protection forests" through silvicultural approaches to increase the resistance and resilience of forests to pests, pathogens, and natural disturbances, empirical data to support the approach are lacking. Not only is there sparse evidence that such approaches achieve their goals of increasing resistance and resilience, little evidence suggests that natural disturbances yield negative functional consequences. Therefore, current management regimes aiming to increase long-term forest health and water quality are ongoing "experiments" lacking controls. In many situations good evidence from true experiments and "natural experiments" suggests that the best management approach is to do nothing.

Acknowledgments

We thank R. Noss, J. DiMaio, T. Kyker-Snowman, J. Scanlon, K. Stinson, J. Mohan, G. Motzkin, and the Harvard Forest Lab Group for feedback on our studies. The research reported here was supported by the National Science Foundation (DEB 02-36897), LTER and Ecosystems programs, the A.W. Mellon Foundation, the U.S. Department of Agriculture Cooperative State Research, Education and Extension Service Program, and the U.S. Forest Service Focus funding. This paper is a product of the Harvard Forest Long-Term Ecological Research Program.

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