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Fire on the New England landscape: regional and temporal variation, cultural and environmental controls

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Abstract

Aim We use a retrospective approach to reconstruct the past distribution of fire in New England and to investigate the important drivers of this pattern across the period of European arrival to North America.

Location Our study sites are in New England, and range from pitch pine and oak forests of coastal Massachusetts, pine and hardwood forests of central Massachusetts, and northern hardwood and spruce fir forests of northern Massachusetts and Vermont.

Methods We collected sediment profiles from eighteen lakes across the study area to assess fossil charcoal and pollen abundance over the past 1000 years, including the time period of European arrival and settlement.

Results Based on presettlement pollen composition, our study sites are divided into three vegetation types: (1) pitch pine and oak, (2) oak, pine and hardwood and (3) northern hardwoods. The abundance of presettlement charcoal in these lakes is closely related to climate and the composition of surrounding vegetation. Charcoal is most abundant in pitch pine forests and least common in northern hardwood forests. Following the arrival of Europeans, charcoal abundance increased at most sites substantially, and vegetation composition changed in a direction of either greater dominance by pitch pine or white pine, depending on whether the forests were located in the southern or northern part of New England.

Main conclusions The major factor influencing the distribution of fire across New England is climate, which has a direct effect on the physical conditions conducive to fire ignition and spread and an indirect effect on fire through its control on the distribution of vegetation at this spatial scale. We find evidence that other factors exert some control over local fire regimes as well including landforms and their impact on vegetation composition, firebreaks and prevailing winds. Native Americans likely influenced the local occurrence of fire, but their impact on regional fire regimes in New England is not apparent from this or other studies. However, additional palaeoecological, archaeological and historical work needs to be carried out to better address this question. In contrast, Europeans had a dramatic effect on fire throughout the New England landscape, increasing its occurrence almost everywhere.

Keywords
Palaeoecology, presettlement vegetation and fire, fossil pollen, fossil charcoal, disturbance, New England, forest ecology, human impacts.

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INTRODUCTION

Human disturbances often interact with an array of natural disturbances of varying intensities to initiate complex patterns of response in vegetation composition, nutrient cycling and wildlife populations (Motzkin *et al.*, 1996; Foster *et al.*, 1997; Donohue *et al.*, 2000; Eberhardt, 2001; Goodale & Aber, 2001; Lorimer, 2001). Understanding variability in past disturbance processes and how these influenced vegetation distribution and dynamics has become a critical feature for ecosystem management and conservation (Christensen *et al.*, 1996; Swetnam *et al.*, 1999). Fires can be a particularly strong force structuring ecosystems because they remove existing vegetation, change soil composition and alter the movement of nutrients. Both the ignition and spread of fire are influenced by climatic, edaphic and landscape-scale features, and species differ widely in their abilities to survive and reproduce following fire (Whelan, 1995; Pyne *et al.*, 1996; Brown & Smith, 2000). Thus, the effects of fire are heterogeneous across a landscape, leaving a patchy distribution of forest types, sizes and ages. On longer timescales the occurrence of fire is directly linked to changes in climate (Clark, 1990; Swetnam, 1993; Winkler, 1997; Long *et al.*, 1998; Millspaugh *et al.*, 2000), so future climate changes will lead to a change in fire occurrence.

People play a central role in fire regimes, often as the leading source of ignition as well as the most important factor controlling its spread (Whelan, 1995; Pyne *et al.*, 1996). In North America, humans have influenced past fire regimes in a variety of ways, from widespread accidental fires near large logging operations at the turn of the nineteenth century to intentional continent-wide fire suppression during the twentieth century (Williams, 1989; Whitney, 1994). The effect of humans prior to 1850 is not fully documented, but they probably altered fire regimes substantially through intentional burning and suppression, and indirectly by altering the structure and distribution of vegetation. Uncertainty concerning the role of humans in controlling fire activity is especially great with regards to Native American activity, a subject that has engendered considerable attention and speculation (Day, 1953; Pyne, 1982; Cronon, 1983; Russell, 1983; Patterson & Sassaman, 1988; Bonnicksen, 2000; Foster & Motzkin, 2002).

Our understanding of the distribution of prehistoric fire on the New England landscape is largely masked by substantial consequences related to recent human activity, and in order to determine the pattern of fire and the major driving factors in the past we must rely on retrospective methods. A network of palaeoecological sites in New England is available to describe past vegetation change over this time period (Gaudreau & Webb, 1985; Russell *et al.*, 1993; Fuller *et al.*, 1998; Russell & Davis, 2001), but very little effort has been made to standardize and interpret a network of fire histories. In this paper, we utilize sedimentary records of fossil charcoal, along with pollen, preserved in lakes across New England in order to reconstruct fire and vegetation of the past 1000 years. Through this approach we seek to: (1) determine the regional distribution of fire in New England before European arrival, (2) investigate the importance of vegetation, climate, and other factors on this distribution, and (3) determine the magnitude and direction of change in fire that occurred as a result of European activity that began 400 years ago.

METHODS

We concentrate our study of fossil charcoal on sediments from eighteen lakes in New England, ranging from sites in northern hardwood forests at higher elevations to pitch pine and oak forests along the coast (Table 1, Fig. 1). The methods used to quantify charcoal abundance and infer fire history vary widely among published studies (e.g. Clark,

Table 1 Location and characteristics of lakes included in this study (See Figure 1)

No.	Site	Reference	Longitude	Latitude	Elevation (m)	Size (ha)	Max. depth (m)
1	Aino	Fuller *et al.*, 1998	−71.9255	42.6807	354	1.8	2.5
2	Bates	Foster *et al.*, unpublished data	−72.0162	41.6587	95	2.7	3.6
3	Deep	Parshall *et al.*, 2003	−70.5796	41.5808	23	1.0	3.3
4	Duarte	Foster *et al.*, 2002	−70.6155	41.4200	18	1.4	1.9
5	Eagle	Parshall *et al.*, 2003	−70.1368	41.6983	11	4.0	6.4
6	Fresh	Parshall *et al.*, 2003	−70.5337	41.5935	7	5.3	5.9
7	Green	Fuller *et al.*, 1998	−72.5110	42.5668	80	5.0	5.7
8	Harlock	Foster *et al.*, 2002	−70.7134	41.4028	32	5.6	5.9
9	Icehouse	Parshall *et al.*, 2003	−69.9613	41.7980	19	1.8	6.3
10	Jemima	Parshall *et al.*, 2003	−69.9851	41.8294	3	2.2	4.3
11	Lake Pleasant	Fuller *et al.*, 1998	−72.5137	42.5596	80	20.0	11.4
12	Levi	Foster *et al.*, unpublished data	−72.2280	44.2252	501	9.1	2.9
13	Lily, New Salem (LNS)	Foster *et al.*, unpublished data	−72.3468	42.4181	303	2.3	1.8
14	Lily, Warwick (LW)	Fuller *et al.*, 1998	−72.3365	42.6880	269	0.8	1.3
15	North Round (NRP)	Francis & Foster, 2001	−72.4519	42.8476	317	4.3	3.4
16	Round	Parshall *et al.*, 2003	−70.0110	41.9707	4	1.6	7.5
17	Sandy Hill (SHP)	Parshall *et al.*, 2003	−70.3648	41.6896	16	2.4	3.0
18	Walden	Foster *et al.*, unpublished data	−71.3380	42.4390	50	25.0	28.8

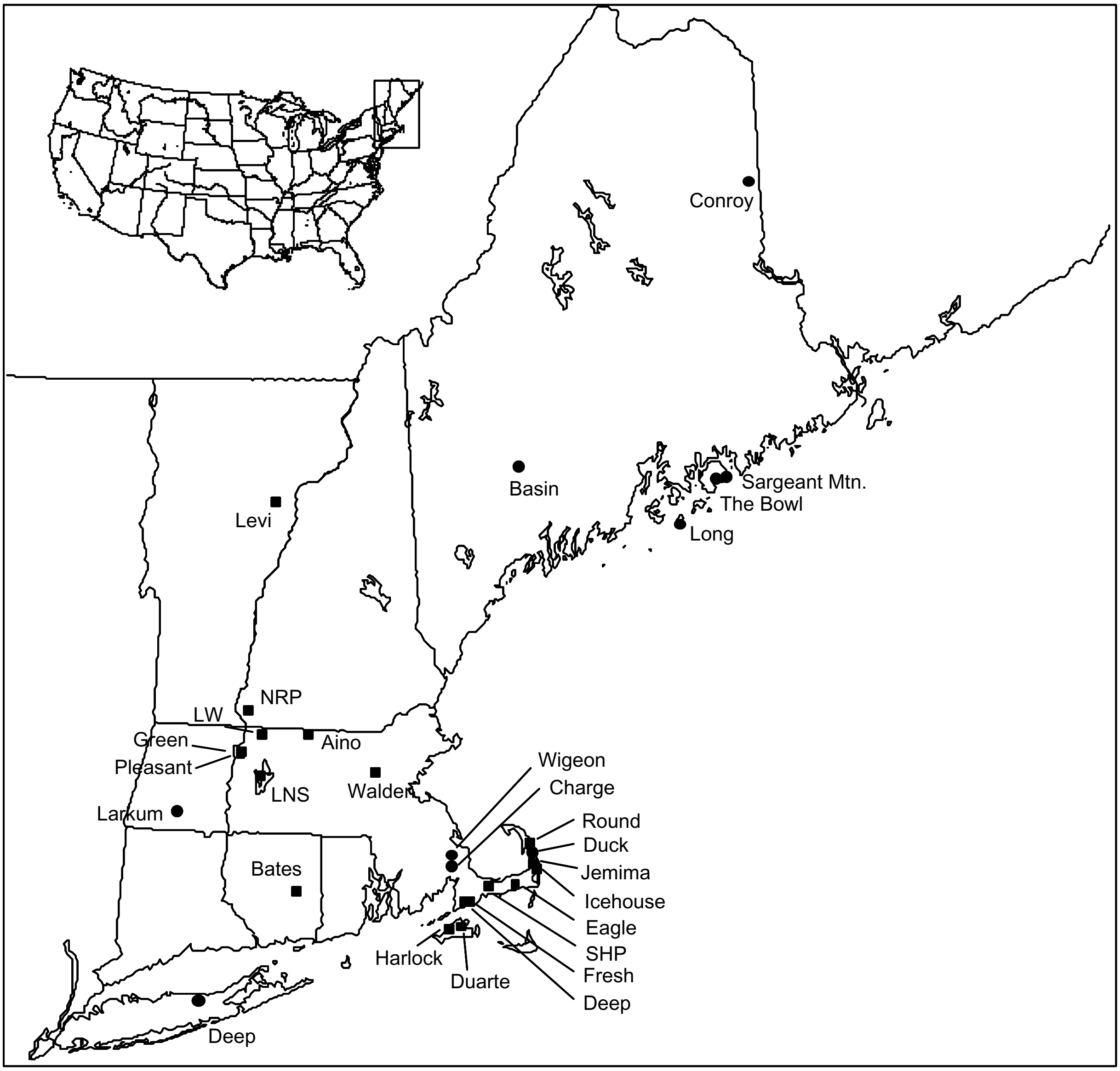

Figure 1 Location of lakes included in this study (squares). Refer to Table 1 for names and lake characteristics. The location and description of other sites on the map and referred to in the text (circles) can be found in Patterson & Backman (1988). Basin and Conroy Lakes are also analysed by Clark & Royall (1996), and Duck Lake is also analysed by Winkler (1985a).

1982; Tolonen, 1986; Patterson *et al*., 1987; Clark, 1988a; MacDonald *et al*., 1991; Millspaugh & Whitlock, 1995), sometimes producing very different results. To ensure that variation among sites is unrelated to laboratory procedures we have standardized our methods, including the manner in which charcoal is identified among researchers, which we have found can substantially influence results.

Lake sediments were retrieved from all lakes using similar field methods (Fuller *et al*., 1998; Francis & Foster, 2001; Foster *et al*., 2002; Parshall *et al*., 2003). A polycarbonate tube fitted with a piston was used to obtain the uppermost sediments with minimal disturbance of the sediment–water interface, while deeper sediments were sampled with a modified Livingstone corer. Sediment preparation for pollen analysis followed standard procedures including a sieving step with a 180-μm screen (Faegri & Iversen, 1989), and pollen was counted to a total of 500 tree and shrub grains at 400×. We quantified microscopic charcoal as the fraction of charred particles observed in these pollen preparations, which excludes fragments larger than 180 μm in length.

The timing of European settlement in the cores was assessed from changes in pollen representing open vegetation, including a decline in tree pollen and an increase in herbaceous pollen, especially ragweed (*Ambrosia*), sorrel (*Rumex*) and grass (*Poaceae*). Age models were derived from radiocarbon dates of lake sediments along with Pb-210 dates when available for each site. We used second and third order polynomials to interpolate ages between these dates and arrive at a sedimentation rate for calculating charcoal influx.

We quantified microscopic charcoal abundance using an image analysis system. The area of all charcoal fragments encountered along transects on microscope slides was measured using the same samples assessed for pollen content, and marker grains were counted at the same time to determine the amount of sample volume observed. Fragments less than 10 μm in length were not included in the final value of charcoal abundance as they can be confused with opaque mineral matter.

If lakes from earlier studies were not assessed for microscopic charcoal using these methods, we reanalysed charcoal abundance for a subsample of the original pollen preparations in order to compare all eighteen sites using the same methodology. A minimum of five samples both preceding and following European settlement were selected. Presettlement samples were limited to the past 1500 years because changes in vegetation and charcoal are likely associated with climate before this time (Webb *et al*., 1993; Winkler, 1997; Parshall *et al*., 2003).

In order to compare vegetation composition across the eighteen sites, we assigned each lake to a vegetation group by classifying fossil pollen assemblages deposited before European settlement. The classification included eleven pollen types, representing the most common upland tree taxa: white pine (*Pinus* haploxylon), pitch pine (*Pinus* diploxylon), spruce (*Picea*), eastern hemlock (*Tsuga canadensis*), oak (*Quercus*), birch (*Betula*), American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), red maple (*A. rubrum*), hickory (*Carya*) and chestnut (*Castanea*). For this classification analysis we used Euclidian distances and Ward's sum of squares method. In a separate analysis, presettlement and post-settlement pollen, using the same eleven taxa, were compared using Detrended Correspondence Analysis on square-root transformed pollen percentages.

In addition to the above procedures, we also looked in more detail at charcoal abundance in Fresh Pond. Larger charcoal fragments were counted in contiguous sediment samples representing the past 2500 years (Parshall *et al*., 2003). Samples of sediment (1–3 cm^3) were soaked in KOH for at least 24 h and passed through a 180-micron sieve. All charcoal fragments retained in the sieve were counted at 20× using a binocular dissecting microscope. From these data, we created a chronology of charcoal peaks by identifying residuals of charcoal influx greater than a five-sample moving average of charcoal abundance.

RESULTS

The assemblages of sedimentary fossil pollen deposited before European settlement varies across study sites in relation to major categories of vegetation composition, which are classified here into three main vegetation types: (1) northern hardwoods and hemlock (2) oak, pine and hardwoods, and (3) pitch pine and oak (Table 2, Fig. 2a). This classification roughly follows the distribution of original New England forests inferred from modern and historical observations (Bromley, 1935; Westveld, 1956; Cogbill *et al*., 2002) as well as from other regional studies of fossil pollen (Russell *et al*., 1993; Russell & Davis, 2001). Grass and herbaceous pollen, representing open vegetation types, is uncommon or rare in presettlement samples, indicating that most of the landscape was in a forested state until the arrival of Europeans (Fuller *et al*., 1998; Foster & Motzkin, 2002).

Table 2 Average charcoal abundance in the sediments of each lake before and after European settlement. Lakes are arranged in order of lowest to highest presettlement charcoal influx values. Vegetation groups were established from classification of presettlement pollen assemblages. Asterisks denote a significant difference between presettlement and post-settlement charcoal influx (*$P < 0.05$, Mann–Whitney U-test)

			Charcoal: pollen (μm^2 $grain^{-1}$)		Charcoal influx (mm^2 cm^{-2} $year^{-1}$)	
No.	Site	Vegetation group	Presettlement	Post-settlement	Presettlement	Post-settlement
12	Levi	Northern hardwood	11	18	0.08	0.14
15	North Round	Northern hardwood	16	55	0.15	1.72*
14	Lily, Warwick	Northern hardwood	16	72	0.22	1.04*
8	Harlock	Oak, pine, hardwood	46	154	0.45	1.64*
1	Aino	Northern hardwood	40	162	0.46	3.06*
10	Jemima	Oak, pine, hardwood	142	321	0.99	10.8*
2	Bates	Oak, pine, hardwood	137	235	1.27	3.17
17	Sandy Hill	Oak, pine, hardwood	273	239	1.27	3.34*
13	Lily, New Salem	Oak, pine, hardwood	198	302	1.29	2.70
11	Lake Pleasant	Pitch pine and oak	193	959	1.42	31.72*
16	Round	Pitch pine and oak	86	472	1.61	7.14*
3	Deep	Oak, pine, hardwood	195	297	1.67	8.62*
18	Walden	Oak, pine, hardwood	201	339	2.01	9.87
9	Icehouse	Oak, pine, hardwood	109	218	2.22	31.04*
4	Duarte	Pitch pine and oak	253	396	3.08	9.00*
5	Eagle	Pitch pine and oak	676	745	4.3	5.76
6	Fresh	Pitch pine and oak	315	462	5.23	12.57*
7	Green	Pitch pine and oak	237	562	7.70	35.43*

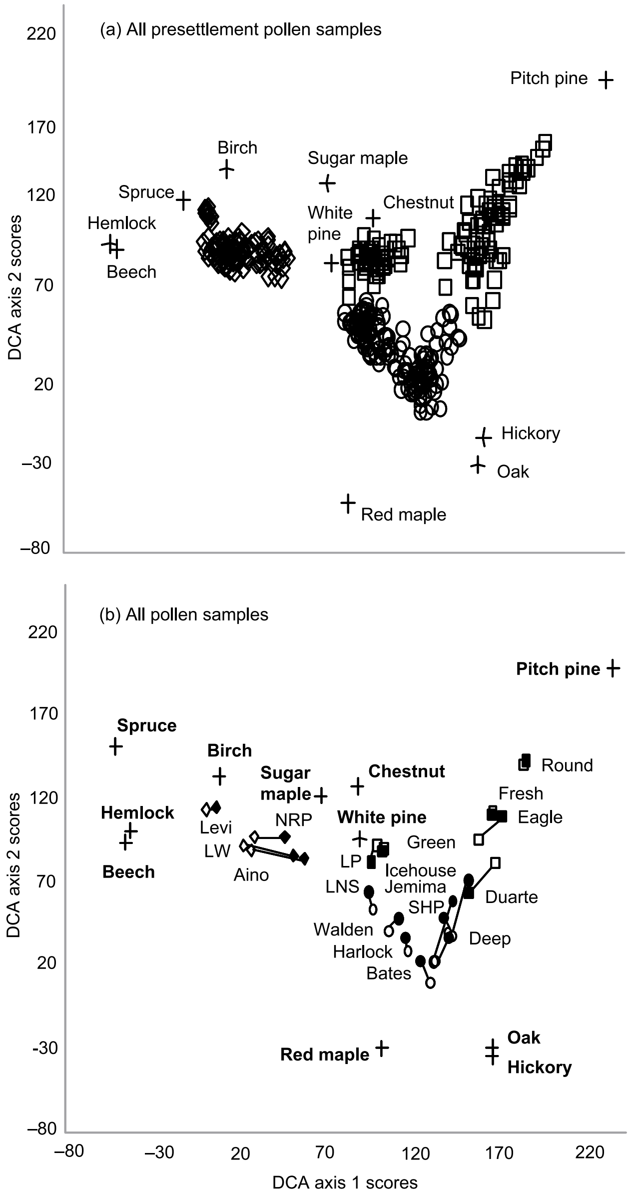

Figure 2 Comparison of past vegetation among sites from the analysis of fossil pollen abundance. (a) Presettlement pollen abundance compared using Detrended Correspondence Analysis, including taxa loadings for each of the eleven pollen types considered. Symbols correspond to vegetation groups identified by classification: northern hardwood and hemlock (diamonds), oak-pine-hardwoods (circles), pitch pine-oak (squares). (b) Change in pollen assemblages across the period of European settlement were assessed using Detrended Correspondence Analysis of all samples. Centroids were calculated for samples within presettlement (open) and post-settlement (closed) time periods.

The distribution of these presettlement vegetation types across New England is broadly related to climate (Fig. 3). For example, northern hardwood sites have the lowest growing degree days (GDD) while pitch pine-oak forests generally have the highest. The exceptions to this pattern can largely be expressed in relation to local physiographical variation. For example, the presettlement pollen assemblages in sites along the coast of New England were dominated either by oak and other hardwoods (Deep, Sandy Hill, Jemima, Icehouse and Harlock) or by pitch pine (Round, Eagle, Deep and Duarte), depending on landform. Pitch pine is dominant on sandy outwash deposits, while oak, hickory and beech are more common in sites on finer-textured soils (Tzedakis, 1992; Eberhardt, 2001; Foster *et al.*, 2002; Parshall *et al.*, 2003). As a result, sites may reside within either the pitch pine-oak or oak-pine-hardwoods group even if they are as near as 10 km from each other.

A similar tie to physiography also exists in central Massachusetts where northern hardwood or oak-pine-hardwoods predominate. Green Pond and Lake Pleasant are both located on sandy outwash deposits and are classified as pitch pine-oak forests, which is a relatively uncommon type in this region (Motzkin *et al.*, 1999). Note that both Green Pond and Lake Pleasant have a larger proportion of pollen from white pine and northern hardwoods than any of the coastal pitch pine-oak sites. The forests nearest these two lakes are primarily composed of pitch pine and oak today, but the surrounding regional forests have a larger abundance of white pine and northern hardwood trees. These sediments are likely enriched in these pollen types compared with sites along the coast, although trees of these species are not abundant in the immediate vicinity (Sugita, 1994; Jackson & Kearsley, 1998; Parshall & Calcote, 2001).

The abundance of presettlement charcoal is closely related to this vegetation classification scheme, indicating a strong link between vegetation and fire or the factors controlling both (Table 2, Fig. 3). Charcoal abundance is not significantly related to basin characteristics such as water depth or lake area, however, it is significantly correlated with elevation and GDD. Charcoal abundance is lowest for sites surrounded by northern hardwoods, which have the lowest GDD. Lakes with the highest abundance of sedimentary charcoal are surrounded by pitch pine and oak forests, occur on sandy outwash deposits and have the highest GDD. Between these two extremes is a large group of lakes with intermediate levels of fossil charcoal abundance, predominantly classified as oak-pine-hardwoods. However, several sites within the pitch pine-oak group, Round Pond and Lake Pleasant, do not contain high amounts of charcoal, although their values are never as low as northern-hardwood sites.

Changes in pollen assemblages across the period of European settlement demonstrate a range of responses by these forests to intense human impact (Fig. 2b), but two patterns emerge. In the northern hardwood forests, hemlock and beech pollen decline as white pine increases and in pitch pine-oak forests, oak and hickory decline as pitch pine increases. The influx of microscopic charcoal increases across the period of European settlement in every lake, often substantially, and this trend is significant for thirteen of the eighteen sites (Table 2). The ratio of charcoal to pollen also increases following European settlement with the exception of just one site (Sandy Hill Pond).

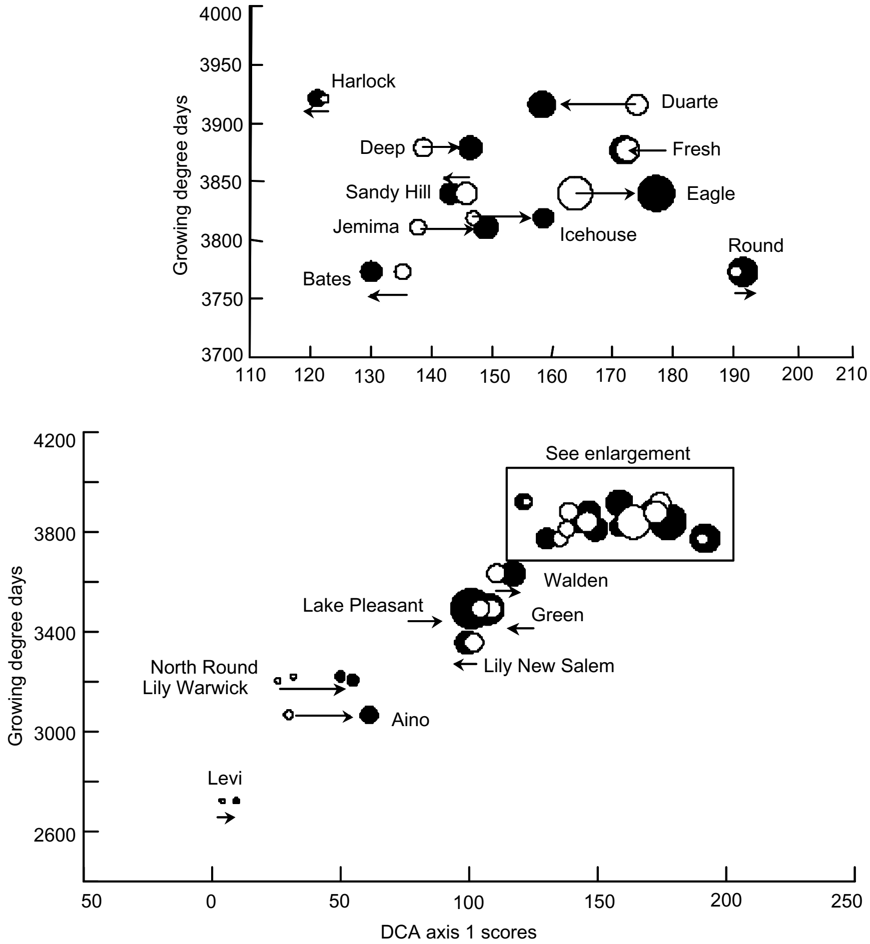

Figure 3 Charcoal abundance (μm²/pollen grain) compared among sites, arranged by growing degree days (GDD) and Detrended Correspondence Analysis (DCA) Axis 1 scores of all pollen samples combined (as in Figure 2a). The size of the circles is proportional to charcoal abundance, with the largest size equal to 1000 μm²/pollen grain. Arrows indicate the change in average charcoal abundance between presettlement (open symbols) to post-settlement (closed symbols) periods (as in Table 2).

Our assessment of macroscopic charcoal in the sediments of Fresh Pond demonstrates a much more detailed history of ecological change over the past 2500 years (Fig. 4). Charcoal abundance is highest before 1500 years ago when pine pollen (predominantly pitch pine) is relatively low. The number of charcoal peaks (residuals) is also higher before 1500 years ago, and likely represents charcoal influx from distinct episodes of fire on the surrounding landscape. Following a period of relatively low charcoal influx, the abundance of charcoal increases following European land clearance, indicated by a rise in herbaceous pollen types, and this increase is most pronounced in the early settlement period.

DISCUSSION

In the study we have compiled a relatively large network of comparable fire histories reconstructed from sedimentary charcoal and by doing so are able to address a number of questions related to the distribution of fire on the New England landscape. To start, what does the pattern of charcoal abundance in lakes that are distributed over tens to hundreds of kilometres tell us about the variability in fires on this spatial scale? Do these patterns reveal controls on past fire occurrence or is the noise related to unique site characteristics too great? We find that there is, indeed, consistency in our results that can be attributed to processes that influence fire regimes today; so methodological problems do not inhibit our interpretation of the pattern of fire across the landscape of the past. In fact, there is much that can be done to uncover more detailed fire histories and address questions that we cannot with our present data set, as we have found from the high-resolution charcoal record from Fresh Pond.

What part did humans play in the history of fire over the past 1000 years? The most notable period to address is the time of European arrival and settlement in New England, which brought sweeping changes to vegetation structure and composition as well as alterations to the sources of ignition and control of fire spread. At this time, charcoal content rises in sediments from almost every lake that has been examined in New England and in most cases the rise is substantial. There are very few sites that over the past 1000 years show anywhere near the change in charcoal seen at this time.

A more difficult question to address is the issue of presettlement human influence on fire occurrence. In New England, most of the discussions on this topic conclude that Native Americans exerted a significant effect, mostly supported by historical documents from the time of European

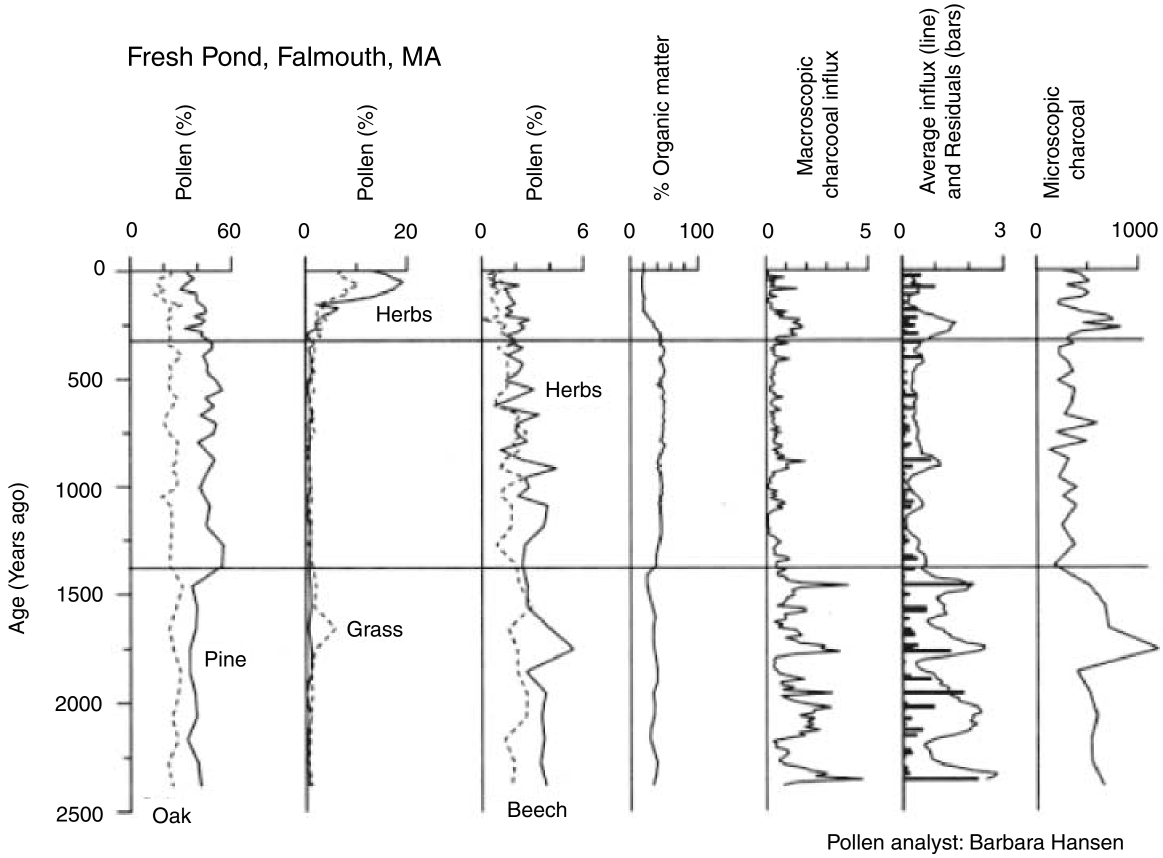

Figure 4 Change in pollen and charcoal in sediments spanning the last 2500 years from Fresh Pond on Cape Cod, Massachusetts. Parshall *et al.* (2003) describe methods of sediment preparation in more detail. Macroscopic charcoal measurements are counts of pieces larger than 180 μm in length in contiguous 1-cm samples, which represent fragments that travel shorter distances than the smaller, microscopic fragments. Macroscopic charcoal data are represented as influx (mm^2 cm^{-2} year^{-1}), a 5-year moving average of influx and residual influx values. The smaller, microscopic charcoal fragments (μm^2 grain^{-1}) were measured on pollen slides and represent the fraction of pieces less than 180 μm in length.

arrival. Up to this point, only one other collection of palaeoecological fire histories has been available for the region (Patterson & Backman, 1988). The pattern of fire that we find here (i.e. high in pitch pine forest and low in northern hardwoods) is in agreement with this prior study. However, we arrive at a different interpretation of the major factors driving this pattern. Basically we conclude that climate and vegetation alone are adequate to explain the regional variation in fire, and we do not find it necessary to invoke human activity in the interpretation (cf. Patterson & Sassaman, 1988). We also find evidence that local features such as landforms and variation in vegetation were influential on this scale as well.

Reconstructing fire in New England

Compared with pollen analysis where the theoretical and empirical basis for reconstructing past vegetation is relatively well developed (e.g. Prentice, 1985; Sugita, 1994; Jackson & Lyford, 1999), our understanding of how to reconstruct past fires from fossil charcoal is hindered by a number of difficult issues. Central to these is the interpretation of how far charcoal particles travel and how to interpret the extent of fires in the past from this single source of information. Theoretically, the distance that airborne charcoal travels is related directly to its size, with larger charcoal fragments travelling shorter distances and representing more local fire events (e.g. Clark, 1988a; Tinner *et al.*, 1998; Carcaillet *et al.*, 2001). The small size of charcoal particles that we measured for this study, 10–180 μm in length, should travel relatively long distances, providing a record of extralocal to regional fires surrounding each lake. This appears to be the case as lakes within the same region tend to have a similar amount of charcoal. There is also variability in charcoal abundance within regions that is consistent with patterns of vegetation and landforms we know to be associated with fire today. For example, higher charcoal abundances occur in pitch pine forests on well-drained sandy soils than in oak-hardwood forests on moraines nearby (Fig. 3; Foster *et al.*, 2002; Parshall *et al.*, 2003). These results suggest that charcoal is recording the pattern of fire on the scale of several kilometres.

Lake basin characteristics can also influence the way in which charcoal is distributed in sediments. In our study, we find no relationship between charcoal abundance and either lake size or water depth, suggesting that neither is important over the wide range of charcoal values observed in this study. However, this does not mean that basin morphometry is unimportant on more local scales. Green Pond and Lake Pleasant, for example, are ice-block depressions only a few hundred metres apart on the same sandplain, have similar presettlement pollen, but exhibit very different levels of presettlement charcoal. Charcoal influx at the smaller lake, Green Pond, is approximately five times as high as that in Lake Pleasant, conforming to the proposed inverse relationship between basin size and sedimentary charcoal abundance (Larsen & MacDonald, 1993; Gardner & Whitlock, 2001). A possible explanation for this relationship is that redeposition of charcoal from the littoral zone to the rest of the lake is more effective in smaller lakes. Other processes within a lake basin probably influence sedimentary charcoal abundance, but in poorly defined ways (Whitlock & Millspaugh, 1996).

The most detailed fire histories come from lakes with annual resolution, often able to reveal fire events of short duration as well as document clear changes in fire regimes over time (e.g. Clark, 1988b; Clark & Royall, 1996). Unfortunately, lakes with annual laminations are rare, especially in the north-eastern United States. If we are to understand the presettlement distribution of fire on this landscape, we must investigate and understand how fire histories are recorded in non-laminated lake sediments. Our results from Fresh Pond, where larger charcoal fragments were measured in contiguous samples over the past two millennia, demonstrate that much more detailed fire records can be obtained (Fig. 4). The variability in charcoal abundance through time indicates both a decline in overall fire abundance *c.* 1500 years ago, as well as a reduction in the number of fire events that were recorded in the sediments.

What factors drive the distribution of fire?

Presettlement fires are strongly related to both climate (here as GDD) and the regional distribution of vegetation (documented by presettlement pollen). However, climate variability significantly influences the pattern of vegetation across the study region, so their effects are clearly interrelated. Fire was least abundant in northern hardwood and hemlock forests, a pattern that is corroborated by a number of other palaeoecological studies of charcoal (Patterson & Backman, 1988; Foster & Zebryk, 1993; Davis *et al.*, 1998; Parshall, 2002). Dendrochronological evidence and historical documents depict a very low incidence of fire in northern hardwood-hemlock forests, with return times more than 1000 years (Lorimer, 1977; Fahey & Reiners, 1981; Canham & Loucks, 1984; Whitney, 1986; Frelich & Lorimer, 1991). Fires in northern hardwood forests are not easily ignited and once started often smolder and move slowly through the thick, moist litter layer (Bormann & Likens, 1979; Frelich & Lorimer, 1991; Lorimer, 2001).

In contrast, presettlement fires were clearly most common in the pitch pine-oak forests along the warmer New England coastal region, especially on the outwash plains of Cape Cod (Parshall *et al.*, 2003), Martha's Vineyard (Foster & Motzkin, 1999; Foster *et al.*, 2002) and Long Island (Patterson & Backman, 1988). Pitch pine is shade-intolerant and does not regenerate well in thick leaf litter, so fires of moderate to severe intensity can encourage stand establishment (Little, 1979; Little & Garrett, 1990).

In addition to this broad relationship between fire, climate and vegetation, the variability in charcoal that exists within regions suggests that local factors also influenced presettlement fire occurrence. Differences in fire are seen at sites along the coast that are only 10 km apart, and this is apparently related to landform. Fires are more abundant on the sandplains where pitch pine forests prevail and less abundant on the moraines in the oak-pine-hardwood forest type. At the same time, both Lake Pleasant (inland) and Round Pond (coastal), which are surrounded by pitch pine forests, have much lower charcoal influx values than other pitch pine-oak forests nearby. As discussed above, Lake Pleasant may have lower than expected values as a result of its large surface area. However, Round Pond is a relatively small lake, so its low charcoal abundance cannot be explained by the same mechanism. One possibility is that its geographical isolation from the main landmass of Cape Cod probably reduces the chance that fires will reach the surrounding forests (Parshall *et al.*, 2003). This same argument may explain the relatively low charcoal values of Harlock Pond, which is located on the westernmost side of Martha's Vineyard where fires burn predominantly in an easterly direction (see also Foster *et al.*, 2002).

Disentangling the interacting effects of climate, vegetation and landform on fire is not a simple task. Fire is less common at higher elevations, but this is likely a result of both a direct reduction in appropriate climate conditions for fire ignition and spread as well as the effect of climate on vegetation composition, which itself has a negative effect on fire occurrence. The effects of physiography on both microclimate and vegetation act in much the same way. Local environmental conditions of well-drained, outwash deposits encourage the spread of fire, which is highest on these landforms. Pitch pine-oak forests are most common on outwash systems, but this may be a result of either local environmental conditions or the prevalence of fire. It seems here that all three factors are interacting to influence the distribution of fire, with the climate-vegetation feedback having a somewhat larger influence on fire than landform across New England.

What was the effect of Europeans on fire and vegetation?

Throughout New England, the composition of forests over the period of European settlement changed in a fairly predictable way. Although a few sites do not change substantially over this time interval, most of the sites have been clearly altered in either of two directions. Northern hardwood and hemlock forests show a reduction in hemlock and beech trees but at the same time see an increase in white pine. This pattern follows the well-documented course of land-use history as many of the original forests were cleared, abandoned and colonized by white pine (Foster, 1992; Foster *et al*., 1998; Russell & Davis, 2001). A similar pattern occurs in the oak-pine-hardwoods and pitch pine-oak forests. Following the decline of oak and other hardwood taxa, pitch pine has become a more common feature of the modern forests.

We have strong and consistent evidence that fires have become more common on the landscape at the same time. The fire history from Fresh Pond provides a detailed picture of when and to what extent this happened. Fires over the past 300 years are higher than any in the previous 1500 years and a great portion of this occurred during the early settlement period (Fig. 4). This pattern appears in other sites on Cape Cod as well (Parshall *et al*., 2003) and probably represents the use of fire during clearing practices and agriculture. A rise in charcoal corresponding with European settlement is also documented by other palaeoecological reconstructions for the north-eastern United States (e.g. Patterson & Backman, 1988; Russell *et al*., 1993; Clark & Royall, 1996; Dieffenbacher-Krall, 1996; Maenza-Gmelch, 1997; Copenheaver *et al*., 2000). Winkler's (1985a) analysis of Duck Lake on outer Cape Cod also suggests that fire has been more common since the arrival of Europeans, although the method used to quantify charcoal does not distinguish charred plant material from carbon produced by fossil fuel burning (Winkler, 1985b). One New England location, the island of Martha's Vineyard, apparently saw a decline in the occurrence of fire (Stevens, 1996; Foster *et al*., 2002). The predominant pattern across New England, however, is that fire occurrence increased following the arrival of European activities.

How much did Native Americans impact landscape fire regimes in New England?

The frequency and extent of prehistoric Native American burning is not well known and probably never will be, but the issue has generated considerable discussion and debate (Day, 1953; Russell, 1983; Patterson & Sassaman, 1988; Whitney, 1994; Bonnicksen, 2000). The fact that Native Americans used fire in a variety of ways is clearly documented in historical accounts, so their activities undoubtedly increased the number of ignitions. Whether this had an effect on vegetation pattern is much more difficult to evaluate. The distribution of presettlement fire broadly corresponds to the pattern of Native American populations *c*. AD 1600, with higher population sizes mirroring higher fires along the coast and inland waterways (Fig. 5). Patterson & Sassaman (1988) argue that this pattern is largely a function of ignitions by humans, because the occurrence of ignitions by lightning is an uncommon phenomenon in north-eastern North America.

However, results presented here indicate that the distribution of fire is strongly related to climate and vegetation across the same area. As these two factors are known from many studies to be major determinants of fire behaviour, there appears no need to invoke additional factors, including people, to explain the pattern of presettlement fire. Even if ignitions were equal throughout New England we would expect this pattern, because fires would spread through some kinds of vegetation (pitch pine and oak forests) more effectively than others (northern hardwoods).

Native Americans may have, indeed, started many pre-European fires, but this does not mean that the distribution of vegetation across New England was a consequence of intentional human burning. We will need more concrete evidence than we have at the moment to make such a claim. Currently, only the example from Crawford Lake in Ontario, Canada, provides strong evidence for a regional impact on vegetation through fires associated with Native American activities (McAndrews & Boyko-Diakonow, 1987; McAndrews, 1988; Clark & Royall, 1995). Both charcoal and herbaceous pollen appear during a period of known Iroquoian occupation, and the vegetation shifts in composition from northern hardwoods towards more oak and pine. However, because Native Americans living in that region of North America lived in more permanent and densely populated settlements and employed more intensive agricultural practices, they probably used fire much more extensively than people in New England (Bragdon, 1996; Chilton, 1999).

We do not conclude from our results that Native Americans did not have a significant impact on the local occurrence of fire or vegetation composition in New England. However, their effects may have been too small to be easily detected in the palaeoecological record or they may have simply accentuated the occurrence or consequences of natural fires. It is also possible that we do not yet have the appropriate palaeoecological records, if they are available at all, to answer this question fully. Identifying the extent and nature of pre-European human impacts on fire and vegetation will require not only a clearer understanding of the representation of fires by fossil charcoal in lake sediments, but also a stronger collaboration among palaeoecologists, archaeologists and historians in order to devise effective research strategies to detect their presence.

CONCLUSIONS

The significance of fire in pre-European ecosystems of North America is well-recognized. Palaeoecologists have assembled a substantial amount of evidence demonstrating that fires were abundant in the past and that fire regimes have changed through time, primarily in response to changing climate. Less well understood, unfortunately, is how the occurrence of fires differed regionally, within a single landscape, and what factors controlled this distribution. In New England, the landscape distribution of fires in the past is particularly difficult to establish because human impacts over the past 3–400 years have changed both vegetation composition and the occurrence of fire dramatically. Almost everywhere, fire has been more common within the last 400 years than before the arrival of Europeans in permanent settlements.

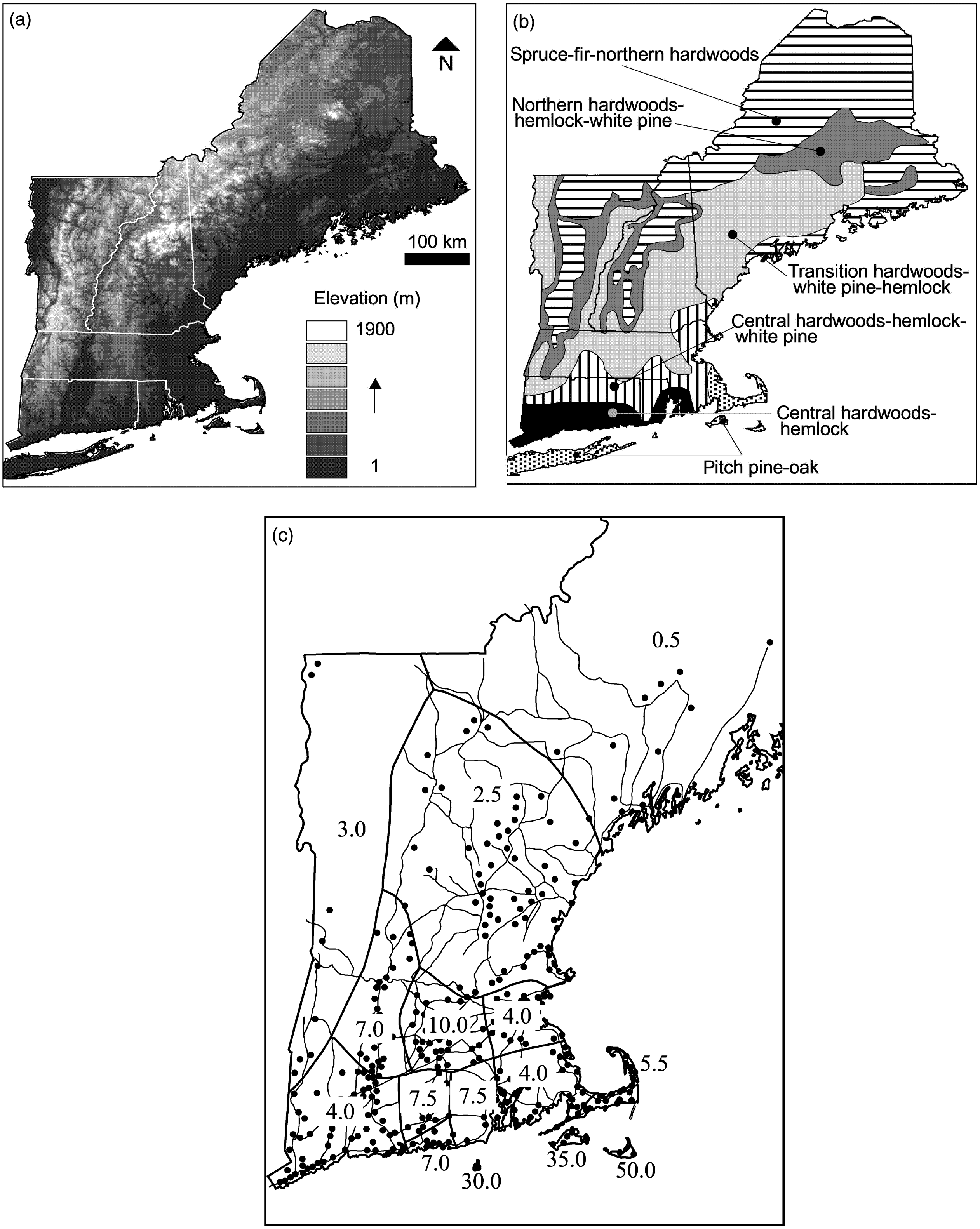

Figure 5 The New England region depicting (a) elevation above sea level, (b) generalized vegetation zones according to Westveld (1956), and (c) distribution of Late Woodland Indian settlements (dots), major trails (thin lines), and estimated population density (numbers) within broad ethnographic units (heavy lines). Note that climate (e.g. growing degree days or annual temperature) in this area closely parallels elevation (Hall *et al*., 2002). Indian data from Cook (1976).

Before the arrival of Europeans, fires were uncommon in the northern regions of New England where hemlock and northern hardwood forests were dominant. Even following the large-scale, landscape changes of the past few hundred years, charcoal abundance remains relatively low. At the same time, fires were most common where pitch pine forests were dominant, along the coast of New England and at isolated sites inland, which are all characterized by sandy, dry deposits of glacial outwash. However, the gradient in vegetation across this spatial scale is largely driven by climate, which also directly impacts fire ignition and spread.

Although this link between fire, climate and vegetation is strong, we also find evidence that other factors likely influenced fire occurrence around these sites. For example, not all pitch pine-oak forests had a similarly high level of charcoal and we believe that landscape attributes must also partly explain the patterns. The presence of firebreaks, the position of forests in relation to prevailing winds and the location of potentially flammable vegetation within a less flammable matrix must have influenced the presettlement fire regime, creating a heterogeneous vegetation mosaic. The effect of local physiographic characteristics exerted a direct effect on fire occurrence by changing microclimatic conditions conducive to fire, as well as indirectly by influencing vegetation composition, which in turn partly controls fire spread.

Native American populations undoubtedly had an effect on local vegetation on this landscape. However, we do not believe that their impact on the regional scale has been effectively demonstrated. Although Native American populations were higher along the coast of New England, the high occurrence of fires in pitch pine and oak forests in these locations can be explained by the climatic and fuel conditions of these forests without having to evoke a higher incidence of intentional burning by people. What is necessary to address this question are archaeological, historical and palaeoecological studies designed in a way that demonstrates a higher incidence of fire where Native American were residing than would be expected in their absence.

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