

# An integrated reconstruction of recent forest dynamics in a New England cultural landscape

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**Abstract** Broad-scale patterns of vegetation response to three centuries of human disturbance in the northeastern United States are well understood, but stand-scale (0.1–10 ha) interactions between land-use history and the ecological processes underlying these patterns are not. Enduring legacies of land-use history, though pervasive in modern forests, are not always obvious or intuitive, particularly in the regenerating stands that cover most of the region. Focusing on a second-growth, post-agricultural landscape in Petersham, Massachusetts, this study integrates (i) a stand-scale sedimentary pollen and charcoal record, (ii) survey and dendroecological data from the surrounding forest, and (iii) analysis of historical documents describing site-specific ownership and land use history. We demonstrate the strength of this multifaceted approach to vegetation reconstruction on sites with long land-use histories that are typical of the modern landscape. We infer that periods of low and high intensity agriculture commenced around 1760 and 1850, respectively, and that the agricultural era was initiated and terminated by episodes of increased fire. Dendroecological data corroborate deed records and suggest that a portion of the forest regenerated and was used for small-scale timber production

during the mid to late 1800s. Most of the forest established in the early 1900s, after which time the greatest disturbance was *Cryphonectria parasitica* (chestnut blight) induced mortality of *Castanea dentata* (American chestnut) and replacement by *Betula* (birch) species. This study highlights the potential to expand integrated historical ecological research into landscapes with lengthy histories of human disturbance and underscores the potential of this research to generate data with spatial and temporal resolution relevant to management and conservation efforts.

**Keywords** Land-use history · Stand-scale palynology · Historical ecology · Forest management · Harvard Forest

## Introduction

In New England (Fig. 1a), there has been much progress in reconstructing the composition and spatial patterning of pre-settlement forests (e.g. Cogbill 2000, 2002), analyzing responses of regional forests to three centuries of intense human disturbance (e.g. Foster et al. 1998, 2004; Fuller et al. 1998), and formulating a broad understanding of the relationship between land use and vegetation dynamics (Foster et al. 2004). In contrast, reconstructions that explore the mechanisms and processes underlying these regional patterns by examining the effect of human impacts on individual forest stands have been comparatively uncommon. The few existing studies provide insights at spatial and temporal scales that are both critical to interpreting the broader-scale patterns and relevant to management and conservation (Motzkin and Foster 2004).

Most of these stand-scale reconstructions have focused on mature stands with relatively limited human disturbance, conditions that are uncommon in the modern landscape

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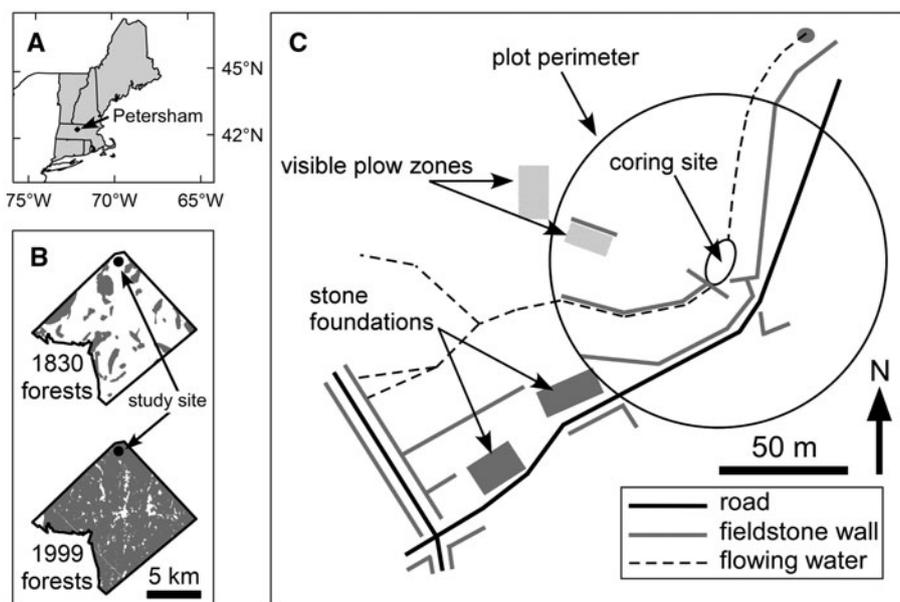
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**Fig. 1** **a** Regional orientation map depicting the New England states, in gray, and indicating the location of Petersham, Massachusetts. **b** Generalized maps of Petersham in 1830 and 1999, where gray areas are forested and white areas non-forested (cf. Foster 1992). **c** Detail map depicting the coring site (335 m above sea level; 42°32'24"N; 72°11'30"W; WGS 1984), plot perimeter, and locations of important anthropogenic features within and surrounding the plot. Redrawn following Nelson (2006; unpublished manuscript)



(cf. Marshall 1927; Foster and Zebryk 1991; Foster et al. 1992; McLachlan et al. 2000; D'Amato and Orwig 2008; but see Bradshaw and Miller 1988; Ireland et al. 2008). Throughout the region, forests are largely 50–100 years in age and shaped by lengthy histories of intense human modification (Foster 2004). Here, we test the utility of the integrated historical approaches previously used to reconstruct the dynamics of old forests with low-intensity disturbance histories in a young highly-disturbed forest, more typical of the broader landscape. We present a stand-scale reconstruction of human disturbances and forest regeneration at a site with a long history of land clearance, agriculture, farm abandonment, and forest regrowth. We integrate (i) pollen and charcoal records from a sediment core collected in a small pool, (ii) survey and dendroecological data from the surrounding forest, and (iii) historical analyses of land ownership and use. We seek to advance the capacity of historical ecology research to provide information on typical landscapes at spatial and temporal resolutions applicable to the development of management and conservation strategies (Motzkin and Foster 2004).

## Study area

### Physical and cultural setting

This study was conducted at the Harvard Forest in Petersham, Worcester County, Massachusetts (Fig. 1). The regional topography is characterized by north-to-south oriented ridges and valleys that are at elevations of 150–350 m above sea level, underlain by metamorphic bedrock, and veneered with shallow glacial till. Soils are acidic sandy

loams and arable primarily on the broad ridges (Foster 1992). The regional climate is humid and continental, receiving on average 110 cm of annual precipitation distributed evenly through the year. January and July air temperatures average  $-4.1$  and  $21.6^{\circ}\text{C}$ , respectively (Earth Systems Research Laboratory, National Oceanic and Atmospheric Administration, USA, <http://www.esrl.noaa.gov>).

The history of Petersham is typical of rural southern New England (Fig. 1b; Foster 1992, 2004). Settlement began in the early 1700s and by 1830, more than 60% of the land was pastured or tilled for active farms (Raup and Carlson 1941; Foster 1992; Foster et al. 2004). As agriculture shifted westward and industrial centers developed across New England, depopulation and regional farm abandonment led to widespread reforestation in towns including Petersham from the mid 1800s through early 1900s (Raup and Carlson 1941; Foster 1992). At present, nearly 90% of the town is reforested (Fig. 1b; Foster 1992, 2004).

### Study site

On the Prospect Hill tract of the Harvard Forest, we selected an approximately 1 ha area for study. The area is completely forested, but includes fieldstone walls, homestead foundations, abandoned agricultural plots, and a small, dammed depression containing a shallow pool (Fig. 1c;  $\sim 140\text{ m}^2$ , 50 cm deep). Informally named French Road Pool (FRP), the depression is situated in a narrow valley ( $<20$  m local relief) and fed by a seep that is reinforced with historic stonework and located 50 m northeast of the pool. Former pastures and plowed fields occur across the property and the forest is a mixture of deciduous trees and *Pinus strobus* (white pine).

## Materials and methods

### Sediment coring and analysis

A 45 cm sediment core was collected from the deepest portion of the pool using an 18 cm diameter Polyvinyl Chloride (PVC) piston corer. The sediment–water interface was intact and the core terminated in inorganic fine-grained material. In the laboratory, samples were extruded vertically in 1 cm intervals.

Loss-on-ignition (LOI) (Heiri et al. 2001) was used to estimate the organic matter content of subsamples (3 cm<sup>3</sup>) collected at 1 cm intervals through the length of the core. Local fire history (within ~10–100 m) was reconstructed by tallying macroscopic charcoal fragments at 10–40× magnification using a standard dissecting microscope (Higuera et al. 2005; Bradshaw 2007). Subsamples (1 cm<sup>3</sup>) for charcoal analysis were collected at 2 cm intervals, disaggregated by boiling in 10% KOH for 30 min, and gently sieved to isolate fragments >200 µm. Subsamples (1 cm<sup>3</sup>) were collected at 2 cm intervals and processed for pollen analysis (Fægri et al. 1989), which was limited to the upper 21 cm due to poor pollen preservation below that level. Pollen and spores were identified at 400× magnification following McAndrews et al. (1973) until a minimum of 300 arboreal grains was tallied in each sample.

An age-depth model for the sediment core was developed using <sup>210</sup>Pb dating. Seven subsamples (3 cm<sup>3</sup>) were collected at 5 cm intervals from 0 to 35 cm and processed using standard procedures, including the addition of a 20 µL <sup>209</sup>Po spike to each subsample as an activity marker (Eakins and Morrison 1978). Samples were plated on copper planchettes and monitored for <sup>210</sup>Pb activity with an alpha spectrometer for 24 h. A constant rate of supply (CRS) model was used to assign ages to each dated interval. The uncertainty of each <sup>210</sup>Pb age was expressed as ±1 standard deviation (cf. Binford 1990) and ages of undated intervals were estimated through linear interpolation. The 1912 mortality of *Castanea dentata* (American chestnut) through *Cryphonectria parasitica* (chestnut blight) was used to evaluate the accuracy of the age-depth model (cf. Kittredge 1913; Brugam 1978).

### Forest sampling and dendroecological analysis

Modeling and empirical studies indicate that pollen records from small, closed canopy forest hollows are representative of the vegetation within about 50 m of the coring site and are therefore suitable for comparison to plot studies (Bradshaw 2007). The vegetation in a circular 1 ha plot centered on the coring site was surveyed for comparison to the pollen record. All stems >2 m in height were identified

to species and diameter-at-breast-height (DBH; 1.4 m above the forest floor) was measured (West 2004).

The forest age-structure was estimated from tree cores collected from 80 trees at 20 cm above the forest floor. Cored trees were selected to represent the dominant taxa and were evenly distributed across the plot and tree size classes (Table 1). Cores were mounted on wooden blocks and sanded with progressively finer sandpaper until annual growth increments were resolvable with a dissecting microscope at 10–40× magnification. The number of rings was taken as an estimate of minimum tree age, with the assumptions that most trees (i) established in open conditions, growing rapidly to 20 cm in height and (ii) experienced few years extreme enough to produce ring anomalies. To account for minor sources of error, ages were binned by decade.

### Analysis of historical documents

Historical documents were used to determine land ownership and use through time. The most valuable resources were deed records (1761–1992) obtained at the Worcester County Registry of Deeds. These were supplemented with qualitative descriptions of land cover from published histories of the Harvard Forest (Raup and Carlson 1941) and the town of Petersham (Coolidge 1948; Mann 1968), the transcript of an interview with a local resident (Wilder 1919, unpublished), and historic maps from the Harvard Forest archives. Of particular interest were references to the acreage of land transferred, land use at the time of sale, and structures, roads and timber resources on the property.

**Table 1** Forest survey results and number of stems cored by taxon

Taxon	Live stems	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	Relative basal area	Stems cored
<i>Pinus strobus</i>	152	8.42	0.22	16
<i>Acer saccharum</i>	335	7.93	0.20	16
<i>Acer rubrum</i>	258	7.32	0.19	16
<i>Fraxinus americana</i>	153	7.35	0.19	16
<i>Prunus serotina</i>	67	3.33	0.09	8
<i>Quercus</i> spp.	59	2.81	0.07	8
<i>Betula</i> spp.	119	0.80	0.02	0
<i>Tsuga canadensis</i>	23	0.63	0.02	0
<i>Populus grandidentata</i>	5	0.48	0.01	0
<i>Fagus grandifolia</i>	16	0.08	0.00	0
<i>Castanea dentata</i>	12	0.04	0.00	0
<i>Tilia americana</i>	4	0.08	0.00	0
<i>Ulmus</i> spp.	1	0.00	0.00	0
<i>Acer pennsylvanica</i>	1	0.00	0.00	0
Total	1,205	39.26	–	–

**Fig. 2** Summary of sedimentary (a–m), dendroecological (d–i), and deed record (n) data. All sediment-based proxies are plotted versus age using the age-depth model presented in (a). Pollen percentages for select taxa appear as dark gray area plots in panels D–M. For ease of comparison, the pollen-percentage axis is identically scaled for each plot and a 5× exaggeration was applied to underrepresented taxa (e, f, h, k). Tree-ring-based estimates of recruitment age are presented in the unfilled histograms in panels D–I. Species cored and sample sizes as also presented in Table 2. Estimates of recruitment age were binned by decade as discussed in text. An inferred history of land use/cover developed by examination of historic deed records is presented in (n) and gray diamonds represent the date of each deed

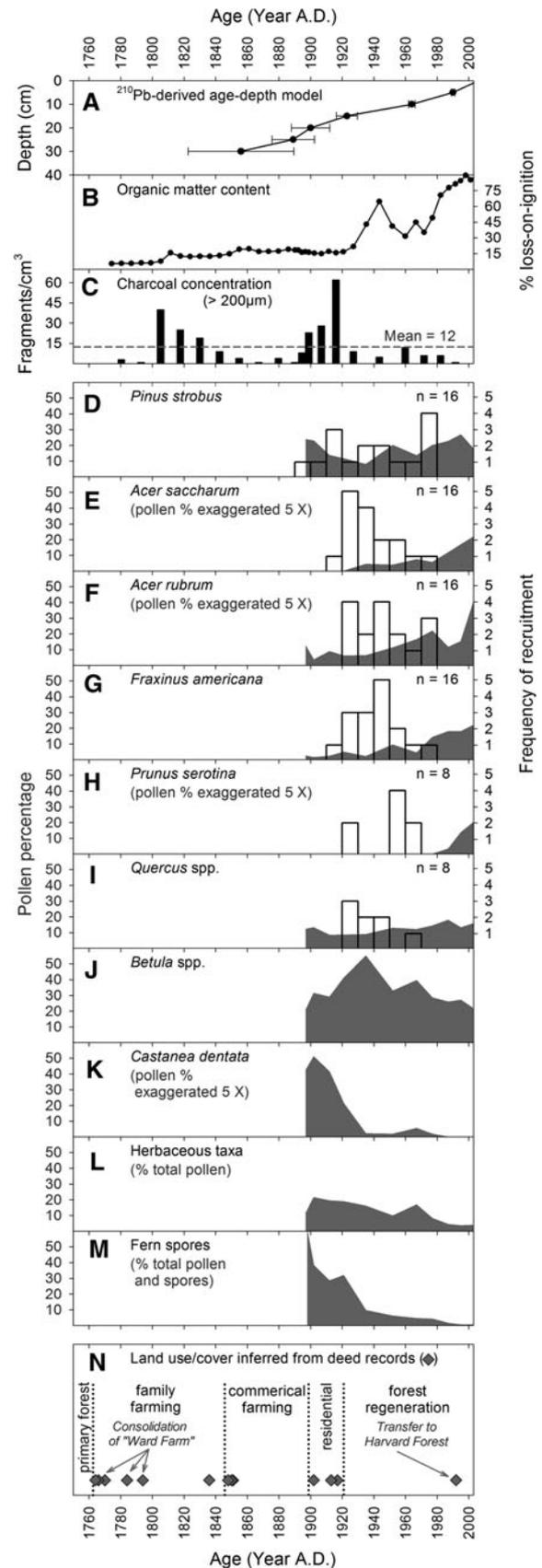
## Results

### Sediment record

Organic matter content is approximately 5% in the deepest portion of the core, approximately 15% in the interval from 40 to 20 cm, and ranges between 30% and 90% in the upper 20 cm (Fig. 2b). The LOI curve does not suggest the presence of depositional hiatuses and both  $^{210}\text{Pb}$  activity and pollen assemblages demonstrated clear changes with depth, indicating intact stratigraphy. *Castanea dentata* pollen declines markedly from 17 to 15 cm and does not recover up core (Fig. 2k). The age-depth model (Fig. 2a) suggests that these intervals were deposited around 1910 and 1920, respectively, which agrees with the timing of *Cryphonectria parasitica*-induced *Castanea dentata* mortality around the study site (Kittredge 1913).

Two intervals of elevated charcoal concentration occur in the core (Fig. 2c). The uppermost interval (18–16 cm depth) is well constrained by the age-depth model (Fig. 2a) and apparently occurred between 1900 and 1920. The deeper interval (38–34 cm depth) occurs below the lowest  $^{210}\text{Pb}$  date, but extrapolation of the age-depth model suggests that these depths were deposited between 1780 and 1860.

The pollen record (Figs. 2d–m) documents 1 century of post-agricultural forest regeneration and displays patterns consistent with other studies in southern New England (Raup and Carlson 1941; Raup 1966; Foster 1992). Fern spores (Fig. 2m) and herbaceous taxa (Fig. 2l) are abundant in the earliest portion of the record. *Pinus* (pine), *Quercus* (oak), *Betula* (birch), and *Castanea* are the most abundant tree taxa prior to 1915. *Pinus* (Fig. 2d) and *Quercus* (Fig. 2i) remain relatively constant through time. *Betula* pollen (Fig. 2j) increases dramatically following the *Castanea* decline and steadily declines after about 1940, a pattern previously observed in southern New England (Bradshaw and Miller 1988; Brugam 1978). *Fraxinus americana* (white ash) pollen increases from the beginning of the record through the present and is the most abundant taxon in the uppermost sediments (Fig. 2g). *Acer saccharum* (sugar maple) and *Acer rubrum* (red maple) pollen



begin increasing around 1940 (Figs. 2e, f) and *Prunus serotina* (black cherry) increases beginning around 1990 (Fig. 2h). Considering well-known issues of disproportionate pollen representation (e.g. Davis 2000), the uppermost sample in the pollen diagram is consistent with the composition of the modern forest (Fig. 2d–m; Table 1).

#### Forest composition and age structure

*Pinus strobus*, *Acer saccharum*, *Acer rubrum*, and *Fraxinus americana* dominate the modern forest stand (Table 1). *Fraxinus americana* and *Acer saccharum* are the most dominant species on the poorly drained lowland soils within 5–10 m of the coring site. *Castanea dentata* sprouts are common at mid elevations on the slope, while *Pinus strobus* dominates at slightly higher elevations. *Prunus serotina* is common in the western portion of the plot, where evidence of past agriculture is visible on the soil surface (Fig. 1c). *Acer rubrum* is the most uniformly abundant species throughout the plot.

Over half of the trees sampled were <20 cm DBH, suggestive of a generally young stand. The largest individuals with mature bark characteristics were *Acer* spp. and *Quercus* spp. growing near fieldstone walls and roads. All of these individuals (about 10) had experienced substantial heartwood decay, precluding tree core sampling. The oldest trees sampled were *Pinus strobus* that established in the eastern portion of the plot around 1900 (Fig. 2d). Recruitment of deciduous trees increased dramatically after about 1920 and peaked around 1930, particularly for *Acer saccharum*, *Acer rubrum*, and *Fraxinus americana* (Fig. 2d–i). An independent-samples *t* test was performed comparing mean age estimates relative to a fieldstone wall bisecting the plot in a generally northeast–southwest orientation (Fig. 1c). The mean age estimate for trees sampled to the east (73 years) of this wall was significantly greater than the mean age estimate for trees sampled to the west (56 years) ( $t(78) = 4.419, p < 0.001$ ).

#### Land-use history

Initial land clearance likely commenced around 1760, when a wealthy family (Ward) began to acquire tracts of land for agricultural production (Fig. 2n; Raup and Carlson 1941). The Ward family farmed 80–90 ha from the late 1700s until about 1830 and operated the first tavern in Petersham, which was located approximately 150 m from the study site (Fig. 1c; Mann 1968). The Ward farm was sold to an individual owner in 1836 and resold to a two-owner business partnership in 1848, likely marking the onset of commercial agriculture on site (Fig. 2n). The property was owned by the business partners and remained in agricultural production until about 1900, later than the

regional average (Raup and Carlson 1941; Foster 1992; Foster et al. 2004). A series of subdivisions and transfers to heirs occurred between 1902 and 1920, when the first director of the Harvard Forest acquired the property. In 1993, the property was transferred to the President and Fellows of Harvard University (Fig. 2n) and the land was incorporated into the Harvard Forest Prospect Hill tract.

Deed records from the early 1900s (Fig. 2n) describe a small woodlot in the eastern portion of the plot, indicating that forest regrowth occurred on a portion of the farm during the mid to late 1800s and suggesting that this portion was subsequently managed for small-scale timber production. A land utilization map, published in 1938 by the Massachusetts State Planning Board, identifies an approximately 5–10 ha area that includes the eastern half of the study plot as supporting potentially merchantable timber. The remainder of the plot is classified as pasture and orchard. However, this map includes the entire town of Petersham (~10,000 ha) at relatively low resolution.

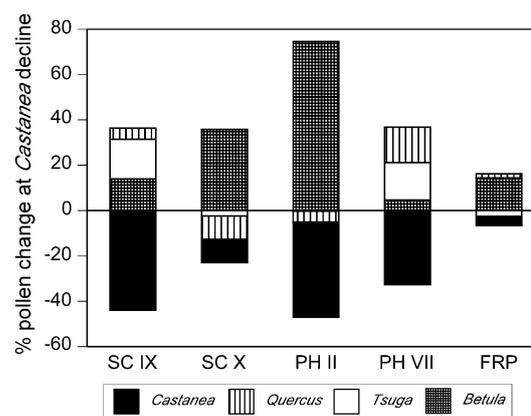
#### Discussion

Although the basal sediments were not dated, extrapolation of the age-depth model suggests that sediment deposition began between 1740 and 1820. Local histories document the wealth of the Ward family and their extensive land improvements in the late 1700s, which may have included the stonework that dammed the basin (Wilder 1919, unpublished; Coolidge 1948). The deepest sediments with the lowest organic matter were deposited from the late 1700s until about 1930 when organic-rich sediments began to accumulate (Fig. 2b). Historical documents suggest the occurrence of low-intensity agriculture from the late 1700s through the early 1800s, high-intensity agriculture during the second half of the 1800s, and garden-scale agriculture during the early 1900s. Visible plow zones in the plot indicate that some of these activities occurred within about 50 m of the coring site (Fig. 1c). Thus, the mineral content of the sediments matches well with the reconstructed history agricultural intensity (cf. Brugam 1978; Francis and Foster 2001). Seasonal drying of the sediments during the agricultural phases is likely to have contributed to the poor pollen preservation in this portion of the record and may represent an important taphonomic difference between anthropogenic and natural forest hollows. Peaks of macroscopic charcoal concentration generally align with the onset and the end of agriculture within the plot (Fig. 2c). These peaks probably represent burning associated with initial land clearance and dismantling of farm infrastructure.

Deed records from the early 1900s and a 1938 land utilization map both indicate that forest regeneration began

earlier in the eastern half of the plot than in the western half, but the age and spatial extent of the historic woodlot are poorly resolved in these references and not readily apparent in the structure or composition of the modern forest. The dendroecological data suggest that the woodlot was allowed to regenerate about 20 years earlier than the rest of the plot and facilitated identification of a prominent fieldstone wall as the western boundary of the historic woodlot. Comparison of the pollen and tree-ring records (Fig. 2d–i) suggests that pulses of tree recruitment were followed by increased pollen representation, with lags of about 10–30 years, which likely relate to species-specific maturation times. The most obvious recent changes in the pollen record are increases in *Acer rubrum* and *Prunus serotina* since the 1970s (Fig. 2e, f, h). This observation is in agreement with the results of the modern forest survey, which documented the presence of many small stems of these species (Table 1).

*Cryphonectria parasitica* is among the most damaging introduced pests in the United States (Pimentel et al. 2005) and there appear to be interactions between land-use history and the magnitude of compositional shifts resulting from *Cryphonectria parasitica*-induced *Castanea dentata* mortality (Bradshaw and Miller 1988; Paillet 2002). In New England, selective logging during the 1700s and 1800s apparently caused expansion of *Castanea dentata*, which in turn exacerbated the ecological consequences of its mortality in the early 1900s (Bradshaw and Miller 1988; Paillet 2002). To assess the potential for past land-use intensity to mediate the impact of *Castanea dentata* mortality, comparisons were made between this pollen record and four stand-scale pollen records previously collected in nearby (<5 km) mature *Tsuga canadensis* stands with limited histories of human disturbance (McLachlan et al. 2000; Table 2). Comparisons were made across the *Castanea* decline in each pollen record (Fig. 3). At each site, the most dramatic change was an increase in *Betula* pollen (Fig. 3), which is consistent with other studies (e.g. Bruggam 1978; Bradshaw and Miller 1988). The magnitude of



**Fig. 3** Summary diagram depicting the magnitude of change in pollen data for select taxa across the *Castanea* decline in this record and at four mature stands (Fig. 1; Table 2)

the compositional shifts in this record was dampened relative to the more mature sites, probably because *Castanea dentata* growing near the coring site were young and small when *Cryphonectria parasitica* was introduced (Paillet 2002). This between-site comparison suggests that past land-use intensity can mediate the effects of pest introductions, but also demonstrates that individualistic species response to disturbance provides resilience to forest ecosystems as a whole (Motzkin and Foster 2004). In this case, *Betula* species filled niche space vacated by *Castanea dentata* in two contrasting types of forest stand.

## Conclusions

Integrated studies of stand-scale ecological data and records of human history are uncommon in the eastern United States, but are frequently employed in Europe (e.g. Lindbladh 1999; Nielsen and Odgaard 2004; Rasmussen 2005; Dahlström 2008) and results of these studies have been used to recommend management and conservation strategies (e.g. Peterken and Game 1981; Brown 2010). This approach could be applied more broadly in the eastern United States than it has been to date. Although intense human land use has only occurred in the last few centuries, the detailed history of human disturbance is poorly understood in most regions and rarely considered when drafting management plans (Motzkin and Foster 2004). Land-use history has been demonstrated to be a strong predictor of spatial patterning of exotic plant species invasions of forests (e.g. Lundgren et al. 2004) as well as the rate of biomass accumulation (e.g. Caspersen et al. 2000). The development of a detailed understanding of site-specific land-use history could benefit management plans aimed at timber production, wildlife conservation, and control of invasive species.

**Table 2** Summary of sites compared in Fig. 3

Site (year sampled)	Dominant taxa	Tree recruitment	
		Median	Earliest
SC IX (1996)	<i>T. canadensis</i> , <i>P. strobus</i>	1900	1800
SC X (1996)	<i>T. canadensis</i> , <i>P. strobus</i>	1900	1725
PH II (1996)	<i>T. canadensis</i> , <i>P. strobus</i>	1900	1830
PH VII (1996)	<i>T. canadensis</i> , <i>P. strobus</i>	1910	1790
FRP (2006)	<i>P. strobus</i> , <i>Acer</i> spp.	1940	1895

Sites SC IX, SC X, PH II, PH VII are located at the Harvard Forest within 5 km of FRP (McLachlan et al. 2000)

This study has demonstrated that (i) sediment cores with intact records of recent ecological change can be collected from anthropogenic pools in historically disturbed settings (cf. McLauchlan 2003), (ii) readily-available deed records contain abundant information useful for ecological inference, and (iii) simple dendroecological studies can be used to validate or clarify vague information contained in historical documents. While this integrated approach can be used to understand the details of site-specific land-use history, several improvements could be made. First, although there is general agreement that pollen records from coring sites under closed canopies are representative of stand-scale dynamics (Bradshaw 2007), a few empirical studies suggest that significant portions of the pollen could be derived from the homogenized regional pollen rain (Calcote 1995). Two approaches could be used to compensate for this potential problem: (i) multiple coring sites could be used to explore spatial patterns and ensure that the records differ from one another (Bradshaw 2007) and (ii) analysis of plant macrofossils, which are not transported long distances and thus represent a local record (Birks 2007), could be used to supplement pollen data. The inclusion of plant macrofossils could also serve to counteract potential problems with pollen preservation in anthropogenic depositional basins. In addition, formal archaeological techniques could be used to interpret the significance of historic human artifacts on the landscape (Briggs et al. 2006). This information would add richness to the record and possibly highlight previously overlooked human impacts on the land.

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