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Land-use history (1730–1990) and vegetation dynamics in central New England, USA

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Summary

1. Histories of changing land use and vegetation of a 380-ha forested area in central Massachusetts (Prospect Hill tract of the Harvard Forest) were reconstructed to investigate (i) the environmental controls over land ownership patterns, agricultural practice and logging activity, and (ii) the vegetation response to these land-use factors.
2. Forest clearance and agricultural expansion parallel trends for central New England: increasing rates of deforestation through the late eighteenth century led to a peak in 1820–80 when more than 80% of the land was open. Reforestation on abandoned fields commenced in 1850 and increased progressively through the early twentieth century.
3. Ownership patterns varied temporally in turnover rate and size of individual holdings. Twenty-five lots comprising the study area were sold an average of 13 times in the period 1730–1910. Land sales were greatest in the period of speculation and low-intensity agriculture (1730–90), lowest during the transition to commercial agriculture and small-scale industry (1790–1840), and high during the period of agricultural decline in the mid to late 1800s.
4. Land use in the mid 1800s, including woodlot (13% of the study area), tilled fields (16%), pasture (70%) and marsh (1%), formed an intricate pattern best explained by soil drainage and proximity to farmhouses and town roads. This land-use pattern controlled the reforestation process: field abandonment and reforestation proceeded outward from poorly drained pasture adjacent to the continuous woodlots and eventually included productive tilled land.
5. The consequences of 250 years of land-use activity vary at different scales. Regionally, the distribution of modern and pre-settlement forest types match well despite structural changes and the loss of some tree species. At a landscape scale, modern forest characteristics are strongly controlled by land use. Canonical correspondence analysis indicates that community variation is best explained by historical factors (distinction between primary and secondary woodlands, forest age, cutting history and timing of site abandonment) and site factors (slope position and soil drainage). *Picea rubens* and *Tsuga canadensis* forests are restricted to primary woodlands, *Pinus strobus* and sprouts of *Castanea dentata* are largely confined to old pastures, and *Betula populifolia*, *Populus* spp. and *Acer rubrum* are most abundant in cut-over old-field *Pinus* stands.
6. Long-term forest trends in the twentieth century include a decrease in the importance of *Pinus strobus* due to logging and the 1938 hurricane, a gradual decline in early successional hardwoods (*Betula populifolia*, *Populus* spp., *Acer rubrum*), and increase in later successional species (*Quercus rubra*, *Q. velutina*, *Acer saccharum*). *Tsuga* and northern-hardwood species (*Acer saccharum*, *Fagus grandifolia*) declined dramatically throughout the settlement period; however, the major forest trend over the past 100 years has been a continual increase in *Tsuga*.

Key-words: agricultural history, canonical correspondence analysis, deforestation, forest dynamics, human disturbance

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Introduction

Despite the long tradition in north-western Europe of utilizing palaeoecological and historical methods to investigate human impacts on the environment and vegetation (Iversen 1973; Peterken & Game 1981; Peglar, Fritz & Birks 1988), there are few comparable studies in North America. This difference is often attributed to the shorter duration of intensive human impact in much of North America versus Europe (*c.* 400 years vs. >5000 years) but is nonetheless remarkable given the intensity and geographical extent of human impact in the New World and the ecological importance of understanding this history (Marsh 1864; Fisher 1933; Ecological Society of America 1991). Investigations of land-use history and vegetation change provide:

1. a background for understanding the development of the modern vegetational landscape, which is essential for any ecological study (Christensen 1989);

2. information on the response of communities to novel disturbance processes or intensities that may be compared with studies of natural processes to evaluate the resistance or resilience of communities to contrasting factors (Houghton *et al.* 1983; Schoonmaker & Foster 1991);

3. perspectives that may be useful in the preservation of unique communities or management of cultural landscapes (Birks *et al.* 1988).

Conclusive studies linking human activity and ecosystem change require comprehensive analyses of land-use history and long-term vegetation records. The present study seeks to evaluate these two kinds of information for a nearly 400-ha forested area in central Massachusetts (Prospect Hill tract of the Harvard Forest) and for a period extending from the mid eighteenth century to the present. The study has three major objectives: (i) to document spatial and temporal patterns of land-use and to relate these to environmental factors and cultural conditions; (ii) to identify the major environmental and human factors that are responsible for changes in the structure and composition in the vegetation during this period, and (iii) to document long-term changes of the vegetation in this study area.

Although the forest investigated is unusual in having an extensively documented history, the major patterns of land-use and change in forest cover are representative of broad upland areas of the north-eastern USA (Bidwell 1916; McKinnon, Hyde & Cline 1935; Black & Brinser 1952). In order to place the results of the research in a broader geographical framework, the study begins with a description of the early post-settlement vegetation of the township of Petersham and Worcester County, Massachusetts. It then examines the specific history and effects of land-use practices on the Prospect Hill tract of the Harvard Forest in Petersham.

Study area

PHYSICAL SETTING

Worcester County occupies 3900 km^2 in central Massachusetts (Fig. 1). The western two-thirds of the county forms an undulating upland generally exceeding 250 m a.s.l., whereas to the east and south-east the land slopes to a prevailing altitude of 100 m. Second-growth forest currently covers approximately 70% of the land area (MacConnell & Niedzweidz 1974).

Petersham is located in north-western Worcester County at an average altitude of 275 m a.s.l. Relief of *c.* 100 m encompasses a series of north–south trending ridges and valleys. The soils are largely acidic and derived from granodiorites and gneisses. The mean annual temperature is 8·5 °C, the frost-free season averages 5 months and the annual precipitation is 105 cm including 150 cm of snow (Rasche 1953). The township is 90% forested.

The Prospect Hill tract of the Harvard Forest comprises 380 ha of the northern, highest portion of the major ridge in Petersham. Altitude ranges from 270 to 420 m a.s.l., steep slopes occur towards the western and north-eastern margins of the tract, and most of the area is undulating (Fig. 2). Variability in

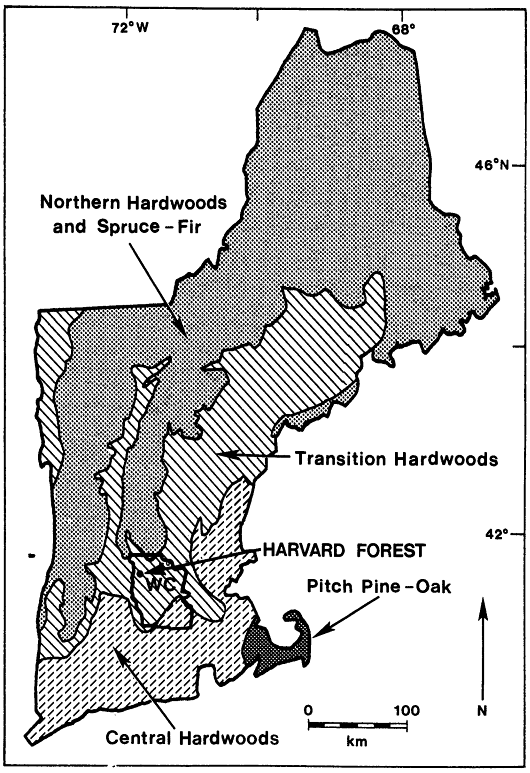
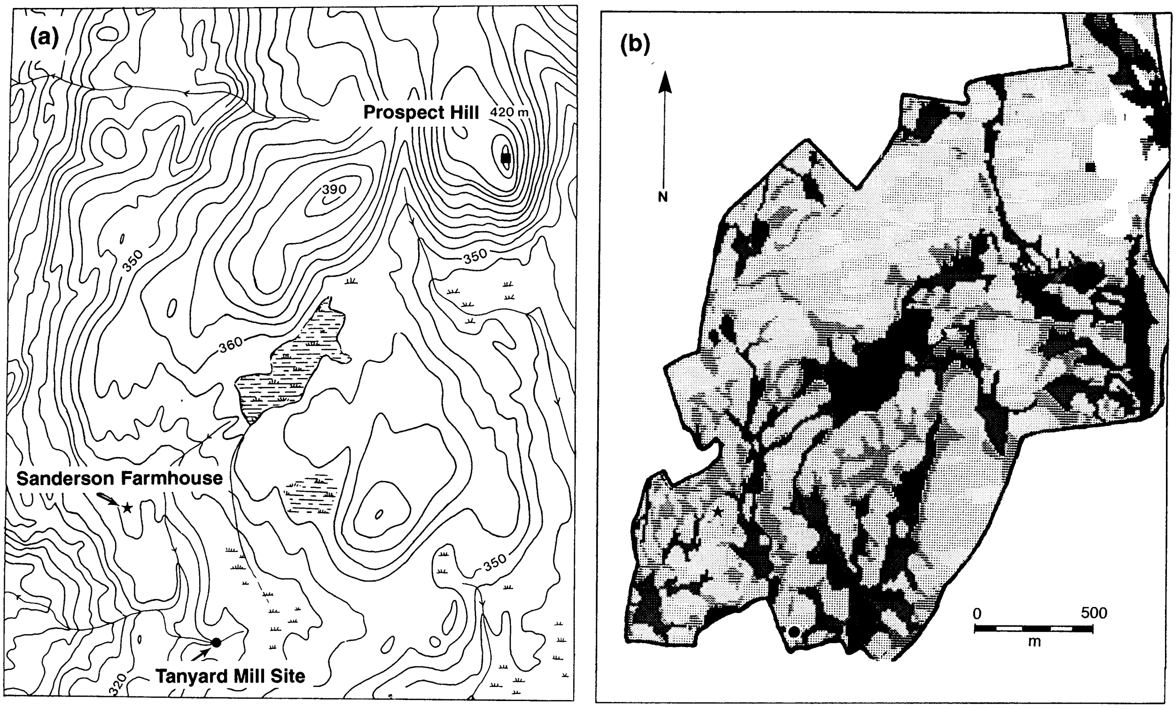


Fig. 1. Forest vegetation map of New England showing Worcester County, Massachusetts (WC) extending from the Central Hardwood zone through to the Northern Hardwood zone. The location of the Harvard Forest in Petersham, Massachusetts in indicated by the solid circle. Modified from Westveld (1956).



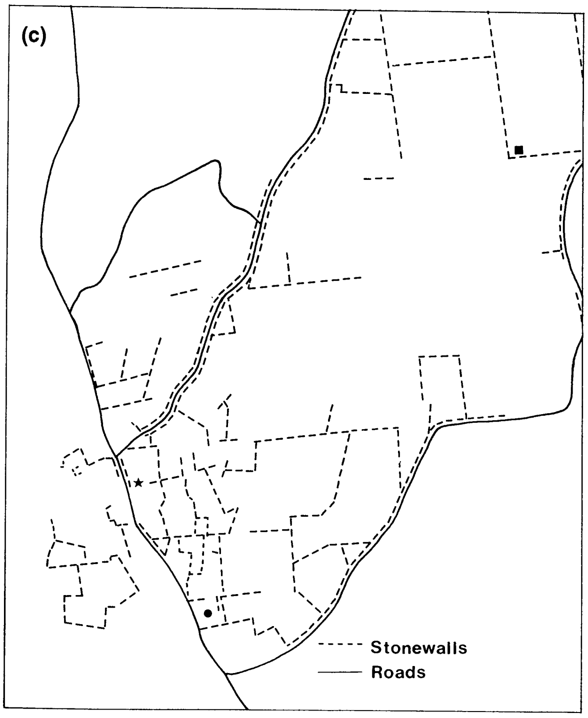


Fig. 2. The Prospect Hill area of the Harvard Forest showing (a) topography (5-m contours), (b) soil drainage (from very-well drained (light shading) to very-poorly drained (black) and (c) location of stonewalls and roads. The maps are at matching scales and the outline of the soils map conforms to that of the study area boundary. Locations of the John Sanderson farmhouse, tanyard mill site and top of Prospect Hill are indicated on all maps.

relief, depth to bedrock, and presence of a fragipan create a highly dissected pattern of soil drainage (Fig. 2b).

CULTURAL SETTING

During the past 250 years the central Massachusetts landscape has undergone several transformations in response to changes in land-use practices and population density (Figs 3 and 4; Torbert 1935; Pabst 1941; Barraclough 1949). This history can be divided into five major periods:
1730–50 speculation;
1750–90 low-intensity agriculture;
1790–1850 commercial agriculture and small industry;
1850–1920 farm abandonment and industrialization;
1920–90 residential period
(Raup & Carlson 1941; Black & Wescott 1959).

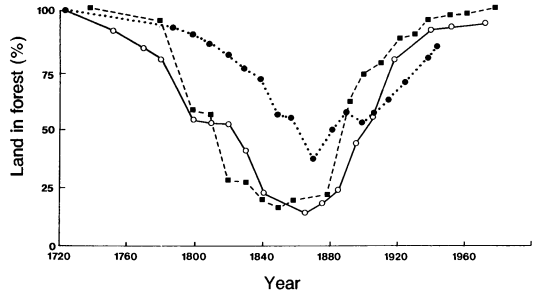


Fig. 3. Historical changes in forest cover for the State of Massachusetts (●), the township of Petersham (○), and the Prospect Hill tract (■). Sources of information include Dickson & McAfee (1988), MacConnell (1975), Rane (1908) and Baldwin (1942) for Massachusetts, and Raup & Carlson (1941), Anonymous (1959), MacConnell & Niedzwiedz (1974), Averill, Averill & Stevens (1923), Cook (1917) and Rane (1908) for Petersham. Estimates of forest cover on the Prospect Hill tract were derived from land-use notes in deeds, Spurr (1950) and unpublished sources in the Harvard Forest Archives.

The township of Petersham was settled in 1733. With limited access to markets, the eighteenth-century rural economy was based on farming and small-scale commercial activity (Coolige 1948; Pruitt 1981; Baker & Patterson 1986). Forest clearance proceeded initially at a pace of 1–4% per year (Fig. 3). Improved transportation and increased demand for agricultural products in the late eighteenth and early nineteenth centuries prompted an increase in commercial farming and small-scale industry in rural central New England (Pabst 1941; Thorbahn & Mrozowski 1979; Rothenberg 1981). Forest clearance to provide pasture land for beef cattle and sheep resulted in an increase in open land from approximately 50% of the township in 1800 to nearly 85% in 1850 (Figs 3 and 4). Remaining forests occupied steep and rocky slopes, wetlands or narrow valleys and were cut for timber, fuelwood and tanbark and were often grazed (Cline *et al.* 1938; Gould 1942; Spurr 1950).

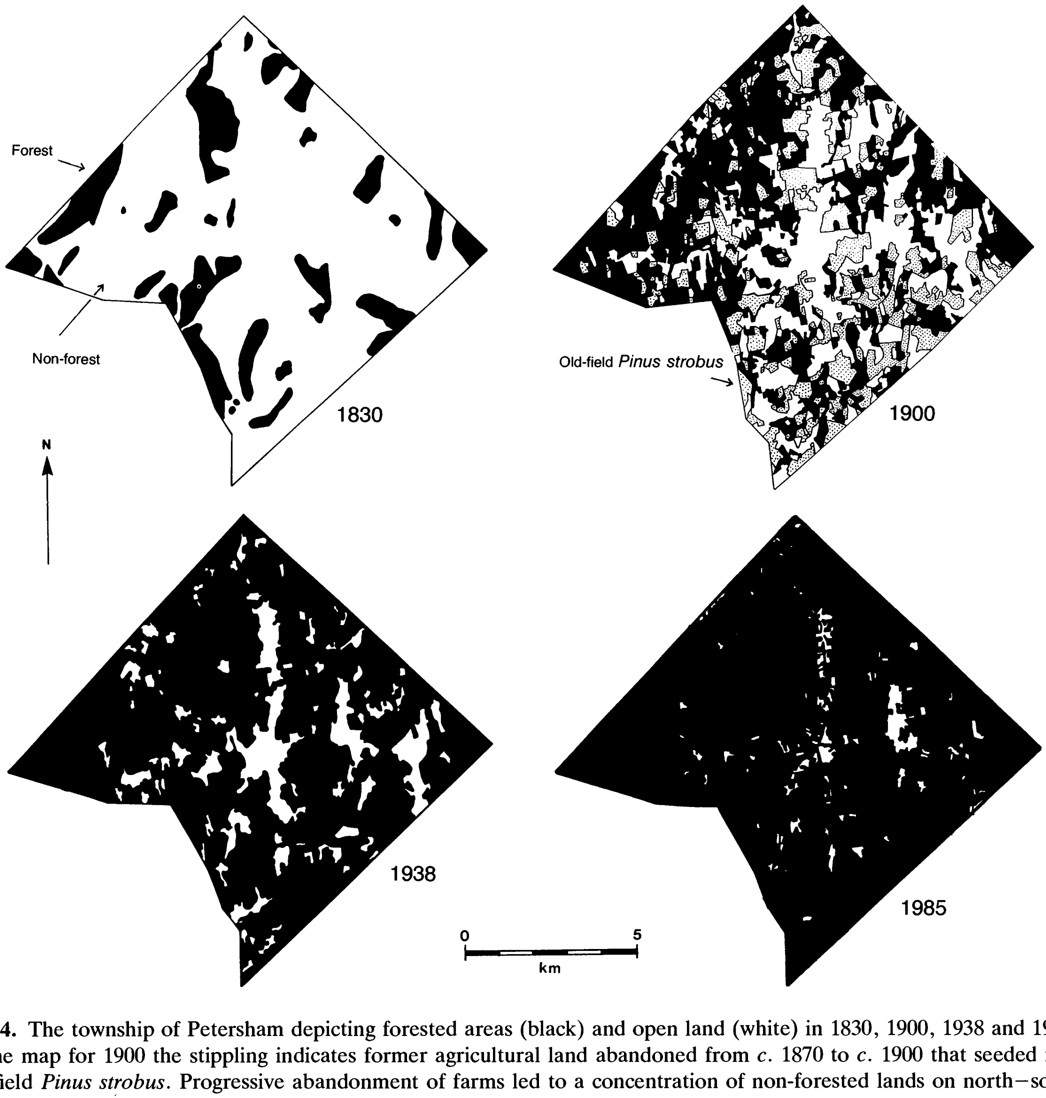


Fig. 4. The township of Petersham depicting forested areas (black) and open land (white) in 1830, 1900, 1938 and 1985. In the map for 1900 the stippling indicates former agricultural land abandoned from *c.* 1870 to *c.* 1900 that seeded into old-field *Pinus strobus*. Progressive abandonment of farms led to a concentration of non-forested lands on north–south ridges. Data were obtained from the *Atlas of Worcester County* (1830, unpublished), unpublished maps from the Harvard Forest Archives (1935–39) and air-photograph analysis (1985; 1:24,000 colour–infra-red).

(a)

(b)

Fig. 5. (a) Millstone, stream and retaining wall of an abandoned mill on the Prospect Hill tract of the Harvard Forest in Petersham, Massachusetts. The mill was actively used from 1780 to 1850 to grind *Tsuga* bark and *Castanea* wood to produce tannic acid for use in leather tanning. Providing a major source of income supplemental to agricultural activity, the mill exerted a pronounced impact on the woodlands in the neighbouring region as they were cut frequently to provide a regular source of tannin. The modern forest is comprised of *Acer saccharum* and *Fraxinus americana* established in the late 1800s. (b) Broad-scale abandonment of agricultural land across New England in the mid to late 1800s gave rise to extensive areas of second-growth forest. Stone walls delimiting the former extent of fields extend through these forests dominated by *Quercus rubra*, *Acer rubrum*, *Betula papyrifera* and *Fraxinus americana*, as here at the Prospect Hill tract, Harvard Forest. (Photographs by M. Fluet.)

Commencing in the mid 1800s the population of Petersham declined as younger inhabitants left for urban jobs or agricultural opportunities in the Midwest (Fisher 1921; Black & Brinser 1952). Farms were abandoned and neglected fields were reforested (Fig. 5) (Munyon 1978; Garrison 1987). The modern period has included a nearly complete cessation of agricultural activity, broad-scale regrowth of forest cover and a conversion of the town to a residential status. Since the 1930s there has been an increase in homes and a reversal in the downward population trend but a decrease in the intensity of direct human impact on the land.

Methods

VEGETATION OF WORCESTER COUNTY

Data on the early post-settlement (*c.* 1770–90) vegetation of Worcester County were derived from Peter Whitney's (1793) account which includes a geographical description of each township, its landscape and vegetation. Whitney travelled the county extensively within 20–30 years of the date of incorporation of most of the townships and described the vegetation before extensive human alteration. Whitney's data were analysed using detrended correspondence analysis (Hill & Gauch 1980) with species abundance assigned as either present or abundant (see Table 1). Results of the samples (townships) ordination were used to identify forest type groupings and to develop a county vegetation map. A phytosociological table was constructed from samples and species output. The map of early forest vegetation was compared to recent regional forest descriptions (Westveld 1956). Species' nomenclature follows Fernald (1973).

LAND-USE AND VEGETATION HISTORY

The history of land ownership (1738–present) of the Prospect Hill tract was compiled from proprietors' grants, deeds and tax valuation lists. Complete ownership chronologies were compiled for each of the 25 property lots that comprise the tract. Turnover rates in ownership were calculated on a decadal basis as the percentage of the 25 lots that had been sold out of a family. Land-use history was derived from various sources. Deeds and sale records provide information on lot status as either wooded, pasture, mowings or tilled field, and on timber rights held on woodlots. For each forest stand in the study area the following information had been reconstructed by earlier researchers at the Harvard Forest: date of clearance, agricultural use, timing of abandonment, successional vegetation, and history of logging (Fisher 1921; Raup & Carlson 1941; Spurr 1950; Gould 1960).

The long-term impact of land-use on present-day forest composition was analysed in two ways. Using a Geographic Information System the spatial overlap between soil drainage, land-use history and forest types in 1908 was examined and transitions in forest communities between 1908, 1937 and 1986 were documented. Information on soils and vegetation was derived from Harvard Forest (HF) Archives. Canonical correspondence analysis (CANOCO, ter Braak 1986) was then used to evaluate the relationship between the vegetation and environmental variables (including site and historical factors) for the forest in 1937. The 1937 vegetation was selected for intensive analysis because of the availability of an extensive data set and the fact that the 1937 vegetation represented the maximum extent of secondary development before the 1938 hurricane, when approximately 75% of the timber was windthrown (Foster 1988; Foster & Boose 1992). Vegetational information analysed in CANOCO, included 253 samples (approximately 0·04-ha plots) and 105 species. Tree species abundance was assigned on a five-factor scale based on volume, whereas shrubs, herbs and mosses were recorded as present or absent. Site variables analysed included soil drainage (five classes; Spurr 1950) and slope position (five classes). Historical and land-use variables included stand age (derived from the 1937 survey), time since agricultural abandonment, presence/absence of cutting in the previous 100 years, historical frequency of turnover in ownership, and the distinction between primary (always forested) and secondary (formerly cleared land) woodlands (cf. Peterken 1981).

Results

WORCESTER COUNTY — EARLY POST-SETTLEMENT VEGETATION

On a regional basis the distribution of forest vegetation in the 1700s closely matches that of today. Forest types including Central Hardwoods, Transition Hardwoods and Northern Hardwoods (Fig. 6) are arranged on a south-east to north-west axis across Worcester County following the altitudinal gradient (Figs 1 and 7, Table 1; Westveld 1956). Central Hardwood forests were dominated by *Quercus* spp., *Carya glabra*, *Castanea dentata* and *Pinus strobus*. Other species included *Acer rubrum*, *Pinus rigida*, *Betula* spp. and *Fraxinus americana*. Transition Hardwood forests include the same species, with more *Acer rubrum*, *Betula lenta* and *Fraxinus americana* as well as *Fagus grandifolia*, *Tsuga canadensis* and occasional *Picea* spp. and *Larix laricina*. In the Northern Hardwood forest, *Carya*, *Castanea* and *Pinus rigida* were minor components; additional common species included *Acer saccharum*, *Betula alleghaniensis* and *B. papyrifera*. In addition to these

Table 1. Forest composition of the townships in Worcester County, Massachusetts in the late 1700s as reported in the journal of Peter Whitney (1793) and interpreted from detrended correspondence analysis (Fig. 6). The towns in each forest type are listed at the bottom of the table. Modal Value (MV) of abundance refers to Whitney's description as (1) occasional, scattered or rare, and (2) common or dominant. Frequency is the percentage of towns in a forest region in which the species occurred

	Central Hardwoods		Transition Hardwoods Pine and Flood Plains		Transition Hardwoods		Northern Hardwoods	
	MV	Frequency	MV	Frequency	MV	Frequency	MV	Frequency
Carya ovata			2	0·50				
Juglans cinerea			2	1·00				
Platanus occidentalis			1	0·83	1	0·04		
Ulmus americana			2	0·66	2	0·24		
Sassafras albidum			1	0·33	1	0·04		
Quercus prinus			2	0·17	2	0·04		
Chamaecyparis thyoides	1	0·45			1	0·04		
Carya glabra	2	1·00	2	1·00	2	0·92	1	0·20
Pinus rigida	2	0·45	2	0·83	1	0·48	2	0·60
Castanea dentata	2	1·00	2	1·00	2	0·96	2	0·80
Quercus spp.	2	1·00	2	1·00	2	1·00	2	1·00
Pinus strobus	1	0·91	1	0·83	2	0·76	2	1·00
Acer rubrum	2	0·36	2	0·33	2	0·72	2	0·60
Pinus resinosa	1	0·09			1	0·16	2	0·20
Betula spp.	2	0·27	1	0·66	2	0·80	2	1·00
Fraxinus americana	2	0·18	1	0·66	2	0·80	2	0·80
Fagus grandifolia			2	0·17	2	0·48	2	0·80
Tsuga canadensis			1	0·17	2	0·40	2	0·80
Picea spp.			1	0·17	1	0·08	2	0·40
Larix laricina					1	0·04	2	0·40
Fraxinus spp.			1	0·17	2	0·04	2	0·40
Betula lenta					2	0·08	2	0·60
Acer saccharum					1	0·04	2	1·00
Betula papyrifera							2	0·40
Betula alleghaniensis							2	0·60
Tilia americana							2	0·20

Forest region	Townships
Central Hardwoods	Douglas, Dudley, Mendon, Milford, Northborough, Northbridge, Oxford, Southborough, Upton, Uxbridge, Webster, Westborough
Transition Hardwoods with Plains	Grafton, Harvard, Lancaster, Leominster, Sutton, West Boylston
Transition Hardwoods	Athol, Barre, Bolton, Charlton, Fitchburg, Hardwick, Holden, Hubbardston, New Braintree, Northbridge, Paxton, Petersham, Phillipston, Princeton, Oakham, Rutland, Shrewsbury, Spencer, Sterling, Sturbridge, Templeton, Westminster, West Brookfield, Worcester
Northern Hardwoods	Ashburnham, Gardner, Lunenburg, Royalston, Winchendon
No information	Berlin, Clinton, Leicester

major forest types, in the eastern half of the county on flood plains and sandy outwash there occurred a distinct assemblage of trees including *Platanus occidentalis*, *Ulmus americana*, *Carya ovata* and *Juglans cinerea*.

PETERSHAM — EARLY VEGETATION AND FOREST CHANGE

Peter Whitney (1793) described the original vegetation of Petersham as predominantly *Quercus* on the uplands and *Betula*, *Fagus grandifolia*, *Acer rubrum*, *Fraxinus*, *Ulmus* and *Tsuga* in the lowlands. *Castanea* and *Carya/Juglans* were noted as increasing following settlement. Changes in forest cover through time for Petersham parallel those for other townships in Worcester County (Black & Wescott 1959), but were more rapid and greater than for the state of Massachusetts as a whole (Fig. 3). At the height of agricultural activity (mid 1800s), the Petersham landscape was a mosaic of small fields (indicated by the pattern of stonewalls; Figs 2c and 5b) and isolated woodlands (Fig. 4). Reforestation proceeded outward from the forest remnants, leaving progressively smaller areas of open land along the ridge tops (Fig. 4). One major pattern of

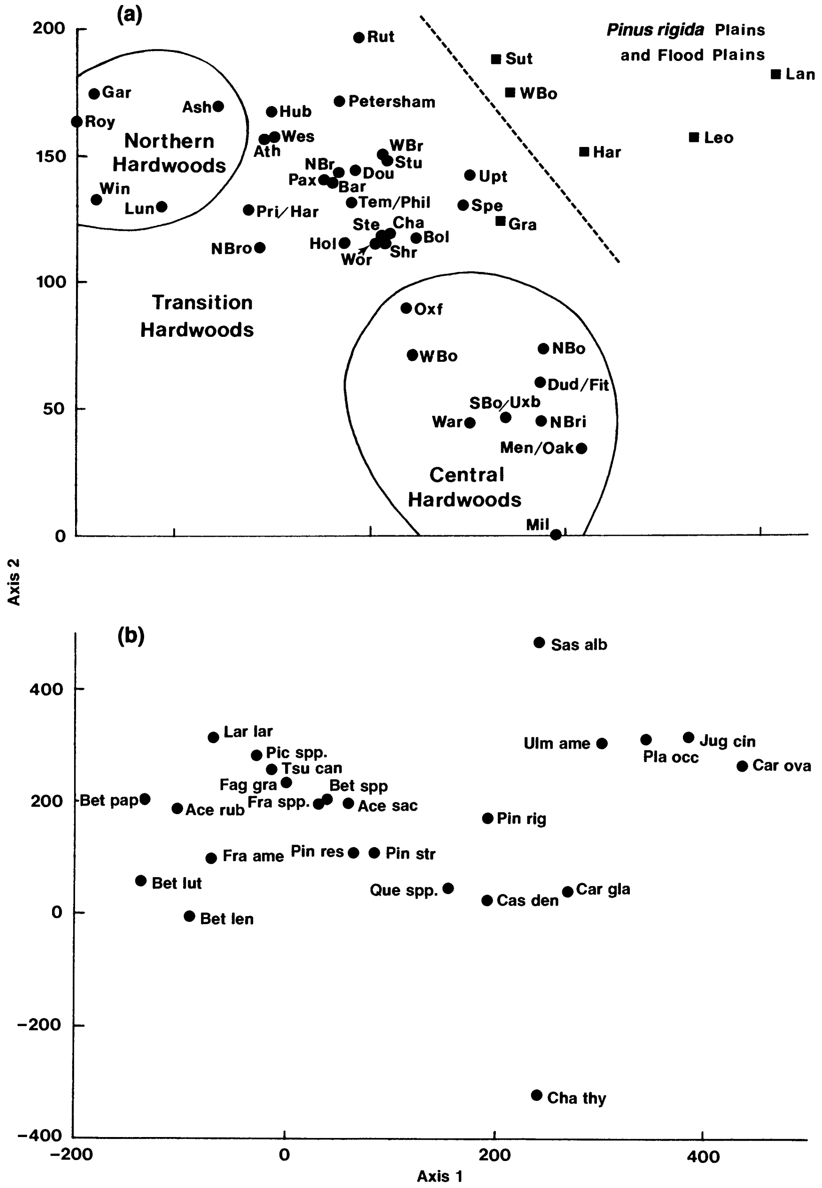


Fig. 6. Sample townships (a) and species (b) plots for Peter Whitney's (1793) description of the forest vegetation of Worcester County, Massachusetts displayed on the first two DECORANA axes. Township points (a) are grouped into major vegetation types (Northern Hardwoods, Transition Hardwoods and Central Hardwoods). The *Pinus rigida* plain and flood plain variant of the Transition Hardwoods is indicated by square symbols and separated by a broken line. Town names are provided in Table 1. Township abbreviations use the first three or four letters of the name. Species abbreviations (b) are based on the first three letters of the genus and species: *Acer rubrum*, *Acer saccharum*, *Betula lenta*, *Betula lutea*, *Betula papyrifera*, *Betula* spp., *Carya glabra*, *Carya ovata*, *Castanea dentata*, *Chamaecyparis thyoides*, *Fagus grandifolia*, *Fraxinus americana*, *Fraxinus* spp., *Juglans cinerea*, *Larix laricina*, *Picea* spp., *Pinus strobus*, *Pinus rigida*, *Pinus resinosa*, *Platanus occidentalis*, *Quercus* spp., *Sassafras albidum*, *Tsuga canandensis* and *Ulmus americana*.

natural reforestation included establishment of *Pinus strobus* on abandoned pastures and fields (Fisher 1918). An alternative pattern involved successional hardwood species, including *Betula populifolia*, *Populus* spp., *Acer rubrum* and *Prunus* spp. Over time, as either the *Pinus strobus* was harvested or the successional hardwoods died, the modern forest of *Quercus*, *Acer rubrum*, *Pinus strobus*, *Fraxinus americana*, *Betula lenta* and *B. alleghaniensis* emerged (Fisher 1933).

PROSPECT HILL TRACT

History of land ownership and development

Historical changes in the size and duration of individuals holdings reflect the type and intensity of land-use and indicate ongoing modification of the forest landscape. During the 160-year period before acquisition by Harvard University in 1907 each of the 25 lots comprising the Prospect Hill tract was

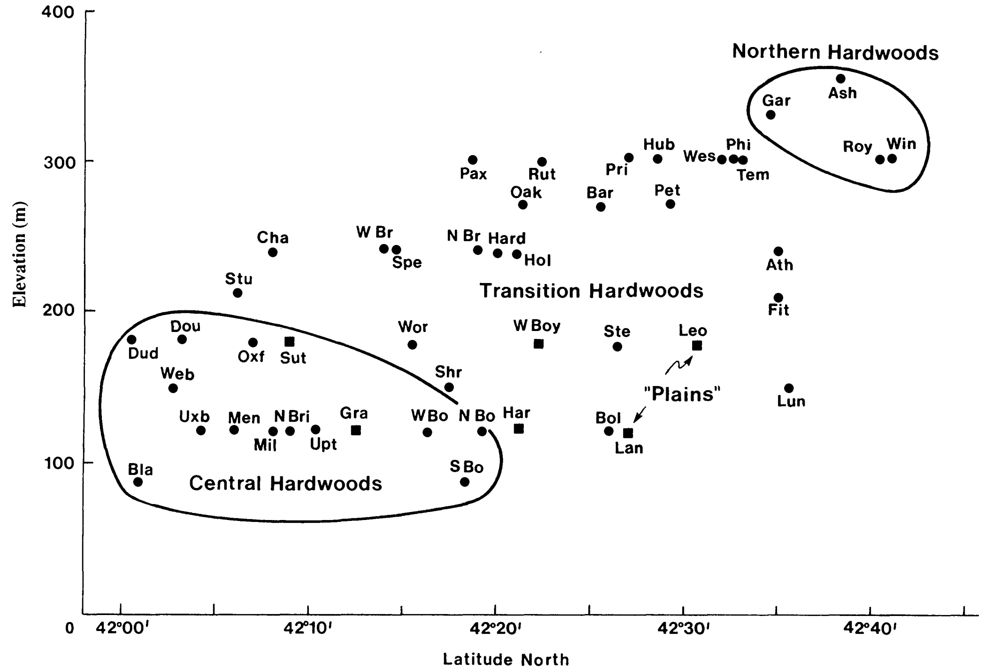


Fig. 7. Location of the townships of Worcester County, Massachusetts on altitudinal and latitudinal gradients. Major vegetational types are indicated. Central Hardwoods vegetation is found predominantly at low altitude in the south-eastern corner of the county, whereas the townships in the elevated north-western area are characterized by Northern Hardwood forests. Townships in the *Pinus rigida* and flood plain subtype of Transition Hardwoods are marked by square symbols. Township abbreviations use the first three or four letters of the name.

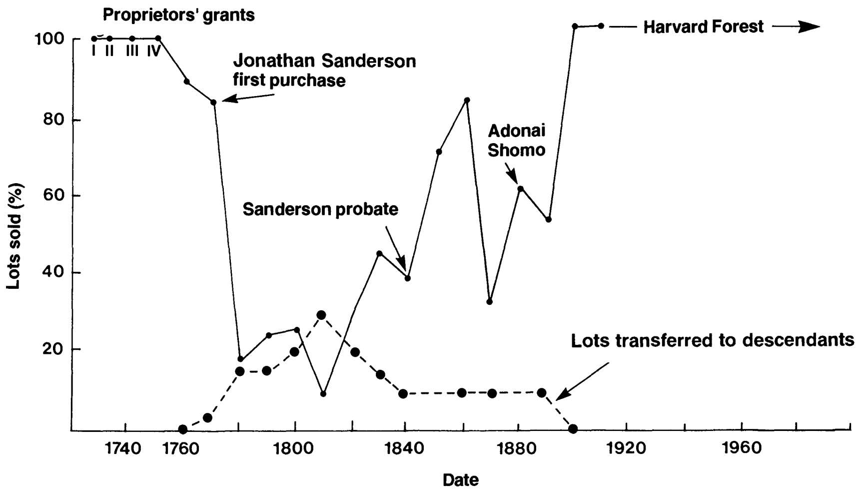


Fig. 8. Historical changes in ownership turnover for the Prospect Hill tract, Harvard Forest. The graph depicts the percentage of lots in the tract that were sold in the preceding decade. The percentage of lots transferred to direct descendants (generally sons) is indicated by the broken line and larger solid dots.

sold an average of 13 times. From 1733 to 1770 turnover exceeded 80% on a decadal basis as absentee owners speculated on land grants and sold their lots to the first settlers (Fig. 8). During the commercial agricultural period through the mid 1800s, the lowest level of turnover occurred (10–40% on a decadal basis) as families retained their land, worked it intensively and gradually expanded their holdings through acquisition of adjoining parcels (Fig. 9). After 1840 and coincident with the beginning of farmland abandonment, ownership turnover increased markedly; owners often held parcels for only 4–12 years between sales. A temporary decline in land sales occurred during the economically depressed period of the American Civil War (1861–65; Coolidge 1948).

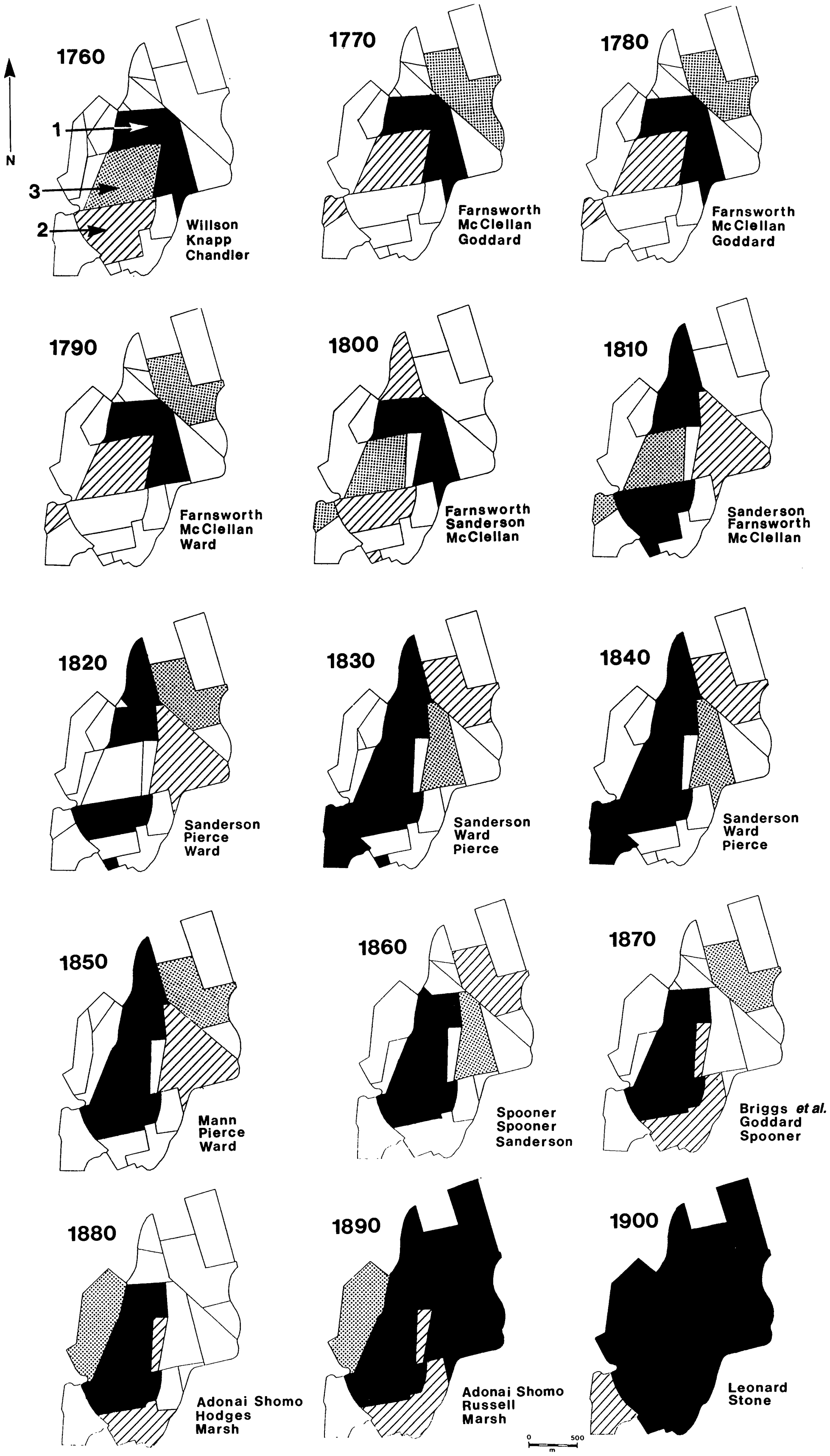


Fig. 9. Ownership maps at 10-year intervals for the period 1760–1900 on the Prospect Hill tract, Harvard Forest. The properties of the three largest landowners for each decade are indicated as (1) black, (2) diagonal lines, (3) shaded. The names of the owners of these areas are listed to the bottom right of the map in descending order of property area. Growth in the size of the larger farms is indicated by the Sanderson farm from 1800 until 1840.

Farm development

Agricultural history on the Prospect Hill tract closely paralleled that of the township. Forest clearance commenced *c.* 1750, proceeded at a slow pace through 1780, and abruptly increased thereafter until 1840–50 when open land peaked at nearly 80% (Fig. 3; Fisher 1933; Raup & Carlson 1941; HF Archives). During the period 1820–80 there was relative stability in the pattern of open land and forest.

The geographic distribution of land-use types relates closely to the physiographic and soil characteristics of the area, and to the distance from major roads and dwellings (Table 2; Figs 2b and 10). The earliest areas to be settled and developed were adjacent to roads and houses. Nearly 50% of this accessible land was tilled (Fig. 10), whereas across the entire tract approximately 70% of the area was cleared for pasture, 17% was tilled, 13% was continuously wooded and slightly more than 1% was marsh (Table 2). Permanent woodland comprised three wooded swamps in the centre of the tract connected along poorly drained seepages and adjoining steep or rocky sites (Figs 2b and 10). Tilled land primarily occupied well-drained and imperfectly drained soils whereas pasture covered the broadest range of drainage conditions including all of the very well drained soils, 75% of the poorly drained sites, and nearly 70% of the well and imperfectly drained soils (Table 3). The process of closely fitting tillage areas to soil drainage led to irregularly shaped and small fields (Figs 2c and 10).

Logging history

The history of logging includes four periods: (i) land clearance; (ii) woodlot cutting during the agricultural period; (iii) commercial harvesting of old-field *Pinus strobus* and old woodlots (1885–95); and (iv) Harvard Forest management. Different objectives on the part of the landowners led to varying effects during these periods. Once agricultural land was cleared, deeds from the nineteenth-century indicate that the remnant woodlands were a valuable source of *Castanea* and *Tsuga* for fuel wood, timber and tan bark. Forest reconstructions indicate that woodlots were cut repeatedly for pole-sized trees after the initial removal of the virgin timber in the mid to late 1700s (E.P. Stephens & S. Spurr, HF Archives; Fig. 11).

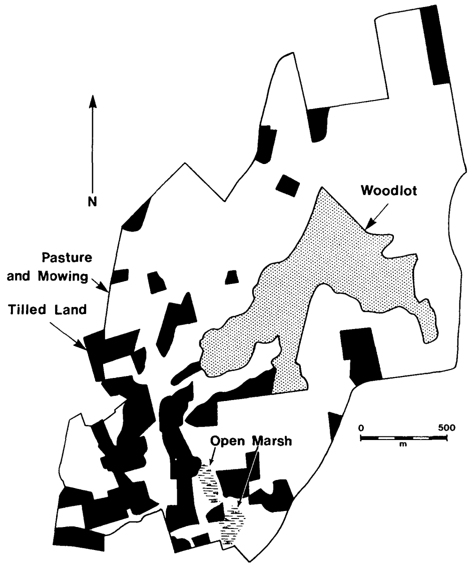


Fig. 10. Land-use history map for the Prospect Hill tract, Harvard Forest depicting pasture and mowing, woodland, tillage and marsh at the time of most intensive land-use in the mid 1800s. Although land use changed over time, this map shows the continuous woodland area and all sites that were ever tilled. Modified from Spurr (1950) and Harvard Forest Archives.

Table 2. Soil drainage and land-use characteristics of the Prospect Hill tract, Harvard Forest. Land-use types describe the primary use of the land during the height of agricultural activity in the mid 1800s (Spurr 1950; HF Archives) with areas given in hectares. In the modern landscape all of the area is forested. All values were calculated on a Geographic Information System and are rounded to the nearest integer

	Land use (ha)				
Soils	Pasture	Tilled	Woodlot	Marsh	Totals
Very well drained	14	–	–	–	14
Well drained	150	49	14	–	213
Imperfectly drained	27	9	4	–	40
Poorly drained	45	2	13	–	60
Very poorly drained	3	–	14	4	21
Totals	239	60	45	4	

Table 3. Weighted correlation matrix for environmental variables, environmental axes and species axes in the canonical correspondence analysis of 1937 data from the Prospect Hill tract, Harvard Forest. Environmental variables include stand age, soil drainage, slope position, pasture/tillage, primary/secondary woodland, cutting history, and abandonment date. Env Ax x represents the sample scores on the xth ordination axis, which are linear combinations of the environmental variables. Spec Ax x represents the sample scores on the xth ordination axis which are derived from the species scores by weighted averaging

	Age	Soil	Slope	Pasture	Primary	Cut old field	Abandonment date
Age	1·00						
Soil	0·21	1·00					
Slope	0·28	0·44	1·00				
Pasture	−0·21	−0·16	−0·34	1·00			
Primary	0·47	0·34	0·53	−0·68	1·00		
Cut old field	−0·31	0·01	−0·17	0·31	−0·29	1·00	
Abandonment date	0·47	0·34	0·49	−0·46	0·84	−0·01	1·00
Env Ax 1	0·79	0·54	0·57	−0·46	0·85	−0·23	0·84
Env Ax 2	0·37	−0·68	−0·51	−0·08	0·02	−0·25	0·09
Spec Ax 1	0·65	0·45	0·47	−0·39	0·71	−0·19	0·70
Spec Ax 2	0·25	−0·46	−0·34	−0·05	0·01	−0·17	0·06

From 1885 to 1895, essentially all of the merchantable timber on the Prospect Hill tract was cut often followed by burning of the slash (Fig. 11) (Fisher 1921; HF Archives). This timber came from woodlots that were cut for *Tsuga*, *Castanea* and *Quercus* and from former pastures abandoned between 1845 and 1865 and then dominated by *Pinus strobus*.

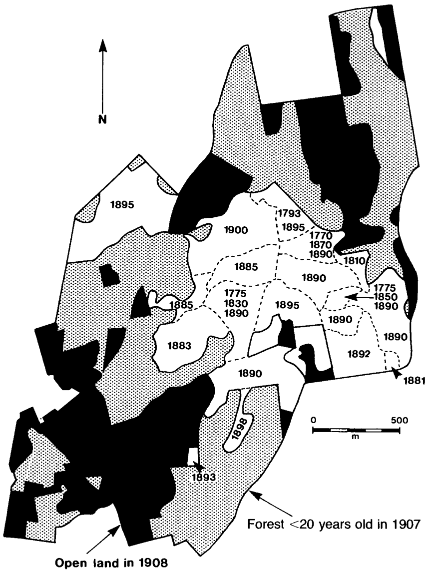


Fig. 11. Cutting history of the Prospect Hill tract, Harvard Forest in the period before Harvard Forest ownership (1907). Dates in white areas indicate the year(s) of cutting. Shaded areas were in immature forest (<20 years old) and black areas were in open field or scrub in 1907. Data were derived from historical maps, notes and forest reconstructions stored in the Harvard Forest Archives. Much of the white area contained merchantable timber in 1907.

Post-agricultural vegetation development

Following the height of forest clearance (1820–80), reduced agricultural activity resulted in rapid reforestation (Fisher 1921; HF Archives). Today, essentially the entire study area is covered by maturing forest (Fig. 12; Gould 1960). The modern forest history is best understood by examining the pattern of land-abandonment and subsequent vegetation development.

Pattern and rate of land abandonment

On the Prospect Hill tract and in central New England in general, farm abandonment and reforestation commenced slowly in the mid nineteenth century and subsequently increased greatly into the 1900s. By 1880 slightly more than 25% of the Prospect Hill tract was forested, whereas this figure increased to 85% by 1937 (Figs 3 and 12). The geographic pattern of field abandonment was complex, controlled in part by an individual farmer's economic situation and land holdings. However, the general process is consistent: abandonment first of poorly drained and low-lying pasture areas adjacent to the intact woodland, followed later by well-drained and arable lands (Fig. 12). From 1840 to 1875 only pastures were abandoned, whereas the first tilled fields were abandoned in the late 1870s. By 1880 the forested area formed a continuous stand with small pasture in-holdings (Fig. 12). Open areas were limited to 25% of the area in 1900, and following the transfer of the land to Harvard Forest, the remaining fields were abandoned or planted with conifers.

Vegetation development from farm abandonment to present

Maps and forest-wide inventories from the twentieth

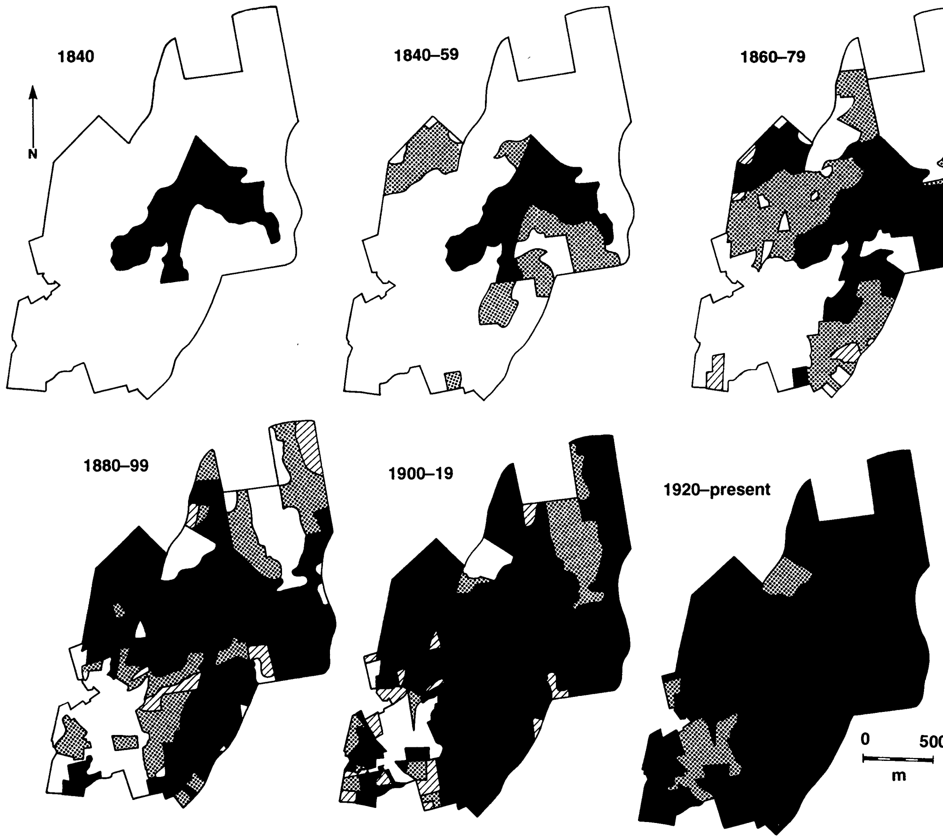
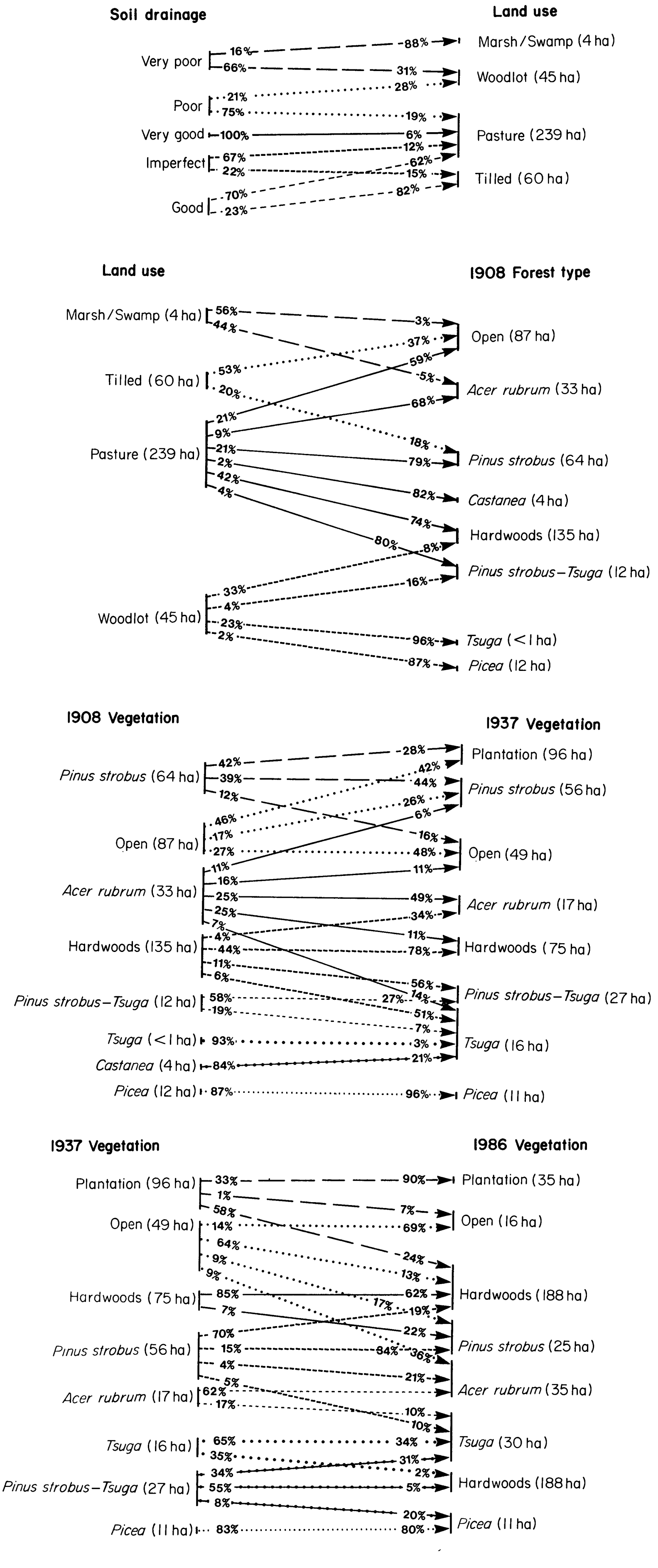


Fig. 12. The history of land abandonment for the Prospect Hill tract, Harvard Forest at 20-year intervals starting at the peak of land clearance in 1840. Areas in forest during the previous 20-year period are depicted in black. For each period abandoned pasture land is shaded, whereas abandoned tilled fields are indicated by diagonal lines. Data were derived from historical reconstructions stored in Harvard Forest Archives.

century (in 1908, 1937 and 1986 — HF Archives) depict striking relationships between vegetation and land-use patterns and dynamics in the vegetation resulting from forest development, management and the 1938 hurricane. In 1908 *Picea* forests and the limited area of *Tsuga* forest were confined to former woodlots (Fig. 13). One-third of the former woodlot area was classified as hardwood forest (*Quercus* spp., *Acer rubrum* and *Betula* spp.) with scattered *Tsuga* understorey. Former pastures were forested with *Pinus* (*Pinus strobus* and *Pinus strobus–Tsuga canadensis* forest) or successional stands of *Betula populifolia*, *Acer rubrum* and *Populus* spp. Approximately 40% of this pasture-hardwood area had supported *Pinus strobus*, which was cut in the 1890s. Only 21% of the one-time pasture land was still open in 1908, whereas 53% of the tilled fields was open.

Major changes from 1908 to 1937 occurred as a result of stand development and silviculture (Fig. 13). Nearly 100 ha of conifer plantations were established on fields (42%), clear-cut *Pinus strobus* land (28%) and successional hardwood areas (12%). The majority of the plantations (81%) were established on well-drained soils; approximately 75% on former pastures and 25% on tilled fields. The mortality of *Castanea* in 1913–16 due to blight (*Cryphonectria parasitica*; Kittredge 1913; Spurr 1950) led to the natural conversion of former *Castanea* stands to *Tsuga* (84%) or hardwood (16%) forest. Overall, hardwood forest was reduced from 135 ha to 75 ha between 1908 and 1937. However, stands of long-lived species (*Quercus*, *Betula lenta*, *B. alleghaniensis*, *Fraxinus*, *Fagus* and *Acer saccharum*) increased from 40 ha to 56 ha, whereas successional hardwood forest (*Betula populifolia*, *Populus* and *Prunus*) decreased greatly (95 ha to 19 ha; McKinnon, Hyde & Cline 1935). The reduction in successional species resulted from clearing for plantations and selective management for longer-lived species (Cline & Lockhard 1925; Gould 1960). Increases in *Tsuga* (<1 ha to 16 ha) and *Pinus strobus–Tsuga canadensis* (12 to 27 ha) forests from 1908 to 1937 were largely due to development of forests that had a substantial component of *Tsuga* in the understorey and perhaps due to a reduction in post-logging burning (Marshall 1927; Spurr 1956).

Within a year of completion of the 1937 forest survey, the forest landscape was completely altered



by the 1938 hurricane (Foster & Boose 1992). Coincidentally, the management objectives of the Harvard Forest shifted to favour natural stand development rather than timber production of conifers (Gould 1960). The changes wrought by natural disturbance and forest development are reflected in major changes in forest composition from 1937 to 1986 (Fig. 13). Overall there was a major increase in hardwood stands (75 ha to 188 ha) resulting from preferential hurricane damage to plantations (reduced from 96 to 35 ha) and *Pinus strobus* forests (56 ha to 25 ha), cutting of conifers, and old-field succession (Spurr 1956; Foster 1988; Foster & Boose 1992). Open areas were reduced by 65%, *Acer rubrum* forest doubled (17 ha to 35 ha) and *Tsuga* forests continued to increase through stand development. Nearly 35% of the *Tsuga* stands developed following hurricane damage, cutting and natural succession in hardwood stands, 41% from hurricane-damaged *Pinus strobus* and *Pinus strobus–Tsuga canadensis* stands and 20% from hardwood stands, including *Acer rubrum* swamps (HF Archives).

LAND-USE HISTORY AND FOREST COMPOSITION

Canonical correspondence analysis of the 1937 forest data identifies considerable variation in stand composition that may be explained using a combination of historical and site factors. A minimal set of variables that best explains the data was identified using the option of forward selection of variables with each variable tested and an overall test applield by means of a Monte Carlo permutation test (ter Braak 1986). Site factors selected included soil drainage and slope position, whereas important historical variables included: primary/secondary woodland, cutting history, abandonment date, and pasture/cultivation. This model was significant at the 0·01 level. The first two CCA axes (Fig. 14) account for 62% of the species–environment relations.

Samples separate out clearly along the land-use and soil-drainage gradients (Fig. 15). Primary woodlands are concentrated on the intermediate to poorly drained sites, whereas secondary woodlands occur more widely on all but the very poorly drained soils (Fig. 15). There are strong correlations between many of the environmental variables, e.g. between primary woodland and abandonment date, forest

Fig. 13. Transition diagrams depicting relationships between land-use, soils and vegetation in 1908, 1937 and 1986. The areal extent of each category or vegetation type is indicated next to it. Percentages refer to the contribution to percentages of the adjacent category or type and do not equal 100% for some types as only major relationships are depicted for clarity.

age and slope position, and between slope and soil drainage (Table 3). These correlations are apparent on the species and stand biplots as axes for the environmental variables lie closely and parallel to each other and can be used to interpret stand distribution. The distribution of primary woodland stands along the first axis is largely explained by variation in age of the forest as controlled by cutting history.

A number of tree and shrub species have an affinity for the primary woodland and swamp sites; these include: *Tsuga canadensis*, *Picea rubens*, *Fraxinus nigra*, *Nyssa sylvatica*, *Viburnum alnifolium*, *Kalmia latifolia*, *Hamamelis virginiana*, *Ilex verticillata* and *Nemopanthus mucronata* (Fig. 14). The *Tsuga* and swamp forests on primary sites generally support little herbaceous growth due to deep shade; consequently, the herb distribution on the CCA does not show any species with an affinity for primary forests. The secondary forests are characterized by early successional species and species of richer, drier sites.

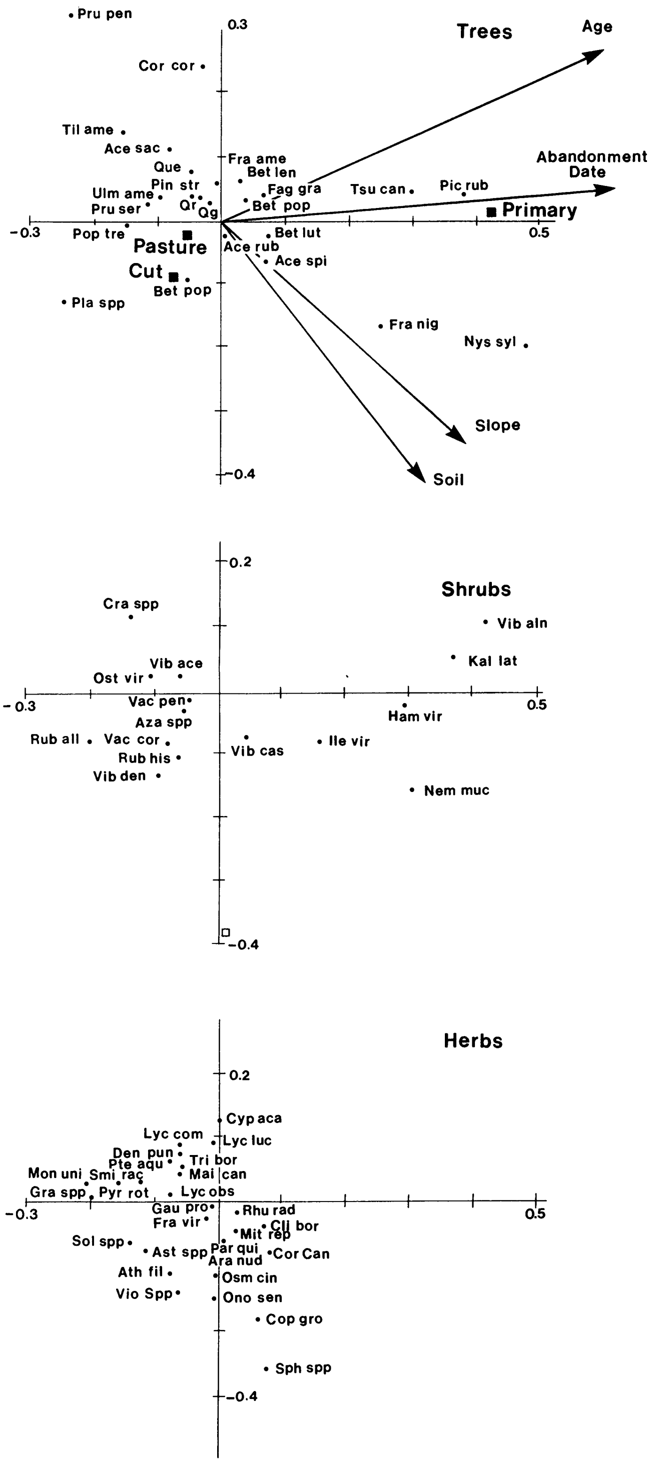


Fig. 14. Species and environmental variable bi-plot on the first two CCA axes for 1937 vegetation data from the Prospect Hill tract, Harvard Forest. Species plots are separated by growth form into trees, shrubs and groundcover. Species abbreviations are based on the first three letters of the genus and species: Trees — *Acer rubrum*, *Acer saccharum*, *Acer spicatum*, *Betula lenta*, *Betula lutea*, *Betula papyrifera*, *Betula populifolia*, *Corylus cornuta*, *Fagus grandifolia*, *Fraxinus americana*, *Fraxinus nigra*, *Nyssa sylvatica*, *Picea rubens*, *Pinus strobus*, Plantation spp., *Populus tremuloides*, *Prunus pensylvanica*, *Prunus serotina*, *Quercus rubra*, *Quercus* spp. *Tilia americana*, *Tsuga canadensis*, *Ulmus americana*; Shrubs — *Azalea* spp., *Crataegus* spp., *Hamamelis virginiana*, *Ilex verticillata*, *Kalmia latifolia*, *Nemopanthus mucronata*, *Ostrya virginiana*, *Rubus allegheniensis*, *Rubus hispida*, *Vaccinium corymbosum*, *Vaccinium pensylvanicum*, *Viburnum acerifolium*, *Viburnum alnifolium*, *Viburnum cassinoides*, *Viburnum dentatum*; Herbs — *Aralia nudicaulis*, *Aster* spp., *Athyrium filix-femina*, *Cypripedium acaule*, *Clintonia borealis*, *Coptis groenlandicum*, *Cornus canadensis*, *Dennstaedtia punctilobula*, *Fragaria virginiana*, *Gaultheria procumbens*, Gramineae, *Lycopodium complanatum*, *Lycopodium obscurum*, *Lycopodium lucidulum*, *Maianthemum canadense*, *Mitchella repens*, *Monotropa uniflora*, *Onoclea sensibilis*, *Osmunda cinnamomea*, *Parthenocissus quinquefolia*, *Pteridium aquilinum*, *Pyrola rotundifolia*, *Rhus radicans*, *Smilacina racemosa*, *Solidago* spp., *Sphagnum* spp., *Trientalis borealis*, *Viola* spp. Environmental variables are labelled on the tree plot, with the centroids of nominal variables (primary/secondary woodland, pasture/cultivation, cutting history) indicated by a large square, and ordinal variables (age, abandonment date, soil drainage, and slope position) indicated by arrows.

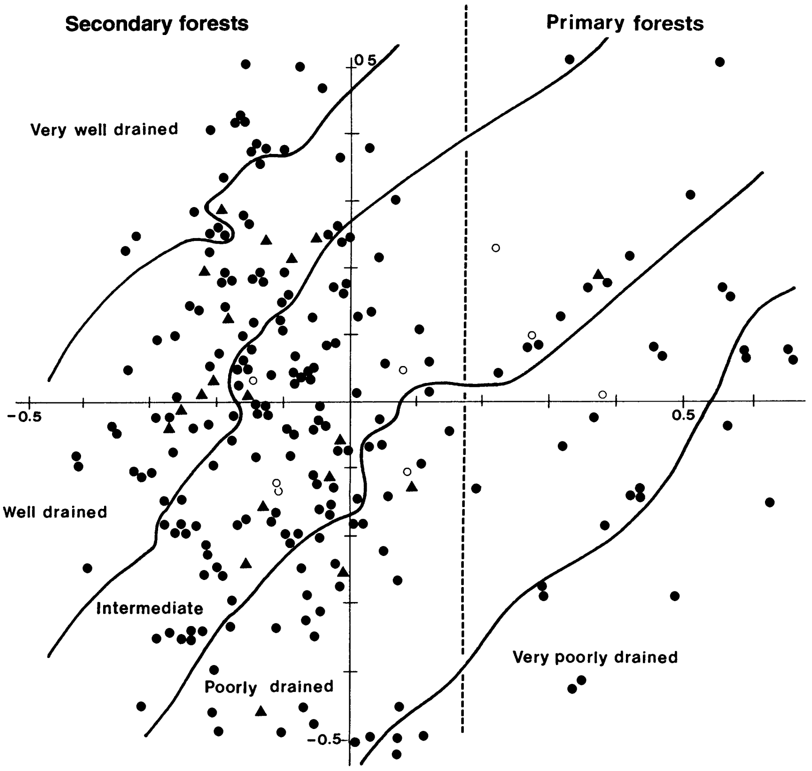


Fig. 15. Sample distribution for 253 plots on the first CCA axes. The division between primary and secondary forests along Axis 1 is indicated by the vertical broken line. Soil drainage classes are separated by solid wavy lines. Outliers within the drainage classes are indicated by different symbols: if a sample belongs to the next drier soil type it is represented by an open dot, if it belongs to the next moister soil type it is indicated by a triangle.

Discussion

One major conclusion derived from this historical analysis is that at any scale — forest, township, county or state — land-use practices and the resulting vegetation patterns have changed continuously (Bradshaw & Miller 1988; Foster *et al.* 1992). Over the past 250 years there have been few periods of stability in which even the extent of forest vs. open land was relatively constant (Fig. 3). Population density, the agricultural, forestry and industrial practices, and the geographical pattern of land use were all highly variable. The changing quality and intensity of human activity resulted in the dynamic vegetation characteristic of this period.

LAND-USE HISTORY

Across central New England there has been great similarity in the regional pattern of land use in terms of the extent and timing of deforestation, major agricultural uses, and the history of farm abandonment and reforestation (Bogart 1948; Gates 1978; Taylor 1982; Garrison 1985). The Prospect Hill tract of the Harvard Forest is clearly representative of the township of Petersham in these characteristics (Figs 3, 4 and 12). Worcester County, in general, was more agriculturally orientated than western parts of the state, and thus the rate and extent of forest clearing in Petersham are greater than state averages. However, temporal shifts in land use followed the same general mode throughout upland areas: land clearance and gradual depletion of the timber resource was followed by low-intensity agriculture, commercial agriculture and industry, and subsequently by population migration and farm abandonment (Bidwell 1916; Garrison 1985; Williams 1989). In the modern period, utilization of the land for natural resources is at a historical low, but pressure for housing and commercial development is leading to a minor second wave of clearance, and a concern for forest preservation (Anonymous 1940; Black & Wescott 1959; Bickford & Dyman 1990). In this pattern, Petersham parallels the trends of many upland townships (MacConnell 1975).

The land-use pattern that emerges on examination of the Prospect Hill tract is exceedingly complex and variable in scale and intensity over time. Each of the individual parcels comprising the tract was owned by an average of 13 individuals in the 160-year period. These owners differed in the size of their holdings, duration of ownership, and undoubtedly in their economic and social perspective (e.g. Garrison 1985). Although the details vary, each forest stand was cut repeatedly, most were cleared, and all were subjected to varying agricultural use, including grazing (Graves & Fisher 1903; Barraclough & Gould 1955).

In the determination of the geographic pattern of land use there were strong interactions between environment, spatial relationships and land-use quality. Each land-use activity triggered various vegetational changes that affected subsequent land-use decisions up to the present. Agricultural use was strongly controlled by site conditions (undoubtedly including the original vegetation; cf. Lord 1973) and distance from the road or farm. Sites adjacent to farms and roads were cleared first, used most intensively and abandoned last (Figs 2c and 10). Soil moisture strongly controlled use, with wet sites used as woodlots, mesic sites tilled for cultivation and extremely dry or moist sites pastured (Table 2). Within Petersham a similar overall pattern of use based on distance and soil conditions appears to hold (Fig. 4) (Raup & Carlson 1941).

The quality and timing of land-use determined the subsequent vegetation, which in turn affects later human activity and the impact of natural disturbance processes. For example, the extensive logging enterprise in the late 1800s and early 1900s was controlled by the timing and placement of field abandonment in the mid 1800s. Similarly, decisions concerning the placement of conifer plantations were determined by the distribution of open fields or early successional vegetation (former fields) in the period 1910–40. In terms of natural processes, it is clear that the effect of the 1938 hurricane was controlled by the structure, composition and spatial distribution of the vegetation that resulted from 200 years of human activity (Foster & Boose 1992). The *Pinus strobus* and plantations on former fields were particularly susceptible to wind damage and are largely responsible for the great extent of damage to the landscape of central New England (Rowlands 1941).

VEGETATION RESPONSE TO LAND USE

Evaluation of the effect of cumulative land use on the vegetation is strongly scale-dependent. Across the region (i.e. Worcester County) the effect is subtle and suggests that the vegetation is resilient to disturbance (Raup 1966). Species assemblages sorted out in the 1700s along climatic gradients defined by latitude and altitude much as they do today (Westveld 1956). However, shifts in the abundance of species are notable, primarily a general increase in successional and sprouting species (e.g. *Betula populifolia*, *Acer rubrum*, *Quercus* spp.) and decline in long-lived tolerant species (*Fagus*, *Tsuga*, *Acer saccharum*) (Cook 1917; Dickson & McAfee 1988). Pathogens have also reduced the abundance of *Castanea*, *Fagus* and *Ulmus* (Gravatt & Parker 1949; Hirt 1956; Karnosky 1979; Paillet 1982).

At a local scale within a forest the effects of land use are compelling (Foster & Zebryk 1993). The pattern of vegetation is clearly abrupt and discontinuous in composition and structure; gradients are steep. Structurally the forests are young and even-aged. In addition to structural characteristics, major compositional trends can be tied to land use. *Picea rubens* and *Tsuga* are largely confined to the areas of permanent woodlot (Fig. 13; cf. Smith 1950; Kelty 1984), and a few tree and shrub species (e.g. *Viburnum alnifolium*, *Kalmia latifolia*, *Hamamelis virginiana*, *Ilex verticillata*, *Fraxinus nigra*, *Nyssa sylvatica*) are associated with these primary forests (Fig. 14). In contrast, pasture areas are dominated by *Pinus strobus*, *Pinus strobus–Tsuga canadensis*, *Castanea* and poor hardwood forests of *Betula populifolia* and *Acer rubrum* (Figs 13 and 14).

During the period of reforestation, compositional changes in the vegetation have accompanied changes in the total cover, and increases in mean height and age. Until the 1938 hurricane, hardwoods declined as a result of increases in *Tsuga* from advanced regeneration, conversion of successional hardwood forests to *Pinus strobus*, and silvicultural management of mixed stands to increase *Pinus strobus* and *Tsuga*. Following the hurricane, which greatly damaged plantations and *Pinus strobus* stands, and subsequent salvage logging, hardwood cover increased greatly. Hardwoods continued to establish in many open areas as active management for conifers ceased. One major trend across this period is the increase in *Tsuga* as a major cover type; 20% of the *Tsuga* forest derives from succession and advance regeneration in hardwood stands, 35% from hurricane-damaged hardwoods and 41% from hurricane-damaged *Pinus strobus* and *Pinus strobus–Tsuga canadensis* forest.

One major question not addressed by the current study but warranting additional investigation is the longevity of these land-use impacts in terms of forest community composition and structure. Analysis of the 1937 vegetation defines striking relationships between composition and historical variables, including primary/secondary forest, age, and timing of abandonment, and site factors (cf. Whitney & Foster 1988). Analysis of the modern vegetation, approximately 55 years later will enable us to see if additional time for forest development and species dispersal and the impact of the 1938 hurricane have reduced the imprint of the history of land-use on vegetation patterns.

Conclusion

The continually dynamic nature of the vegetation pattern in central New England is one of the most remarkable aspects of the post-settlement landscape. A complete transformation occurred in the regional and local landscape from 1770 to the present as the countryside was deforested, farmed and subsequently reforested. Within a landscape such as that of the Harvard Forest, this history of use was dependent on original site factors and has greatly affected subsequent vegetation characteristics. These effects are long-lasting as they continue to control the way in which humans use sites and the ways in which natural processes affect them. The ramifications of this history in terms of contemporary ecological processes are too great to be dismissed by modern-day ecologists.

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