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Three hundred years of forest and land-use change in Massachusetts, USA

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Abstract

Aim The aim of this study was to document changes in forest composition, structure and distribution across Massachusetts, USA, from the time of European settlement (seventeenth century) to the present, and to investigate environmental and historical influences on regional patterns of variation.

Location The study area encompasses the State of Massachusetts (69.9–73.5°E, 41.3–42.9°N), a 21,000-km^2 area in the north-eastern United States.

Methods A wide range of historical sources was used to document changes in land use and land cover for the historical period. Witness trees from early land surveys enabled us to evaluate vegetation patterns prior to widespread European settlement, and to compare historical and modern species composition. Nineteenth century maps of forest cover and contemporary agricultural censuses documented forest patterns during the peak agricultural period. Geographic Information System analyses were used to relate variation in climate, geology and land-use history to historical and modern forest composition.

Results Massachusetts has a complex east-to-west environmental gradient involving changes in physiography, climate, geology and natural disturbance. Until the middle of the twentieth century, agriculture was the most important land-use across the region; although the percentage of land in agriculture and the timing of major land-use changes were remarkably consistent across the state, historical forest patch sizes varied locally and regionally in relation to physiography. Forest composition of both early historical and modern forests is most strongly related to environmental conditions, especially variation in climate. Historical land-use resulted in a state-wide increase in early successional tree species and a dramatic, although recovering, change in forest structure.

Main conclusions At a regional scale, environmental conditions apparently control broad patterns of variation in vegetation composition. Historical land-use practices were relatively homogenous across Massachusetts and local variation was reduced through data averaging at broad spatial scales. At finer spatial scales, historical land-use has strong and persistent impacts on vegetation composition and structure.

Keywords
Land use, history, disturbance, scale, New England, Massachusetts, ecoregions.

INTRODUCTION

An understanding of disturbance history is increasingly recognized as critical for the interpretation of modern landscapes, the evaluation of conservation objectives and the development of management approaches for natural areas (Foster & Motzkin, 1998; Foster, 2000; Marcucci, 2000; Egan & Howell, 2001). In regions with long histories of human settlement, such historical perspectives must consider the relative influence of past land use vs. natural disturbance or environmental variation in controlling modern community composition and function. Unlike many regions of Europe where a wealth of historical data have enabled rigorous evaluation of landscape history (e.g. Rackham, 1986; Birks *et al.*, 1988; Bürgi, 1999; Verheyen *et al.*, 1999), studies of landscape history in North America are frequently hampered by limited data on past landscape conditions and

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land-use history. As a result, prior studies in the north-eastern USA have generally been restricted to local investigations of sites with well-documented histories of disturbance (e.g. Glitzenstein *et al.*, 1990; Motzkin *et al.*, 1996), and few studies have attempted to relate regional variation in environment and history to broader vegetation patterns (Foster *et al.*, 1998).

In this study, we evaluate the influence of environmental variation and land-use history on forest composition and distribution across the State of Massachusetts from the early historical period (seventeenth–eighteenth centuries) to the present. The study region is particularly appropriate for such investigations because variation in vegetation, environmental conditions and disturbance history are broadly representative of conditions across the north-eastern USA (Whitney, 1994), and critical historical data exist that are unavailable for other regions of North America. For instance, although much of the eastern USA was cleared for cultivation or grazing in the eighteenth and nineteenth centuries, to our knowledge Massachusetts is the only state where detailed maps depict statewide forest cover during the peak of the agricultural period at a town-scale ($\sim$ 100 km^2), which corresponds to the scale at which settlement patterns and land-use practices were determined and the scale at which a wide range of historical data were compiled. These and other historical sources present an unusual opportunity to document changing land cover through the historical period and to evaluate potential shifts in the factors that have controlled forest distribution and composition over time (cf. Motzkin *et al.*, 1999a, 2002).

The relative importance of historical vs. environmental factors in controlling vegetation patterns is strongly dependent on the scale of investigation. Local studies document the persistent influence of past land-use practices, even those that occurred hundreds of years ago, on modern forest structure, composition and distribution (Milne, 1985; Glitzenstein *et al.*, 1990; Whitney, 1990; Bratton & Miller, 1994; Schneider, 1996; Cowell, 1998; Bellemare *et al.*, 2002); in some instances, land-use history has been found to more strongly influence modern vegetation than current variation in environmental factors such as soils (Motzkin *et al.*, 1996; Eberhardt *et al.*, 2003) or climate (Foster *et al.*, 1998). In contrast, regional and subregional studies have typically emphasized the importance of environmental controls on vegetation composition (Siccama, 1971; Abrams & Ruffner, 1995; Cogbill *et al.*, 2002), and have generally not evaluated landscape history (although see Foster *et al.*, 1998 and Bürgi *et al.*, 2000). We present a regional case study in which we evaluate environmental and historical influences on the composition, structure, and distribution of forests across Massachusetts for the historical period. Specific objectives for this study include: (1) to determine the relationship of forest distribution through the historical period to variation in physiography and land use and (2) to document changes in forest composition from the early historical period to the present and determine whether the environmental and historical factors that influence vegetation composition have changed over time.

MATERIALS AND METHODS

Study area

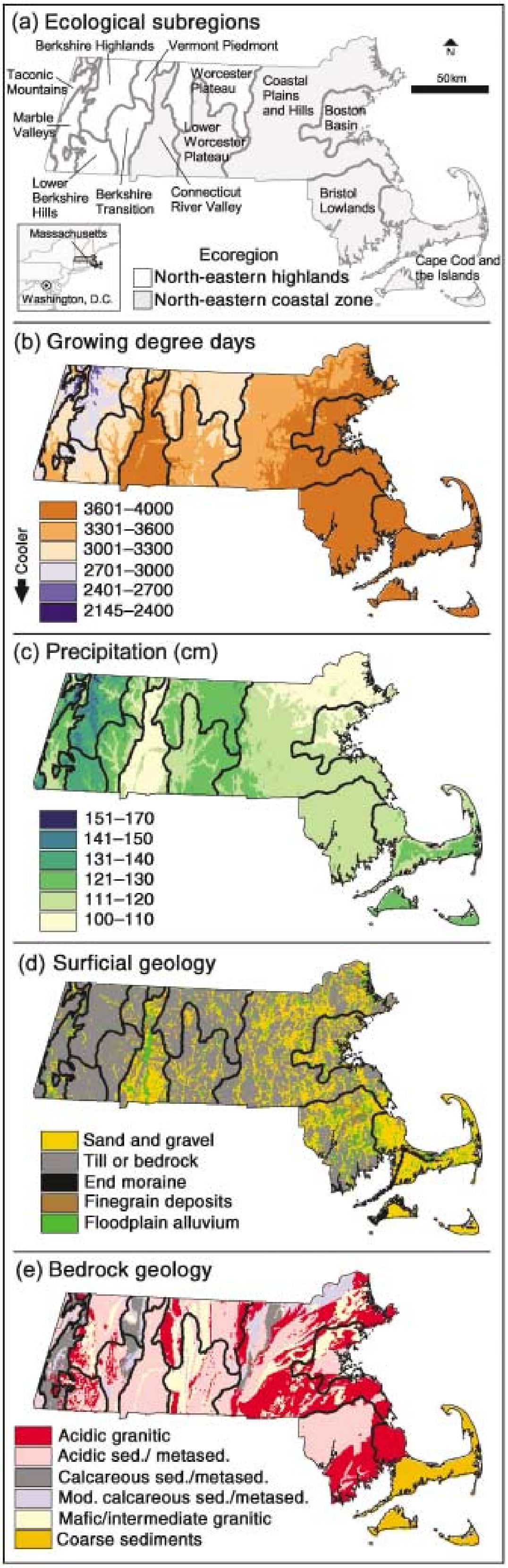
The study area includes the entire state of Massachusetts (69.9–73.5°E, 41.3–42.9°N), a 21,000-km^2 area in the north-eastern United States, *c.* 500 km north-east of Washington, DC. Massachusetts is organized into 351 towns and the state includes portions of two ecoregions and thirteen subregions defined according to the homogeneity of geology, physiography, vegetation, climate and land use (Griffith *et al.*, 1994). The western and north-central portions of the state lie in the North-eastern Highlands (Fig. 1; Table 1), a primarily mountainous region of granitic and metamorphic bedrock overlain by glacial till (Zone M212 in Bailey, 1995). Elevations range from 60 to 1014 m, with a mean of 359 m. The average annual temperature is 7.3 °C and average growing-season temperature (May–September) is 17.0 °C. Average annual precipitation is 119 cm and average growing season precipitation is 51 cm (National Oceanic and Atmospheric Administration, 1994). The region is largely forested with northern hardwoods, hemlock, and some spruce and fir at higher elevations (Griffith *et al.*, 1994), but supports many rural villages, old industrial towns and some agricultural lowlands. Eastern Massachusetts lies in the North-eastern Coastal Zone (Zone 221 in Bailey, 1995), a region of lowlands and rolling hills supporting hardwood, white pine, and hemlock forest, urban and suburban areas, and scattered agriculture. Elevations range from 0 to 364 m, with a mean of 79 m. The average annual temperature is 9.4 °C and average growing-season temperature is 18.4 °C. Average annual precipitation is 117 cm and average growing season precipitation is 46 cm (National Oceanic and Atmospheric Administration, 1994).

Although most of Massachusetts is characterized by acidic soils that developed on granitic or metamorphic bedrock, the North-eastern Highlands in the western part of the state includes some areas with calcareous and moderately calcareous bedrock (especially in the Marble Valleys and Vermont Piedmont subregions; Zen *et al.*, 1983; Anderson *et al.*, 1998).

Environmental data

A one arc-degree (1 : 250,000 scale) digital elevation model (DEM) was created by joining existing Geographic Information System (GIS) datalayer grids (USGS, 1993) in ArcView GIS© (ESRI, 1996). The DEM was then projected to the Massachusetts State Plane, North American Datum 1983 coordinate system and re-sampled to a grid size of 230 m in ArcInfo© (ESRI, 1999). All subsequent grids had the same

Figure 1 The ecological subregions and environmental characteristics of the state of Massachusetts. Ecological subregions follow Griffith *et al.* (1994), climatic data were modelled from techniques described in Ollinger *et al.* (1995), surficial geology is from MassGIS (1999), and bedrock geology is from Zen (1983) and Anderson *et al.* (1998).



projection and grid size. In order to evaluate relationships between vegetation and climate, regression equations from Ollinger *et al.* (1995) were used to calculate annual precipitation and monthly average temperature based on elevation, latitude and longitude for each grid cell of the DEM. Monthly average temperatures less than 0 °C were changed to 0 °C, and the average monthly temperature grids were then multiplied by the number of days in the month to calculate the number of growing degree days (GDD) for each month; all 12 months were then summed into a grid of annual GDD. Although climate may have changed in the 350 years since European settlement, we assume that climatic gradients across the study area are likely to have remained relatively consistent, and all analyses are conducted with modern climate data (Foster *et al.*, 1998; Cogbill *et al.*, 2002).

Datalayers of surficial (MassGIS, 1999) and bedrock geology (Zen *et al.*, 1983) were used to evaluate relationships between land use/land cover and environment over time. For analyses of bedrock, lithographic units were categorized into seven classes that are likely to influence vegetation following Anderson *et al.* (1998). Environmental variables were Log10 (X + 1) transformed to improve normality (Jongman *et al.*, 1995) and Pearson correlations were conducted to identify correlated variables.

Historical land use and land cover

Estimates of town land use and land cover were gathered from a variety of sources including tax evaluations (1801–1860), state agricultural census records (1865–1905), Massachusetts MapDown project (1951, 1971; MacConnell, 1973), and MassGIS land use/landcover GIS datalayers (1985, 1999; MassGIS, 2002). Data prior to 1801 rarely covered the entire study region and were excluded. Data on forest structure were available for several time periods, including 1885 and 1895 (Agricultural Censuses), 1916–20s (forestry surveys), 1951 and 1971 (MacConnell, 1973), 1985 (Dickson & McAfee, 1988) and 1998 (Alerich, 2000).

Forest composition at the time of European settlement

Following methods described more fully in Cogbill *et al.* (2002), we used early surveyors' tree records from initial land divisions in each town to reconstruct the vegetation at the time of European settlement and before extensive Euro-American land use. All available original seventeenth–early nineteenth century survey records located at the state archives and individual town halls were examined and colloquial or common names of marker trees were noted. These names were assigned to modern taxa groups based on previous studies and eighteenth century manuscripts (Kalm, 1770; Whitney, 1994; Bürgi *et al.*, 2000; Cogbill, 2000) following the designations of Cogbill *et al.* (2002). Common names that could not be positively identified at least to the genus level, and taxa that did not have a relative frequency > 5% in at least one town, were excluded from analysis. With few exceptions, only surveys that occurred

Table 1 Environmental characteristics of the thirteen ecological subregions in Massachusetts

	North-eastern highlands ecoregion						North-eastern coastal zone							
Variable	Taconic Mountains	Marble Valleys	Berkshire Highlands	Lower Berkshire Hills	Berkshire Transition	Vermont Piedmont	Worcester Plateau	Connecticut River Valley	Lower Worcester Plateau	Coastal Plains and Hills	Boston Basin	Bristol Lowlands	Cape Cod and Islands	Statewide
Mean elevation (m)	518	307	490	431	299	257	288	76	219	85	32	27	19	163
SD	120	64	97	64	95	83	58	31	52	60	20	15	16	158
Modelled growing degree days	2908	3271	2931	3100	3282	3283	3220	3671	3403	3588	3674	3804	3839	3497
SD	196	129	154	109	169	144	104	77	102	93	41	45	63	284
Modelled precipitation (cm)	136	122	135	133	124	118	124	109	121	114	112	117	121	119
SD	9	4	7	4	7	6	5	3	4	4	1	2	2	8
Mean per cent slope	16.0	5.7	8.6	6.3	7.8	9.8	5.2	2.4	4.2	2.3	1.7	1.0	1.3	3.7
SD	9.9	5.8	7.3	5.6	6.2	5.9	4.5	3.5	3.7	2.2	1.6	1.0	1.4	4.9
Mean January temperature (°C)	−7.2	−5.5	−7.1	−6.1	−5.4	−5.7	−5.8	−3.9	−4.8	−4.2	−3.8	−2.8	−2.5	−4.5
SD	1.0	0.6	0.7	0.5	0.7	0.6	0.4	0.4	0.4	0.5	0.2	0.3	0.4	1.4
Mean July temperature	18.9	20.5	19.0	19.7	20.5	20.6	20.3	22.1	21.0	21.8	22.1	22.5	22.6	21.4
SD	0.9	0.5	0.7	0.5	0.7	0.6	0.4	0.3	0.4	0.4	0.2	0.1	0.2	1.1
Surficial geology type (%)														
Till/bedrock	98	73	96	97	90	87	84	27	76	57	47	43	2	59
Sand/gravel	2	19	4	3	9	11	14	52	22	37	44	40	73	32
Fine grain	0	8	1	0	1	2	2	15	2	6	8	13	8	6
Floodplain	0	0	0	0	0	0	0	0	0	0	0	0	15	1
End moraine	0	0	0	0	0	0	0	7	0	1	2	4	1	1
Bedrock type (%)														
Acidic sedimentary (sed.)	60	5	56	41	51	6	46	92	53	20	38	62	0	38
Acidic granitic	0	9	19	40	12	0	28	1	7	50	32	37	26	29
Mafic/intermediate granitic	0	1	20	14	5	7	22	6	36	16	30	1	0	14
Course sediments	0	0	0	0	0	0	0	0	0	0	0	0	74	7
Calcareous sed./metased.	11	75	1	3	19	51	0	0	0	4	0	0	0	7
Mod. calcareous sed./metased.	29	10	3	1	13	35	5	1	4	10	0	0	0	6

within 80 years of town settlement were used in order to limit the potential influence of European land use on species composition. Towns with fewer than fifty trees were also excluded ($n = 25$), and data for forty-six modern towns could not be located. A total of 144 historical towns (representing 274 modern towns) were included in witness-tree analyses with a mean of 394 trees per town.

Although most of our data are derived from lotting surveys, road surveys were occasionally included where lotting data were unavailable (see Bürgi & Russell, 2000; Cogbill *et al.*, 2002) or, where both sources were available (total of twenty-two towns included road-survey data), to remove subjectivity in deciding which source more accurately reflects historical forest composition. A GIS datalayer of modern town boundaries was altered to approximate the bounds at the time of the survey. If a town was divided early in the historical period, it was possible to have survey data for both resulting towns, in which case data from each 'daughter' town were analysed separately. If a town was divided long after the original survey then the two modern towns were analysed together. Individual species distributions and mean frequencies were displayed in GIS as a series of distribution maps and cluster analysis with group average linkage based on Bray–Curtis distances was performed in PC-ORD© (McCune & Mefford, 1999) in order to classify early historical vegetation.

Forest distribution in the agricultural period

In 1830, the state of Massachusetts mandated that each town produce a town plan at the scale of 100 rods/inch (1 : 19,200). Most of these maps indicate roads, prominent buildings and businesses, meadows and woodlands. Copies were made of the original maps housed at the Massachusetts State Archives and were geo-referenced to US Geologic Survey topographic quads using a zoom-transfer scope before digitizing in ArcView GIS©.

Modern forest composition

United States Department of Agriculture Forest Service 1998 Forest Inventory and Analysis data (FIA; Hansen *et al.*, 1992) for Massachusetts were used to describe modern forest composition. Plot data were aggregated to town and subregion levels to facilitate comparison with environmental data and early colonial forest composition. Towns with fewer than fifty trees in the FIA data set were excluded from our analyses. FIA data on modern forest composition included ninety-five towns with > 50 trees, with an average of ninety-eight trees per town and a total of 9272 trees.

RESULTS

Environmental characteristics of Massachusetts

Across Massachusetts, elevation, climate and geology covary to form a complex east–west gradient and a less-pronounced north–south gradient in the uplands of the central and western portions of the state (Fig. 1). For instance, as elevation increases to the west and northward across the Worcester Plateau and Berkshire Highlands/Lower Berkshire Hills subregions, there are corresponding decreases in GDD and increases in precipitation and average slope. The surficial geology of higher elevation subregions is also characterized by abundant till or bedrock with less sand or gravel. The Connecticut River and Marble Valleys have environmental characteristics more similar to the eastern part of the state than to their neighbouring subregions.

Historical land use and land cover

Settlement patterns

Geography and physiography strongly influenced the timing of European settlement (Fig. 2). The earliest settlements occurred along the eastern seaboard in the Plymouth and Massachusetts Bay Colonies (Boston Basin area), in areas of first landfall near protected harbours and where marshes provided hay for livestock (Russell, 1976). The Connecticut River Valley and the central part of the Lower Worcester Plateau (near Brookfield, MA, USA) were also settled relatively early because of the rich, easily tilled soils, abundant freshwater meadow grass and history of use by Native Americans (Russell, 1976; Cronon, 1983). As the European population grew, settlement expanded westward from the Boston Basin, eastward to Cape Cod and the Islands from the Plymouth area, and northward up the Connecticut River Valley from early settlements in Springfield, Longmeadow and Agawam. Regions of higher elevation such as the Worcester Plateau and the Berkshire subregions were not settled until the middle-to-late eighteenth century, following the granting of land to veterans of the French and Indian wars (Wilkie & Tager, 1991). Many of the states' earliest settlements subsequently developed into large urban centres, including metropolitan Boston, Springfield and Worcester.

General patterns of agriculture

The thirteen subregions in Massachusetts supported similar trends in agricultural land use between 1801 and 1999 (Fig. 3). Agriculture generally peaked between 1830 and

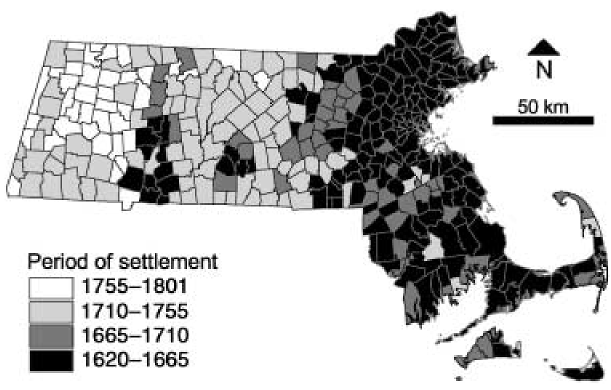


Figure 2 The timing of initial Euro-American settlement of towns in Massachusetts (E. Gould, unpubl. data).

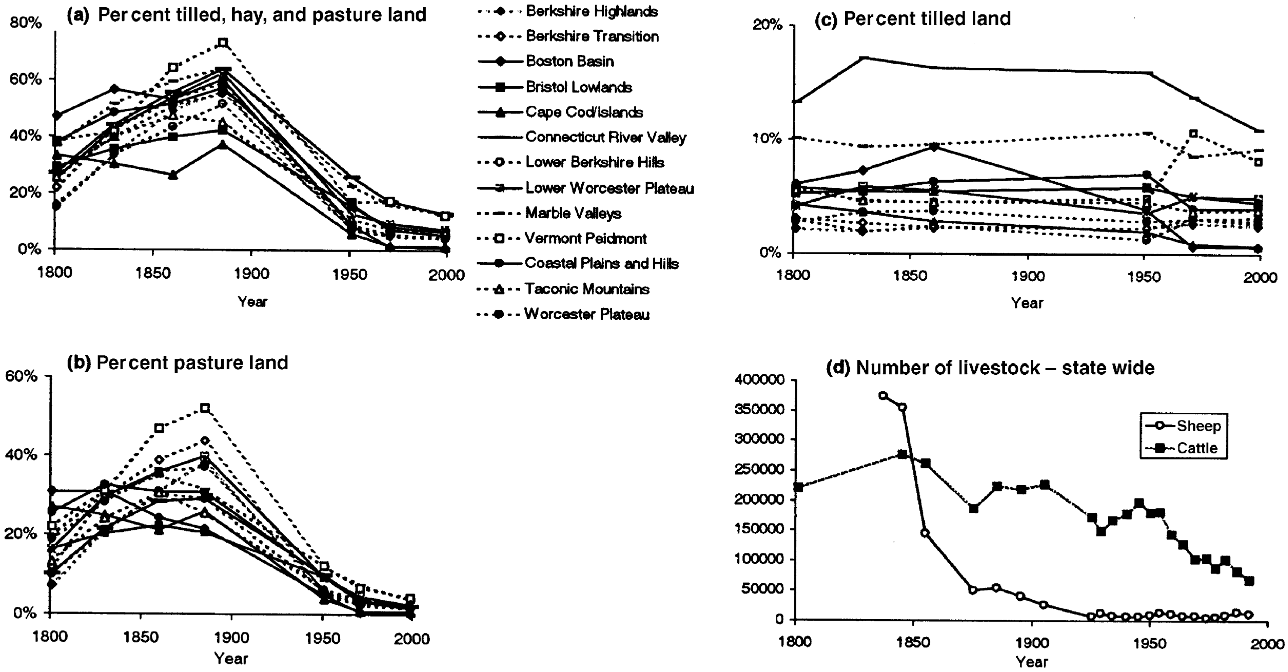


Figure 3 Agricultural land use from 1801 to 1999 in Massachusetts. Shown are percentage of land cover of tilled, upland hay and pasture (a), pasture land only (b), and tilled only (c) by ecological subregion and the number of adult cattle and sheep for the state (d). See Methods for data sources.

1885 (although perhaps earlier on Cape Cod and the Islands), when *c.* 50% of the land was in pasture, hay, or cultivated fields, and the number of sheep and cattle reached more than 650,000 (Fig. 3d). Agriculture subsequently declined rapidly through the twentieth century and currently occupies only 7% of the land area. Broadly, the opening of productive agricultural lands in the western USA, development of rail transportation, and a regional shift to industrial activity prompted agricultural decline beginning in the second half of the nineteenth century. Remaining agricultural activity largely shifted to production of bulky and perishable items including dairy products, fruit and vegetables (Russell, 1976).

Whereas pastures and upland hayfields, which together comprised most of the non-forested land, expanded and then declined dramatically through the historical period, the amount of tilled land remained relatively constant ($\sim$ 2–16%) for $\sim$150 years until a decline after 1950 in most portions of the state. The fertile and tillable soils of the Connecticut River and Marble Valleys typically supported more than twice the cultivated land than other subregions, whereas the lowest percentage of tilled lands occurred in the North-eastern Highlands (except for the Marble Valley), Cape Cod and the Islands, and the Coastal Plains and Hills. Generally, the North-eastern Highlands supported more pasture than the North-eastern Coastal Zone, with the greatest extent occurring in the Vermont Piedmont and Berkshire Transition subregions. Prior to the 1860s, the Boston Basin had the highest percentage of pasture and upland haylands, presumably because of its high population density and the limited ability to import perishable or bulky goods from more distant areas.

Forest cover change

Prior to the early twentieth century, forest history was intimately linked to agricultural activity and the amount of these land-cover types was negatively correlated (Figs. 3 and 4). Consequently, forest cover reached a nadir during the mid-nineteenth century (1830–85) and increased rapidly following widespread agricultural abandonment until the 1950s. Across most of the North-east Highlands (except for the Worcester Plateau), forest area continued to increase through the twentieth century, with large portions of the region supporting greater forest cover today than at any point in the past 200 years. Conversely, forest cover in the North-east Coastal Zone generally declined from 1950 to 1999 as a result of residential and commercial development (Fig. 5).

Changes in forest distribution since the peak of agriculture

The 1830 maps (Fig. 6) document regional variation in the amount and size of woodlands during the height of the agricultural period and indicate that the largest forest patches remained on Cape Cod and the Islands, where stands averaged 490 ha (SD = 2970 ha) due primarily to two large forest blocks of *c.* 26,000 ha each. The Taconic Mountains, Lower Berkshire Hills, Berkshire Highlands, and Bristol Lowlands supported somewhat smaller forest areas, avera-

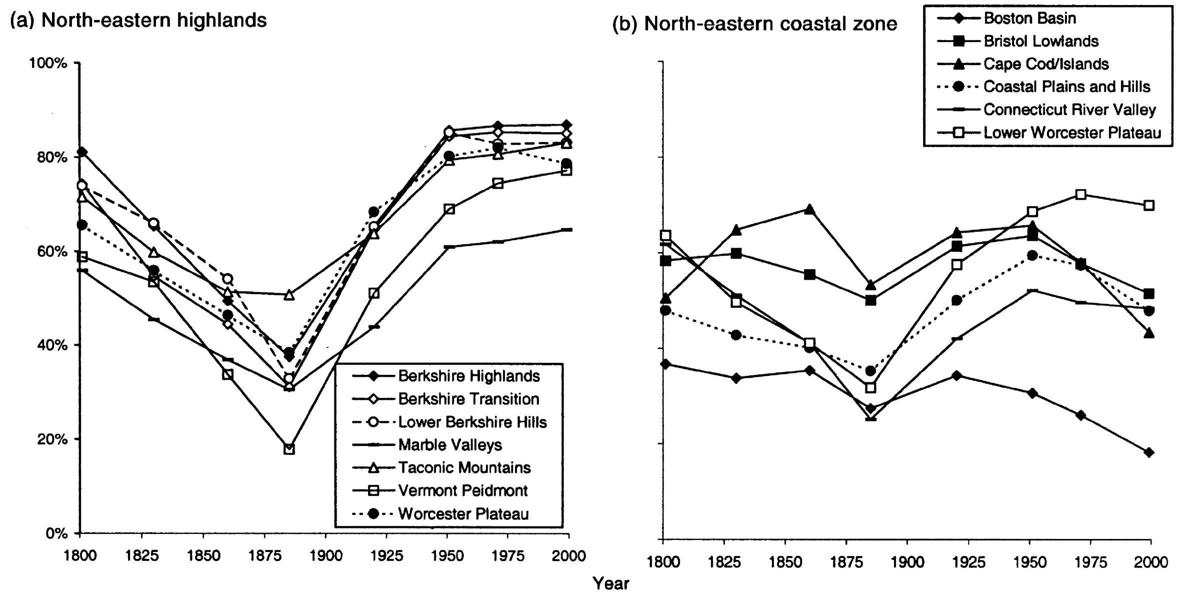


Figure 4 Percentage of forest cover from 1801 to 1999 for ecological subregions in the North-eastern Highlands (a) and the North-eastern Coastal Zone (b). Nineteenth century data include lands described as 'unimproved' and 'unimprovable'.

ging 204, 188, 188 and 119 ha, respectively. Across much of the centre of the state individual woodlots were much smaller, averaging < 85 ha. Following this pattern of forest patch size, the greatest amount of forest cover also occurred in Cape Cod and the Islands, Taconic Mountains, Berkshire Highlands and Lower Berkshire Hills. The lowest forest cover occurred in the Boston Basin, Vermont Piedmont, Coastal Plains and Hills, and Worcester Plateau.

Woodlands were most common in 1830 on poor agricultural lands such as mountains, swamps and dry sand plains. This pattern was notable across several spatial scales. For instance, as noted above, across the state, the greatest amount of forest remained in mountainous or sandy areas, whereas lowlands and areas of moderate relief such as the Worcester Plateau were heavily cleared. At the subregional scale, the hilly north-western and south-western Bristol Lowlands and the hilly western Worcester Plateau remained heavily wooded. At the town level, forest remained on hills even in towns with gentle topography, including those in the Boston Basin where the elevation range is only 30 m.

Forest composition at the time of European settlement

At the time of European settlement, Massachusetts forests were dominated by oaks (*Quercus* spp.) [mean relative frequency (average of town relative frequencies) = 43%, frequency of occurrence (per cent of towns in which taxa occurs) = 96%], pines (*Pinus* spp.) (14%; 94%), maples (*Acer* spp.) (7%; 88%), hemlock (*Tsuga canadensis*) (7%; 61%), beech (*Fagus grandifolia*) (7%; 56%), chestnut (*Castanea dentata*) (5%; 65%), hickory (*Carya* spp.) (4%; 82%) and birch (*Betula* spp.) (4%; 88%) (Fig. 7). Minor but locally abundant taxa included ash (*Fraxinus* spp.), cherry (*Prunus* spp.), poplar (*Populus* spp.), basswood (*Tilia americana*), elm (*Ulmus* spp.) and spruce (*Picea* spp.). The higher-elevation Berkshire and Worcester Plateau subregions supported abundant northern taxa such as beech, hemlock and birches, whereas lower-elevation subregions to the south and east had abundant oak and hickory. Pine occurred statewide except in the Berkshire subregions, but was most abundant on the Worcester Plateau and on Cape Cod. Maple also occurred statewide but reached its highest values in the Berkshire subregions, Worcester Plateau and Bristol Lowlands. Modern species distributions suggest that sugar maple (*A. saccharum*) predominated in the Berkshire subregions, whereas the Bristol Lowlands probably supported abundant red maple (*A. rubrum*). Pine on Cape Cod was presumably largely pitch pine (*P. rigida*), whereas white pine (*P. strobus*) was probably more important on the Worcester Plateau. Chestnut occupied much of the centre of the state but was uncommon or absent from many towns in the east.

Linear correlations indicate that GDD and sand and gravel substrate (variables that are correlated) are highly correlated with seven of eight taxa that were most common in the colonial period (Table 2). Beech, birch, maple and hemlock were negatively correlated with GDD, while pine, hickory and oak were positively correlated. Chestnut was more strongly correlated with the SD of GDD ($r = 0.58$; $P < 0.001$) than with the mean GDD ($r = -0.27$; $P = 0.09$), reflecting its abundance in hilly regions.

Classification of the witness tree data identified five broad forest types at the time of European settlement (Fig. 8): hemlock–northern hardwoods at high elevations; oak–hickory with chestnut and pine in the Lower Worcester Plateau, Connecticut River Valley and Coastal Plains and Hills; a transitional type with hemlock and northern hardwoods as well as oak, pine and chestnut in areas between the

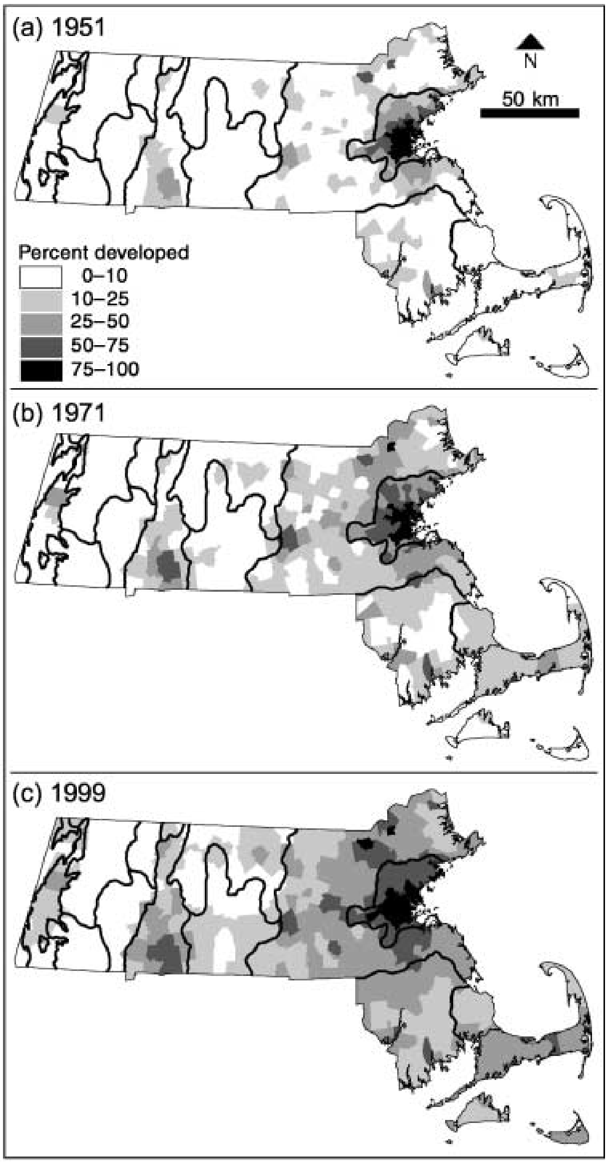


Figure 5 Map of developed lands in Massachusetts in 1951 (a), 1971 (b) and 1999 (c). The developed land category includes industrial, commercial, transportation, residential, urban open and cemetery lands, as defined by MacConnell (1973). Data from MacConnell (1973) and MassGIS (2002).

hemlock–northern hardwoods and oak–hickory types; pine–oak on Cape Cod; and pine–oak with relatively abundant swamp taxa in the Bristol Lowlands and in scattered towns in eastern Massachusetts.

Comparison of modern and colonial forest composition

Statewide, the taxon with the greatest mean importance in the modern data is maple [mean relative frequency (average of town relative frequencies) = 27%; frequency of occurrence (per cent of towns in which taxa occurs) = 98%], followed by oak (22%; 90%), pine (19%; 88%), birch (9%; 80%), hemlock (7%; 50%), ash and cherry (both 3%; 56%, 58%, respectively) and beech (2%; 40%).

Discriminant function analysis of colonial and modern (FIA) data indicates that differences between the two periods are largely attributable to decreases in beech, hickory and chestnut, and increases in maple and cherry (Table 3). Correlations between axis scores and environmental variables of separate ordinations of colonial and modern data indicate that overall, climate remains similarly important in determining modern vegetation patterns as in the colonial period (mean GDD: $r^2 = 0.62$ in colonial forests vs. 0.64 in modern forests). However, the strength of correlations between GDD and seven of eight dominant taxa declined somewhat from the colonial to modern periods. The strength of the relationships between the vegetation ordinations and surficial deposits increased from the colonial to modern periods (per cent till/bedrock: $r^2 = 0.25$–0.36; per cent sand/gravel: $r^2 = 0.49$–0.62; and per cent floodplain deposits: $r^2 = 0.09$–0.30).

In order to examine broad relationships between land-use history and modern vegetation, correlations were calculated between the abundance of modern taxa and the percentage of land in cultivation and upland hayfields, pasture, and the sum of these categories for 1885. Census data from 1885 were used because they are most complete and town boundaries most closely resemble the modern configuration. Axis 1 of the modern vegetation ordination was correlated with the percentage of pasture in 1885 ($r^2 = 0.20$; $P < 0.001$). Only three taxa had significant correlations with the agricultural data: birch and cherry were positively correlated with percentage of pasture land ($r^2 = 0.19$; $P < 0.001$ and $r^2 = 0.17$; $P = 0.002$, respectively) and cherry and ash were positively correlated with the sum of cultivated/upland hayfields and pasture ($r^2 = 0.16$; $P = 0.006$ and $r^2 = 0.13$; $P = 0.034$, respectively). Each of these genera are dominated by species that are well known to increase after disturbance and to colonize former agricultural fields.

Changes in forest structure

Census records from 1885 to 1895 confirm that woodlands in the late nineteenth century were dominated by young trees growing in frequently cut woodlots or in former agricultural fields (Fig. 9). In the middle of the twentieth century, only *c.* 30% of forests in the state exceeded 12.2 m in height; by 1971 this percentage had increased to 77%. As forest products are now predominantly imported to the state (Berlik *et al.*, 2002), forest size structure has continued to increase; for instance, between 1972 and 1985, the area of timberland increased only by 6%, whereas the growing-stock volume of the state's forests increased by 37% and the volume of sawtimber (trees with *c.* 25.4 cm d.b.h.) increased by 57% (Dickson & McAfee, 1988). Between 1985 and 1998, despite a 3% decrease in timberland area across Massachusetts, there was a 17% increase in the volume of growing-stock and a 34% increase in sawtimber (Alerich, 2000).

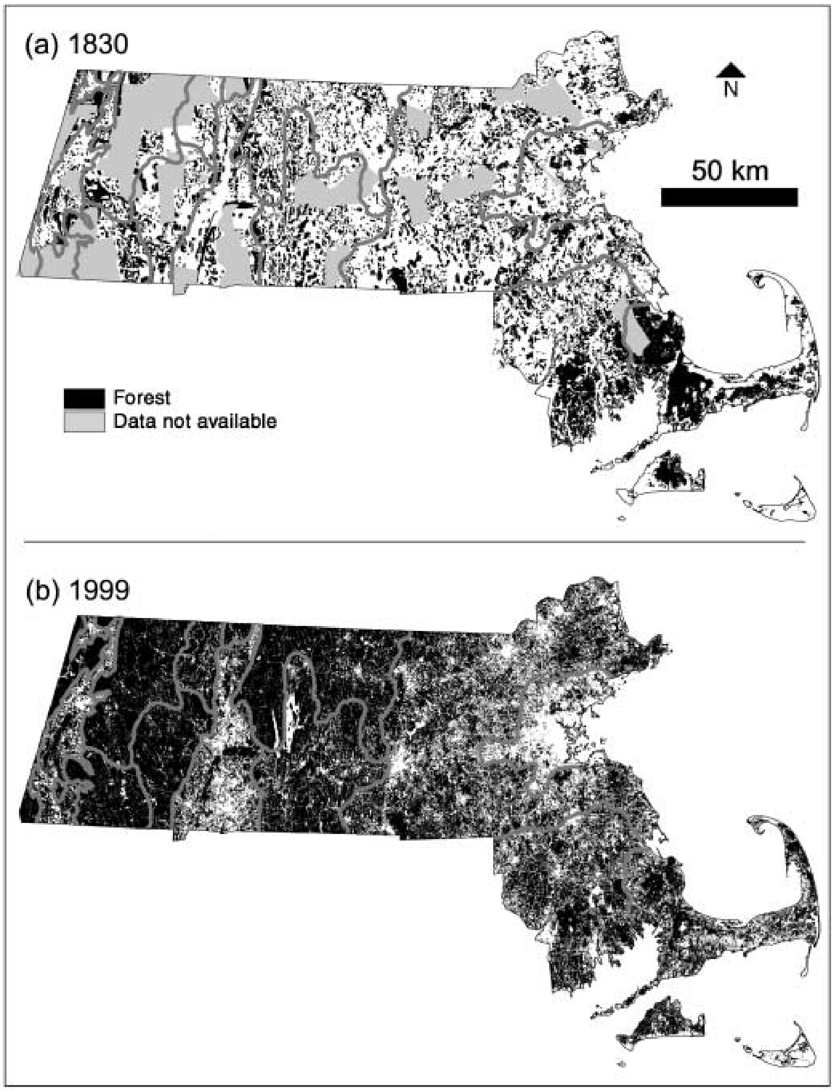


Figure 6 Massachusetts forest cover in 1830 (a) and 1999 (MassGIS, 2002) (b). The original 1830 maps are stored at the State Archives in Boston, Massachusetts.

DISCUSSION

Uncertainties in historical records

Ecological interpretations based on historical data must be tempered by an appreciation of the limitations inherent in the data (Whitney, 1994). In particular, care must be taken due to potential biases, uncertainties and changes in definitions, changes in geographical boundaries, and difficulties in comparing data assembled for diverse purposes with inconsistent methodologies. For example, in New England, during the first half of the nineteenth century, the term 'unimproved' is thought to have meant land that was not cleared of trees (Bell, 1989; Williams, 1989; J. Larkin, pers. comm.), while towards the end of the century it more likely referred to rough land, wooded areas, old fields not currently in cultivation or pasture, or even lands that were never ploughed (Bell, 1989). Even more problematic is uncertainty in how categories such as 'unimproved', 'unimprovable' and 'woodland' were applied by early nineteenth century tax assessors and whether there was consistency among assessors. Although 'unimproved' lands may generally refer to woodlands, wooded pastures, scrubby vegetation and young forests on abandoned agricultural fields, after 1830 there was a dramatic decrease in the amount of land recorded as 'unimproved' and 'unimprovable', and a corresponding increase in land classified as 'woodland'. These trends may highlight real shifts in land use as knowledge, equipment and economics allowed or forced New England farmers to shift from extensive to intensive agricultural practices, or they may simply represent artefacts resulting from changing definitions or assessors, or the perception that formally 'unimproved' and 'unimprovable' lands had developed into recognizable 'woodland'.

Although data limitations preclude us from determining a particular year or decade when forest cover was at its lowest point, diverse historical sources confirm that forest clearing across the state peaked between 1830 and 1885 (Russell, 1976; Foster, 1992). As the number of livestock was greatest in the 1830s, we assume that grazing/pasturing was most

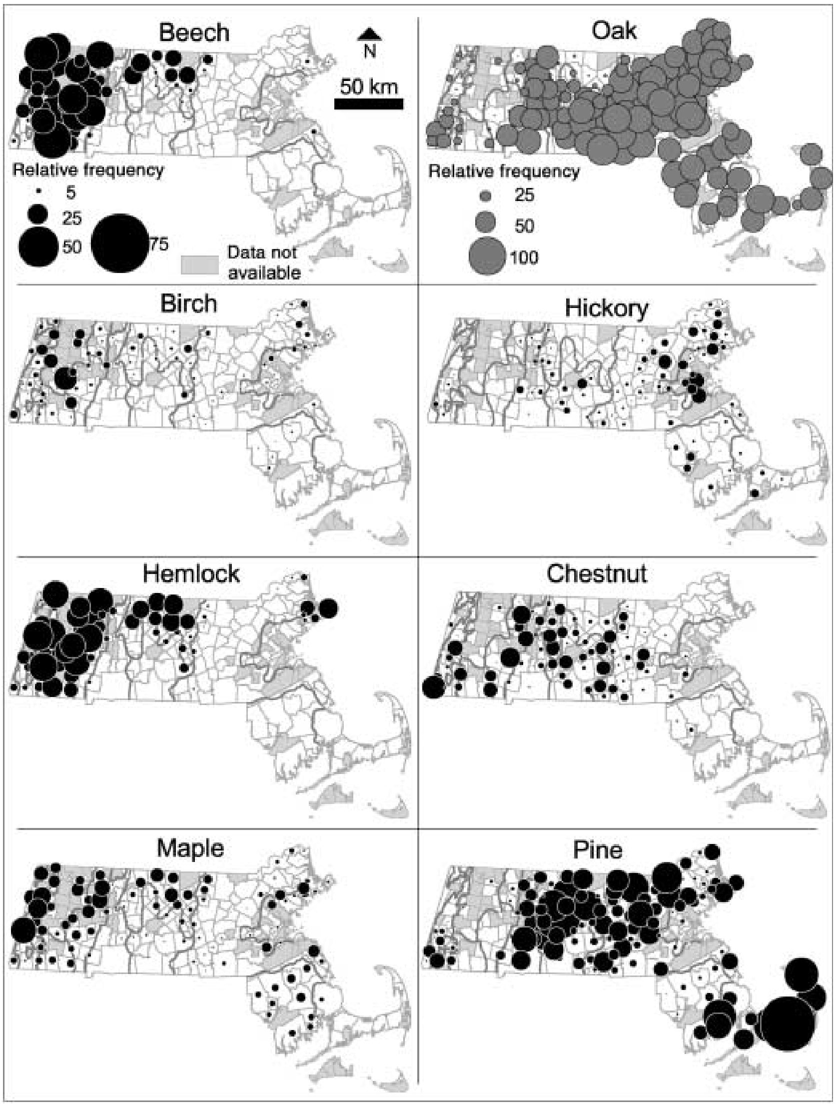


Figure 7 Forest composition at the time of European settlement as suggested by town survey witness trees (*c*. 1620–1801). Dot sizes indicate the relative importance of each taxon. Note oak is on a different scale than the other taxa.

extensive at this time and that forest cover was at or near its lowest level. Agricultural records indicate that land classified as pasture increased between 1830 and 1885, while land classified as unimproved declined, suggesting a shift to more intensive management. Thus, we assume that many of the forests of 1830 were used as wooded pastures which would have had more open understories and overstories than ungrazed woodlands and that this practice declined over time with more intensive pasture management.

Different considerations emerge regarding the reconstruction of colonial vegetation using proprietors' survey data. Most studies evaluating early vegetation in the United States have relied on witness trees recorded as part of the General Land Office (GLO) survey, a rectangular system that allows for bias estimation (cf. Bourdo, 1956; Siccama, 1971). In contrast, the proprietors' records for New England and most other surveys conducted prior to the late eighteenth century used the metes-and-bounds system in which trees often marked corners but other reference data required to estimate surveyor bias are lacking (McIntosh, 1972). Although the proprietors' survey data used in this study were recorded by numerous surveyors, the geographical consistency of the data suggests that surveyor bias is largely unimportant at the scale investigated (Winer, 1955; Foster *et al*., 1998; Cogbill *et al*., 2002). In fact, although they have been largely ignored by ecologists and geographers, the colonial survey witness trees are a remarkably complete quantitative description of forest composition at the time of European settlement and are reasonably consistent with independent information on modern species' distributions and environmental conditions (Winer, 1955; Whitney, 1994; Foster *et al*., 1998; Cogbill, 2000).

Table 2 Pearson correlation coefficients (r) of environmental variables and compositional data from colonial and modern forests

Variable	Beech		Birch		Hemlock		Maple		Chestnut		Pine		Hickory		Oak	
	Colonial	Modern	Colonial	Modern	Colonial	Modern	Colonial	Modern	Colonial	Modern	Colonial	Modern	Colonial	Modern	Colonial	Modern
Climate																
Growing degree days (mean)	−0.78***	−0.64***	−0.62***	−0.60***	−0.76***	−0.57***	−0.49***	−0.24	−0.27	–	0.51***	0.40**	0.67***	0.16	0.79***	0.61***
Growing degree days (SD)	0.55***	0.43***	0.40***	0.61***	0.52***	0.47***	0.31*	0.16	0.58***	–	−0.37***	−0.25	−0.43***	−0.06	−0.50***	−0.45***
Surficial geology type (%)																
Till/bedrock	0.34**	0.26	0.45***	0.55***	0.38***	0.35	0.48***	0.56***	0.39***	–	−0.40***	−0.36*	−0.16	0.06	−0.29*	−0.34
Floodplain	−0.29*	−0.35*	−0.26	−0.61***	−0.30*	−0.34	−0.10	−0.20	−0.34**	–	0.28	0.33	0.30*	0.17	0.33**	0.35*
Sand/gravel	−0.66***	−0.59***	−0.55***	−0.55***	−0.65***	−0.54***	−0.47***	−0.31	−0.31*	–	0.54***	0.46***	0.48***	0.16	0.64***	0.63***
Bedrock type (%)																
Acidic sedimentary (sed.)	0.17	0.30	0.12	0.32	0.12	0.30	0.17	0.25	0.39***	–	−0.19	−0.09	−0.08	−0.09	−0.17	−0.25
Calcareous sed./metased.	0.44***	0.16	0.28	0.19	0.40***	0.28	0.30*	−0.07	0.21	–	−0.37***	−0.01	−0.28	0.09	−0.39***	−0.29
Course sediments	−0.16	−0.13	−0.37***	−0.29	−0.21	−0.16	−0.44***	−0.61***	−0.25	–	0.29*	0.24	−0.02	−0.10	0.10	0.15
Mod. calcareous sed./metased.	0.34**	0.08	0.23	0.24	0.33*	0.22	0.29*	0.10	0.29	–	−0.20	−0.05	−0.30*	0.21	−0.21	−0.21
1885 agriculture (%)																
Pasture	–	0.16	–	0.43**	–	0.32	–	0.25	–	–	–	−0.13	–	0.16	–	−0.34
Cultivated and upland hay	–	−0.22	–	−0.16	–	−0.18	–	0.11	–	–	–	−0.10	–	0.14	–	0.01
Total agriculture land	–	−0.04	–	0.28	–	0.19	–	0.24	–	–	–	−0.15	–	0.19	–	−0.27

$*P \le 0.05$; $**P \le 0.01$; $***P \le 0.001$: Pearson correlations with Bonferroni procedure.

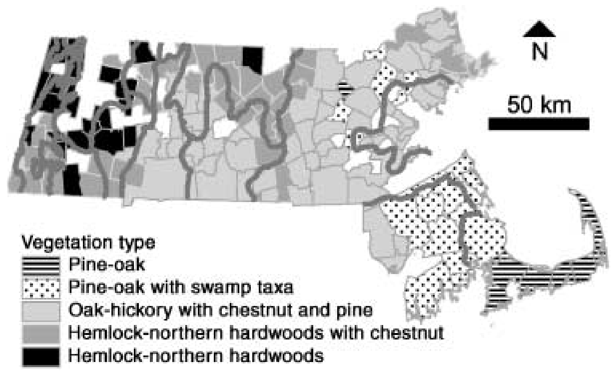


Figure 8 Vegetation types of settlement-period forests as determined by classification of town survey witness trees.

Changes in forest composition, structure and possible causes

Despite widespread alteration of the Massachusetts landscape since European settlement, there have been few major shifts in species distributions, but rather several notable changes in the relative abundance of tree taxa (Fig. 10). In the North-eastern Highlands ecoregion, there has been a general decline in long-lived, mature forest taxa (e.g. beech, sugar maple, hemlock, yellow birch) and a corresponding increase in shorter lived, rapidly growing taxa (e.g. red maple, paper birch, poplars, cherry, white pine and white ash). Repeated cutting, fire and abandonment of agricultural fields apparently favoured these widely dispersed and fast-growing taxa (Whitney, 1990; Foster *et al*., 1998; Fuller *et al*., 1998). In much of the North-eastern Coastal Zone, except for Cape Cod and the Islands, oak, hickory and chestnut dominated prior to European settlement, presumably as a result of longer, warmer growing seasons and perhaps due to moderate disturbance by fire (Foster *et al*., 1998, 2002a; Fuller *et al*., 1998). Increased anthropogenic disturbance following European settlement allowed for an increase in early successional species such as red maple, black, grey or white birch, poplar and cherry. Cape Cod and the Islands experienced subtle shifts in the relative abundance of oak and pine over the nearly 400 years of European land use (Foster *et al*., 2002b; Parshall *et al*., 2003).

These findings are similar to those reported from across the north-eastern United States where previous comparisons of early settlement and modern data have documented decreases in beech (Siccama, 1971; McIntosh, 1972; Whitney, 1990; Abrams & Ruffner, 1995; Bürgi *et al*., 2000), hemlock (Siccama, 1971; McIntosh, 1972; Whitney, 1990; Abrams & Ruffner, 1995; Bürgi *et al*., 2000), spruce (Siccama, 1971), elm (Siccama, 1971), hickory (Russell, 1981; Nowacki & Abrams, 1992; Abrams & Ruffner, 1995), pine (Nowacki & Abrams, 1992; Abrams & Ruffner, 1995; Bürgi *et al*., 2000), and oak (Glitzenstein *et al*., 1990), and the near elimination of chestnut (Russell, 1981; Glitzenstein *et al*., 1990; Nowacki & Abrams, 1992; Abrams & Ruffner, 1995; Bürgi *et al*., 2000). Taxa that increased across the region

Table 3 Standardized function coefficients of first axis of discriminant function analysis between witness-tree data and modern FIA data. The first axis explained 91% of the total dispersion and correctly sorted 98% of the towns

Taxa	Coefficient
Beech	−0.920
Hickory	−0.581
Chestnut	−0.502
Cedar	−0.402
Spruce	−0.245
Poplar	−0.228
Larch	−0.198
Basswood	−0.166
Pine	−0.143
Elm	−0.107
Gum	−0.003
Hemlock	0.014
Sassafras	0.064
Ash	0.097
Birch	0.129
Oak	0.175
Cherry	0.523
Maple	0.635

include: maple [Siccama, 1971 (sugar maple); McIntosh (1972) (red and sugar maple); Russell (1981); Glitzenstein *et al.* (1990); Whitney (1990) (red and sugar maple); Nowacki & Abrams, 1992; Abrams & Ruffner, 1995; Bürgi *et al.*, 2000], birch (Siccama, 1971; Russell, 1981; Nowacki & Abrams, 1992; Abrams & Ruffner, 1995), poplar (Siccama, 1971; Bürgi *et al.*, 2000), fir (Siccama, 1971), oak (Siccama, 1971; McIntosh, 1972; Nowacki & Abrams, 1992; Abrams & Ruffner, 1995), cherry (Whitney, 1990; Abrams & Ruffner, 1995; Bürgi *et al.*, 2000) and ash (McIntosh, 1972; Bürgi *et al.*, 2000). The most dramatic change has involved maple (primarily red maple), which increased from 7 to 27% in Massachusetts from the colonial to modern periods, presumably because of its rapid colonizing and sprouting abilities, high seed production and tolerance of a wide range of moisture and light conditions.

Perhaps the greatest impact on the species composition of Massachusetts forests over the past 400 years results from the twentieth century introduction of exotic pests and pathogens, which continue to eliminate dominant tree species (cf. Orwig, 2002). Chestnut, once widespread across the central part of the state, persists exclusively as subcanopy sprouts because of a fungal pathogen introduced in the early twentieth century (Hepting, 1974; Paillet, 2002). Beech bark disease has been particularly important in areas supporting northern hardwoods, causing the mortality of many large beech trees that subsequently form dense sprout thickets and facilitate the increase in other species (Houston, 1975; Twery & Patterson, 1984). Currently, hemlock is poised to decline dramatically across the North-east as a result of the introduction of the hemlock woolly adelgid (Orwig & Foster, 1998; Orwig *et al.*, 2002).

Because quantitative data on forest structure are lacking for the early settlement period, we must rely on contemporary descriptions, remnant artefacts (e.g. construction material in early colonial structures), and interpretations of forest composition and disturbance dynamics in order to characterize seventeenth century forests. Early accounts often describe old, large-statured trees with unbroken canopies and dense canopy layers (Whitney, 1994); logging records, timbers, planks and boards in contemporary houses testify to the presence of large, slow growing trees in the early historical period (Carroll, 1973; Motzkin *et al.*,

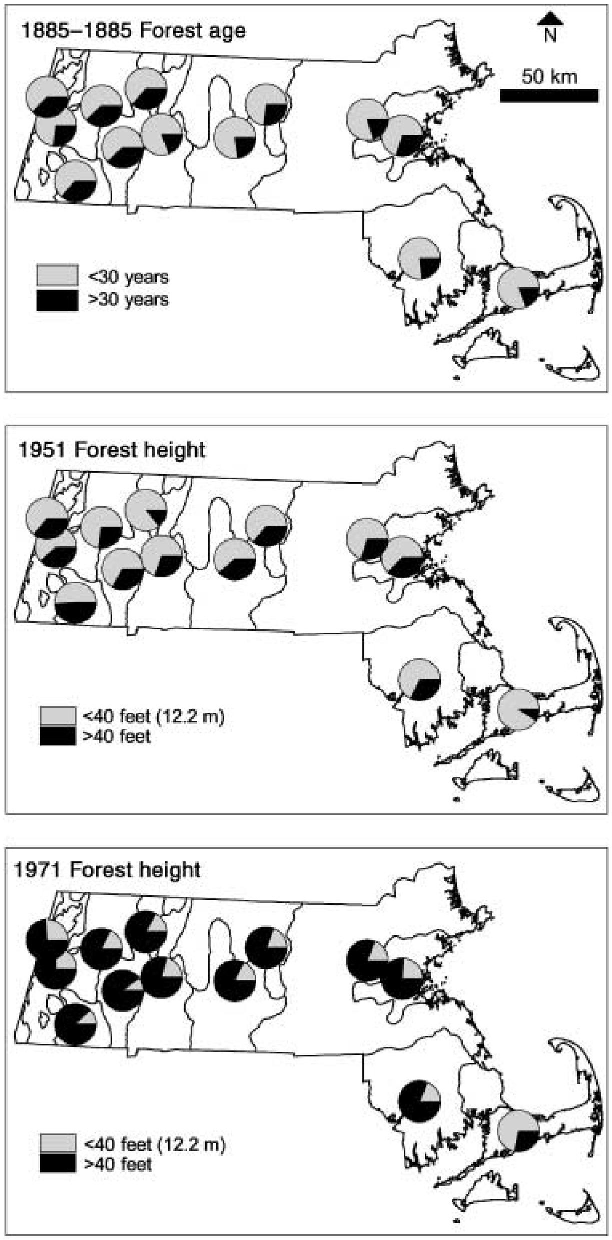


Figure 9 Changes in forest structure in Massachusetts: age of stands harvested between 1885 and 1895 (a), and forest height in 1951 (b) and 1971 (c). Data sources are 1885 and 1895 state agricultural censuses and MacConnell (1973).

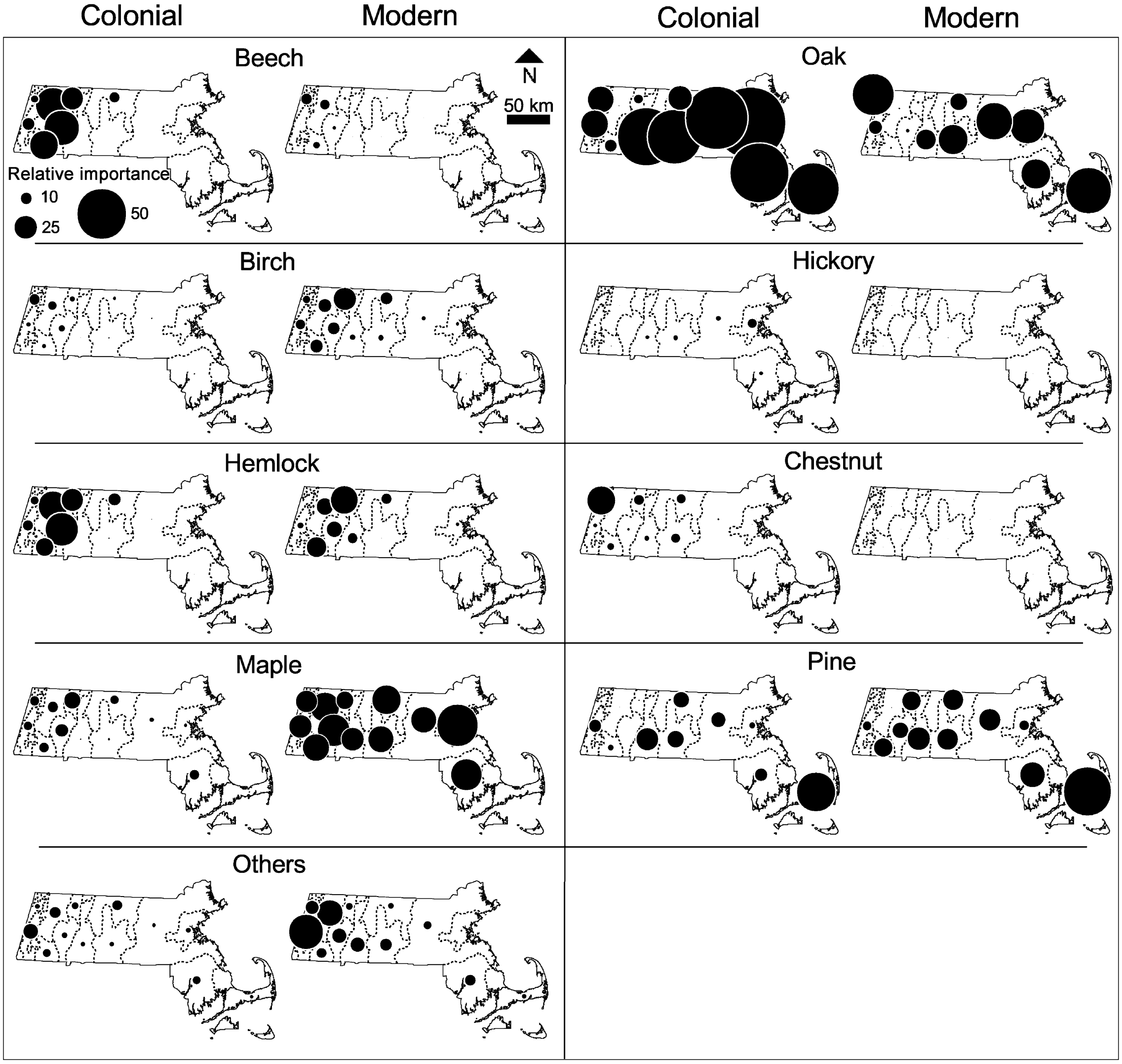


Figure 10 Forest composition of ecological subregions at the time of European settlement and in modern forests (Hansen *et al.*, 1992). 'Others' is primarily ash, cherry and poplar.

1999b). Historical descriptions and palaeoecological studies also suggest that New England forests have long been affected by natural disturbances such as fire (Lorimer, 1977; Foster, 1988; Fuller *et al.*, 1998), wind (Siccama, 1971; Lorimer, 1977; Foster, 1988; Boose *et al.*, 2001), insect infestations and disease (Allison *et al.*, 1986; Bhiry & Filion, 1996), as well as anthropogenic disturbances from Native American activity. However, these disturbances are highly varied in frequency and intensity across Massachusetts (cf. Patterson & Backman, 1988; Boose *et al.*, 2001; Cogbill *et al.*, 2002; Parshall & Foster, 2002). For instance, prior to European settlement, fire was apparently more common in the warmer, lower-elevation oak and pine forests of the North-eastern Coastal Zone and Connecticut River Valley than in the interior highlands (Patterson & Sassaman, 1988; Fuller *et al.*, 1998; Foster *et al.*, 2002a; Parshall & Foster, 2002), perhaps, in part, as a result of Native American settlement patterns. Damage from hurricanes similarly exhibits a pronounced gradient in frequency from the south-eastern coast to the western portion of the state (Boose *et al.*, 2001; Foster *et al.*, 2002a). As a consequence of these broad patterns of disturbance, it is likely that the hemlock–northern hardwood forests of the North-eastern Highlands comprised the greatest proportion of uneven-aged and mature forests, and that in the coastal and valley areas, the structure of oak and pine forests varied from young to mature depending on the time since disturbance (cf. Motzkin *et al.*, 1999b, 2002; Foster *et al.*, 2002b).

European settlement initiated immediate and widespread impacts on forest pattern and structure (Fuller *et al.*, 1998). From the seventeenth through late nineteenth centuries and moving from areas near settlements to more remote locations, forests were cleared or cut repeatedly producing even-aged stands of predominantly small stature and multiple-stemmed trees. At the peak of deforestation, remaining woodlots were intensively utilized, resulting in woodlands with remarkably young stands. Commencing in the mid-nineteenth century, even-aged forests of early successional species including white pine, pitch pine, red maple and birches developed on former agricultural lands; since that time, tree size, age and volume have increased continually, although disturbances like the 1938 hurricane (Foster, 1988; Boose *et al*., 2001) and ongoing harvesting delayed the development of widespread mature forests until the second half of the twentieth century. In areas protected or neglected from harvesting, mature forests that are increasingly dominated by long-lived and shade-tolerant species continue to develop.

Influence of land use on forest pattern and composition is scale-dependent

Comparison of our results with those of previous studies suggests that the relative influence of environmental vs. historical factors on forest composition is strongly dependent on the scale of analysis. Across the broad environmental and compositional gradients that characterize Massachusetts, environmental drivers such as climate apparently exert greater influence on modern forest composition than past land use, despite the intensity and extent of historical impacts. These results contrast with local studies where environmental gradients are frequently weaker and where past land use often exerts substantial influence on patterns of species abundance and distribution (cf. Motzkin *et al*., 1996, 1999, 2002; Bellemare *et al*., 2002; Gerhardt & Foster, 2002).

This scale-dependent shift in the relative importance of environmental vs. historical factors apparently results from more than a simple increase in environmental variation as spatial scale increases. For example, at the scale (statewide or regional) and resolution (township) of this study, there is relatively little variation in land-use history, resulting in a moderate land-use gradient relative to environmental variation. In particular, despite regional differences in specific crops or other land-use practices, there was little clear spatial patterning of the amount of land cleared for different agricultural purposes (e.g. cultivation, hay, pasture, woodland) across the state. Similarly, at broader geographical scales, the New England landscape exhibits little variation in broad patterns of historical land-use until extremely different landscapes are compared (e.g. continually forested mountainous regions vs. the generally rolling topography that was formerly used for pasture or crops). In contrast, at local scales, major differences in land-use, such as whether a site was cleared of forest, ploughed or remained continuously wooded, has great impact on subsequent forest composition and structure (cf. Motzkin *et al*., 1996, 1999a). With town-level resolution, our study integrated landscape variation that is important in controlling local patterns of forest composition and structure. This interpretation fits the general pattern that, as scale or grain increases, a larger proportion of the spatial heterogeneity in a system is averaged out and between-unit differences decrease (Wiens, 1989). Consequently, climatic and geological factors influence vegetation at broader scales and coarser resolution, while at finer scales the importance of biological and local disturbance factors, such as demographics, competition or land-use history, becomes greater (Wiens, 1989). Even at broad spatial scales, however, extensive, although relatively homogenous, land-use practices greatly altered forest structure and composition over time, including dramatic changes in forest cover and contiguity, shifts towards young and relatively even-aged forests, and an increase in early successional tree species that persist as a result of ongoing forest cutting and other disturbances. Thus, forest patterns and dynamics well into the future will be strongly conditioned by both environmental variation and disturbance history.

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