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Conservation implications of limited Native American impacts in pre-contact New England

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An increasingly accepted paradigm in conservation attributes valued modern ecological conditions to past human activities. Disturbances, including prescribed fire, are therefore used by land managers to impede forest development in many potentially wooded landscapes under the interpretation that openland habitats were created and sustained by human-set fire for millennia. We test this paradigm using palaeoenvironmental and archaeological data from New England. Despite the region's dense population, anthropogenic impacts on the landscape before European contact were limited, and fire activity was independent of changes in human populations. Whereas human populations reached maxima during the Late Archaic (5,000–3,000 yr BP) and Middle–Late Woodland (1,500–500 yr BP) periods, lake-sediment charcoal records indicate elevated fire activity only during the dry early Holocene (10,000–8,000 yr BP) and after European colonization. Pollen data indicate closed forests from 8,000 yr BP to the onset of European deforestation, and archaeological evidence of pre-contact horticultural activity is sparse. Climate largely controlled fire severity in New England during the postglacial interval, and widespread openlands developed only after deforestation for European agriculture. Land managers seeking to emulate pre-contact conditions should de-emphasize human disturbance and focus on developing mature forests; those seeking to maintain openlands should apply the agricultural approaches that initiated them four centuries ago.

An increasingly accepted paradigm in ecology, conservation and land management attributes many ecological conditions, habitat types and even global-scale carbon cycle changes to past cultural activities[1–4]. Humans are now inferred to have driven ecosystem dynamics for millennia across much of the globe, including many areas that were formerly interpreted as pristine or dominated by mature forests[5–7]. This new perspective has led to the conclusion that many valued characteristics of historical and modern landscapes, such as high levels of plant and animal diversity—including the occurrence of many rare and endangered species—may represent legacies of earlier cultural activities[8,9]. In many forested or potentially forested landscapes, a wide array of openland habitats including grasslands, shrublands, heathlands and early successional forests have been ascribed to purposeful landscape management by ancient people[10,11].

This human-centred interpretation has led to policies that encourage active management of important conservation landscapes modelled after, or seeking to achieve, many of the physical effects of cultural processes that are no longer operative[12,13]. These policies include the prescription of disturbances, especially fire, but also forest clearance and varied mechanical treatments, to mimic the impacts of inferred past human activities. This stewardship is supported by the argument that the cessation of ancient cultural disturbances has been accompanied by significant changes in landscape structure and function, such as reforestation and succession, accompanied by a loss in critical habitat and biodiversity[14,15]. The scientific, historical and conservation literature[1,6,10] and popular environmental books[16–18] widely embrace this thinking.

Often overlooked in such sweeping cultural interpretations of nature is the great geographical and temporal variation in the importance of human versus environmental controls on ecosystem patterns and processes. To improve our understanding and stewardship of modern landscapes for specific goals, conservation strategies need to be grounded in strong, interdisciplinary, retrospective science on past environments, socioecological systems and ecosystem dynamics. Here we report results from an integrated palaeoecological, palaeoenvironmental, archaeological and historical study that seeks to test the cultural management paradigm in one of its source regions, southern New England, and thereby inform the understanding of landscape dynamics and application of conservation practices at the regional scale.

Origin and application of the anthropogenic paradigm

Ecological and conservation thinking in New England shifted dramatically in the twentieth century from a wild to humanized interpretation of the past, representing an early and powerful precursor to the much broader acceptance of the anthropogenic paradigm. This shift arguably commenced with the seminal paper 'The Indian as an ecological factor in northeastern forests' by Day[19] in 1953 and became solidly established and popularized in the 1980s with the elaboration of these ideas in Cronon's *Changes in the Land*[20]. Both works argued that purposeful landscape management by horticulturally based native people sought to increase plant and animal resources by creating a diverse landscape mosaic, including non-forested habitats and successional forests. The use of fire by the indigenous people of New England has received particular attention in subsequent academic and popular writings. For example, Mann[16] suggested that pre-contact Native Americans "reshaped entire landscapes to suit their purposes", using fire as a "principal tool". Similarly, Poulos[21] wrote in a recent synthesis that "Native Americans used fire as a means

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for generating a mosaic of resources across the landscape". Spurred by these and other compelling accounts[9,22], stewards of public and private conservation lands routinely manage vegetation today with fire and mechanical means to create and maintain open and early successional habitats. Given that these habitats have declined precipitously over the past century[23–25], we address the question of when they appeared and what factors created them and controlled their abundance and distribution in the landscape.

New England provides an ideal setting to examine the empirical underpinnings of the anthropocentric paradigm in ecology and conservation as it: (1) features a high density of sites with detailed reconstructions of postglacial climate, vegetation, fire and human activity; (2) supported high concentrations of native people beginning at least 8,000 yr BP[26]; (3) provides among the most widely cited early written records used to formulate and support the interpretation of widespread indigenous use of fire in eastern North America[27]; and (4) continues to be recognized as a region where the drivers and consequences of past fire require further study[21,22,28].

Interdisciplinary study design

We collected sediment cores from 21 lakes across southern New England (Supplementary Table 1), concentrated along the coast from Long Island to Cape Cod, the adjacent islands (Elizabeth Islands and Martha's Vineyard) and adjoining areas of Connecticut and Massachusetts (Fig. 1a). The lakes are relatively small (mean 4.9 ha; range 1–26 ha), augmenting local pollen and charcoal signals and yielding landscape-scale records of vegetation and fire[29,30]. The study area features cold winters, warm summers and even precipitation throughout the year (totalling 1,000–1,500 mm yr^{-1}). Acidic soils occur on glacial till and granitic or metamorphic bedrock in inland parts of the region, whereas sandy soils occur on glacial outwash and glaciolacustrine kame-delta deposits in the Connecticut River Valley and on Long Island, Cape Cod and Martha's Vineyard. The regional vegetation is dominated by deciduous hardwood trees, including *Quercus* (oak), *Carya* (hickory), *Betula* (birch), *Acer* (maple) and *Fagus grandifolia* (beech). *Pinus strobus* (white pine) and *Tsuga canadensis* (eastern hemlock) are common on mainland sites, and *P. rigida* (pitch pine) is prevalent on sandy soils[31]. European colonization began from the coast in the 1620s, with deforestation and agriculture opening 40–80% of the landscape through the mid-nineteenth century, when farmland abandonment and succession led to the largely forested condition that prevails today[32].

Thirteen of the lake-sediment records begin between 14,000 and 9,600 calibrated ^{14}C yr BP; the other eight records cover the past 1,600–2,000 yr. We analysed pollen and charcoal, calculating pollen percentages and charcoal accumulation rates (pieces $cm^{-2} yr^{-1}$; CHAR) and interpolating the pollen and CHAR data to 50-yr intervals. We then calculated CHAR *z* scores (CHAR-*z*) and compared the charcoal and pollen data with palaeoclimate[32] and archaeological records[25,33,34]. Lacustrine and marine records show that the region has experienced a steady increase in effective moisture since the early Holocene (Fig. 2e), with a peak in temperatures occurring 8,000–6,000 yr BP (Fig. 2d)[35]. Reconstructions of relative human population levels for the northeastern United States[34] and coastal New England[25,33] are based on syntheses of ^{14}C dates from archaeological materials (Fig. 2c) and numbers of sites assigned to different archaeological periods, respectively (Fig. 2b). Both reconstructions indicate peaks in human population during the Late Archaic and Middle–Late Woodland periods. We also interpret the palaeoecological data in the context of site-level spatial distributions of Middle–Late Woodland subsistence activities for coastal New England[25,33] (Fig. 1b).

Results

The charcoal records exhibit considerable temporal variation, but similar CHAR values suggest that they capture changes in fire severity[36] in a consistent way. The mean pre-European CHAR values are <12 pieces $cm^{-2} yr^{-1}$ (Supplementary Table 1) for all but one site (Fresh-Falmouth; 28 pieces $cm^{-2} yr^{-1}$). The CHAR-*z* time series feature similar temporal trends that are interpretable in terms of the regional history of climate, vegetation and human activities (Figs. 2 and 3).

New England climate was cool and dry and the indigenous, Palaeo-Indian population was low during the late glacial period and the beginning of the Holocene[34,35,37] (Fig. 2). Initially, at 14,000–12,000 yr BP, CHAR-*z* values were also low when *P. banksiana* and *Picea*-dominated boreal forest prevailed regionally[38]. The CHAR-*z* values increase at some sites during 12,000–10,000 yr BP, when *P. strobus* became prevalent, but mean CHAR-*z* values remain low.

Temperature and precipitation increased region-wide 10,000–8,000 yr BP, with precipitation remaining considerably lower than at present[35] (Fig. 2). This change in climate brought about shifts in plant functional types, fuels and fire. An increase in CHAR-*z* values at nearly all sites indicates higher fire activity as *Quercus* increased and *P. banksiana* and *P. strobus* declined[38] (Fig. 3). Elevated abundances of *Ambrosia* and Poaceae pollen indicate the presence of openlands or an open forest structure maintained by fire and dry conditions (precipitation 600–1,000 mm yr^{-1}), much like that found historically along the eastern margin of the Great Plains[35,39] (Fig. 2). Human population levels remained low during this Early Archaic interval[34].

CHAR-*z* values declined 8,000–6,000 yr BP as moisture increased and temperature reached a postglacial maximum[35] (Fig. 2). *Fagus* and *Carya* expanded across the region as *Quercus* remained abundant and *Ambrosia* and Poaceae declined to trace amounts[38]. The pollen and charcoal data portray a landscape of closed-canopy mesic hardwood forests with little fire, even though the Middle Archaic human population was apparently larger than that of the Early Archaic[33,34,37,40].

The middle Holocene (6,000–3,000 yr BP) featured cooler, wetter climates than 8,000–6,000 yr BP, yet with drier conditions than today[35] (Fig. 2). Across the southern New England coast and broader region, human populations increased dramatically, reaching a peak during this Late Archaic period[25,33,34]. Closed-canopy forests persisted regionally and around all study sites, with no evidence of grass or weed-dominated openlands or successional woodlands. Despite the substantially larger human population, mean CHAR-*z* values remained lower than 10,000–8,000 yr BP, indicating that fire was less widespread than during the earlier, drier period. Peaks in CHAR-*z* values appear at several sites (West Side, Umpawaug, Ware and Black ponds), suggesting local areas of higher fire severity, perhaps related to human activity.

Charcoal values declined further during 3,000–1,500 yr BP, an interval in which precipitation continued to increase[35] (Fig. 2). The Early Woodland human population was low relative to that of the Late Archaic[34]. Subtle shifts in forest composition, including a decline in *Quercus* and an increase in *P. rigida*[38], seem to be driven by changing climate.

A second peak in the indigenous population occurred during the Middle–Late Woodland period, 1,500–500 yr BP (Figs. 2 and 4). Across the Northeast, this increase has often been attributed to the emergence of horticulture of native plants and tropical cultigens, especially maize[34]. However, New England archaeological data indicate that horticulture was adopted relatively late and played a minimal role in subsistence before the European arrival[41] (Fig. 1b). Similar to the Late Archaic, CHAR-*z* values and pollen abundances of *Ambrosia* and Poaceae remain low during the Middle–Late Woodland. Umpawaug and Deep-Falmouth ponds feature peaks in CHAR-*z* at 700–600 yr BP, a pattern suggesting landscape-scale heterogeneity of fire in a region characterized by a low occurrence of fire overall. Indeed, some sites with local evidence of intensive and extended human occupation, such as Black Pond on Martha's Vineyard[25,42,43], exhibit no rise in CHAR-*z* or pollen

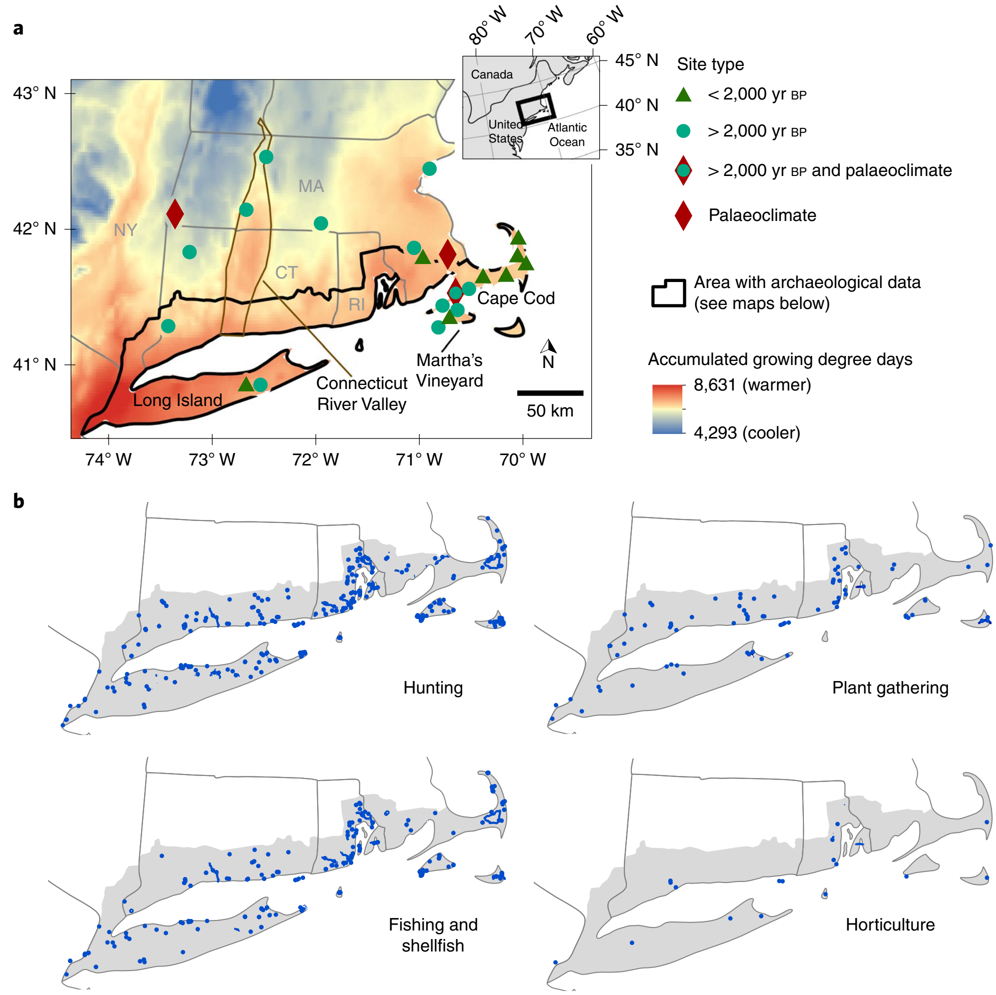

Fig. 1 | Maps of southern New England showing study sites and archaeological data. a, Locations and types of study sites plotted on a map of accumulated growing degree days[54] (0 °C base). **b**, Maps of archaeological data (grey shading) from the coastal region of the study area. Blue dots indicate the locations of Middle–Late Woodland materials associated with different subsistence activities[25,33]. The archaeological data reflect the widespread use of various upland and marine resources, but evidence for horticulture is uncommon across the region. NY, New York; MA, Massachusetts; CT, Connecticut; RI, Rhode Island.

evidence for open, non-forested vegetation during the Late Holocene. Middle–Late Woodland subsistence practices, such as hunting, fishing, plant gathering and small-scale farming (Fig. 1b), apparently resulted in local ecological impacts without transforming the broader forested landscape.

The widespread European deforestation and agriculture that commenced in the seventeenth century and continued into the mid-nineteenth century produced a decline in *Quercus* abundance and abruptly increasing pollen percentages for *Ambrosia* and Poaceae, exceeding the highest values of the early Holocene (Figs. 2 and 4). CHAR-*z* values also rose sharply at this time, with the values at half of the sites (7 of 13) exceeding the high values recorded during 10,000–8,000 yr BP.

Discussion

Humans were present across southern New England and thus could act as ignition sources throughout the postglacial interval, but fire regimes in the region were controlled primarily by climate interacting with vegetation. Fire was most prevalent 10,000–8000 yr BP, when the climate was as dry as modern Minnesota[35] and open *Quercus* woodlands expanded regionally, creating an environment, fuels and forest conditions conducive to burning (Fig. 3). From 8,000 yr BP until European arrival, increases in *Fagus* and *Carya*, high levels of arboreal pollen and low abundances of *Ambrosia*, Poaceae and charcoal indicate the regional dominance of increasingly mesic, closed-canopy forests and a decline in fire. Archaeological evidence indicates a dense pre-contact population that used a range of upland, estuarine, near-shore and marine resources (Fig. 1b), undoubtedly resulting in fine-scale ecological impacts. Charcoal peaks at some sites (4 of 13) during the Late Archaic and, to a lesser extent (2 of 21), the Middle–Late Woodland suggest a dispersed pattern of fire that may represent local human influence. Broadly, however, the charcoal and pollen data and archaeological record do not support the interpretation of significant indigenous impact—including human-set fire, forest clearance and horticulture—as a regional-scale driver of vegetation composition and structure. The regional flora bolsters this interpretation. The majority of species display generalized disturbance adaptations that facilitate recovery from physical and biological disturbances including windthrow, stem and branch break, ice damage, defoliation, browsing and tree-felling by beaver, whereas fire-specific adaptations such as serotiny are exceedingly rare[44,45]. Moreover, a recent synthesis of work on the efficacy of prescribed fire for maintaining openland habitats concluded that "there has been no study that found fire alone to be a viable long-term management solution; rather, fire in combination with other tools is necessary"[46].

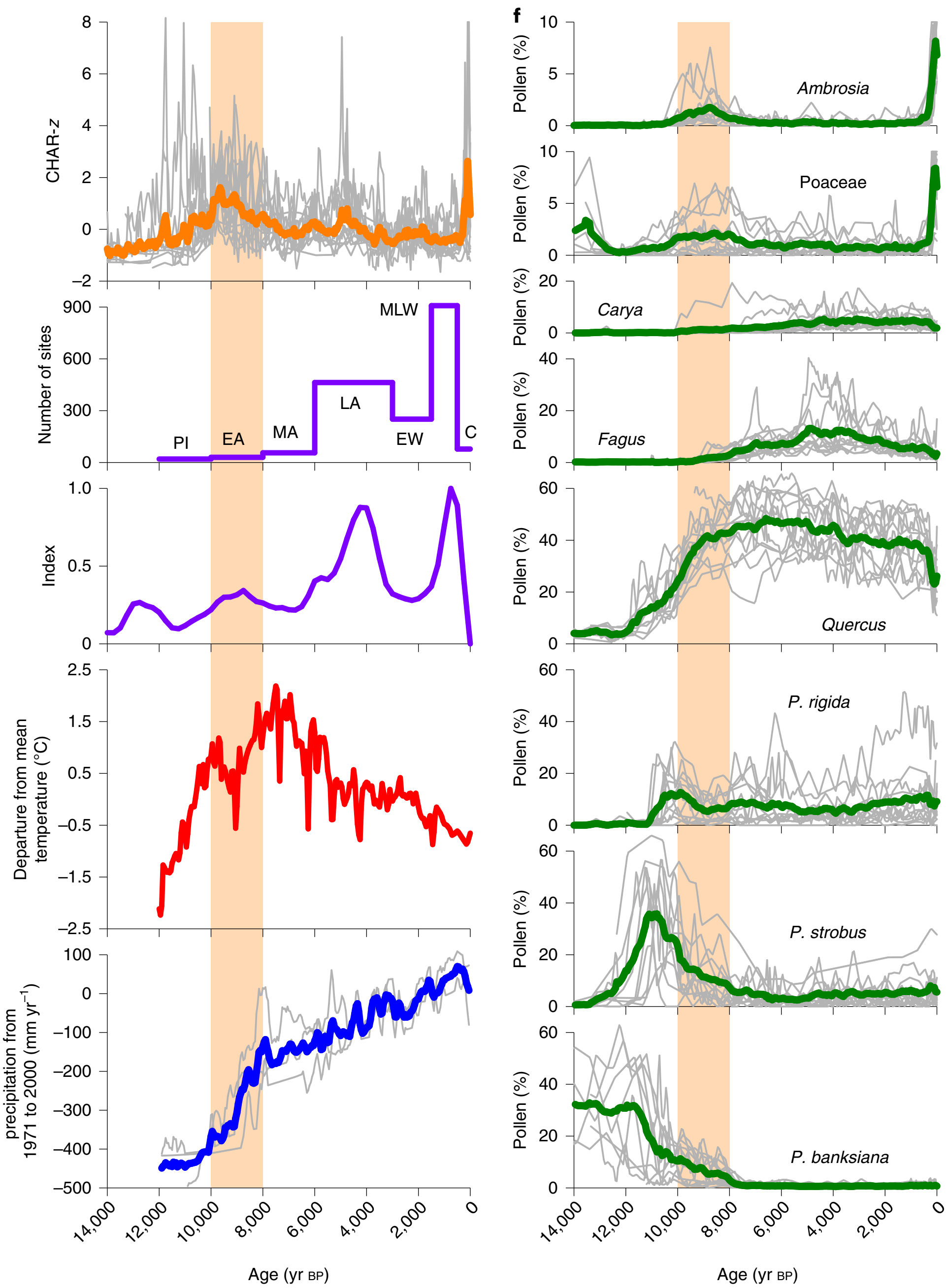

Fig. 2 | Postglacial palaeoenvironmental and archaeological data from southern New England. **a**, Lake-sediment charcoal data spanning the past 9,600–14,000 yr from 13 study sites located across southern New England. Values are CHAR-*z* interpolated at 50-yr intervals and based on the means and standard deviations for the period >500 yr BP. Grey lines are records from individual sites; the orange line is the mean. Two sites have *z* scores of 10–25 at 50–100 yr BP. **b**, Numbers of archaeological sites in the coastal region of southern New England during different periods: PI, Palaeo-Indian; EA, Early Archaic; MA, Middle Archaic; LA, Late Archaic; EW, Early Woodland; MLW, Middle–Late Woodland; C, Colonial[25,33]. **c**, Index of the indigenous human population over the past 14,000 yr for the northeastern United States[34]. **d**, Sea surface temperature reconstruction from site GGC30[35]. **e**, Reconstruction of effective precipitation for southern New England. Grey lines are the moisture reconstructions for Davis, New Long and Deep-Falmouth[31]; the blue line is the average of the three records. **f**, Pollen percentage data for selected taxa from the same 13 study sites as in **a**. Grey lines are records from individual sites; green lines are means. For *Ambrosia*, values reach 10–17% at four sites during 50–200 yr BP. For Poaceae, values reach 10–18% at six sites during 0–200 yr BP. In all graphs, orange shading marks the 10,000–8,000 yr BP period of high fire severity and open *Quercus* woodlands.

The pollen data suggest that mature, closed-canopy forests dominated New England for the eight millennia before European colonization. Four centuries ago this situation changed abruptly as deforestation, widespread grazing by sheep and cattle, and intensive use of the remaining woodlands created a pastoral landscape of expansive pastures, hayfields, croplands, shrublands and successional forests[32]. European disturbance of the New England landscape included intentional and accidental fires, as reflected by the increases in CHAR-*z* values at that time, but the primary mechanisms for creating and maintaining openland habitats included tree-felling, animal grazing, mowing and ploughing. Long-lived trees, such as *Quercus* and *Carya* in the south and *Tsuga* and *Fagus* in

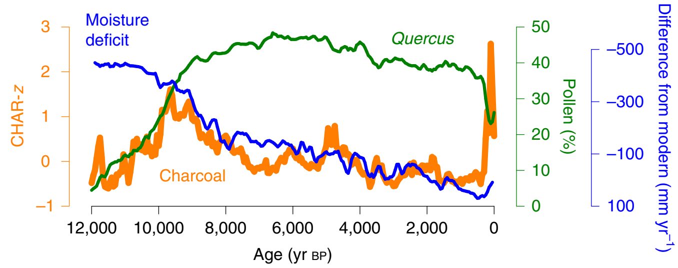

Fig. 3 | Postglacial climate, vegetation and fire in southern New England. This summary diagram shows the mean CHAR-*z* values and *Quercus* pollen percentages for 13 study sites located across the region, as well as the mean moisture-deficit reconstruction for Davis, New Long and Deep-Falmouth[35]. Fire severity was high during 10,000–8,000 yr BP, when climate was dry and the expansion of *Quercus* woodlands increased the availability of flammable fuels, then decreased after 8,000 yr BP as the climate became wetter. Note that the mean CHAR-*z* values associated with European forest clearance exceed those of the early Holocene.

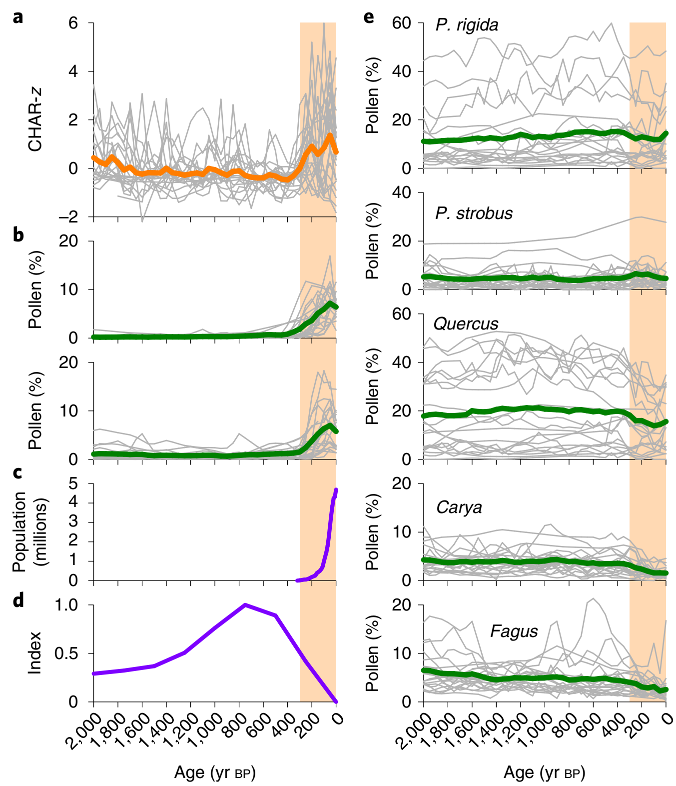

Fig. 4 | Late-Holocene palaeoenvironmental and archaeological data from southern New England. a, Lake-sediment charcoal data spanning the past 2,000 yr from 21 study sites located across southern New England. Values are CHAR-*z* interpolated at 50-yr intervals and based on the means and standard deviations for the period <2,000 yr BP. Grey lines are records from individual sites; the orange line is the mean. **b**, Pollen percentage data for the herbaceous taxa *Ambrosia* (top) and Poaceae (bottom) from the same 21 study sites as in **a**. Grey lines are records from individual sites; green lines are means. **c**, Euro-American population of Massachusetts[55]. **d**, Index of the indigenous human population over the past 2,000 yr for the northeastern United States[34]. **e**, Pollen percentage data for tree taxa from the same 21 study sites as in **a**. Grey lines are records from individual sites; green lines are means. In all graphs, orange shading marks the <300 yr BP period following European colonization. Note that the peak in the indigenous population during the Middle–Late Woodland (1,500–500 yr BP) coincides with low mean CHAR-*z* values, whereas fire severity increases during the time of European land clearance.

the north, declined as successional taxa (including *Betula*, *P. strobus* and *P. rigida*) increased[31]. Plant, mammal, bird and insect species of open, grassy, disturbed and successional habitats increased and thrived through the late nineteenth century when natural reforestation followed a regional decline in farmland to create the forested conditions prevailing today[47]. Viewed in terms of global carbon dynamics[3,4], the regrowth of New England forests is taking up some of the carbon that was lost to the atmosphere during the period of European deforestation[48].

Across New England, a rich array of non-forested habitats that support many rare and threatened openland taxa is cultural in origin but dates back centuries rather than millennia. Using interdisciplinary science and history as a guide, human land use could continue to be of great value in conservation stewardship, although the tools engaged would be chainsaws, cattle and sheep grazing, and hay production, rather than fire. The growing movement towards local agricultural production of grass-fed meat and dairy, diversified fruits and vegetables, and the use of local timber and fuelwood have the potential to expand and revitalize open and successional habitats regionally[49].

These findings confirm the great variability in the relative importance of human and environmental controls on ecosystems across space and time, highlighting the need for conservation strategies and land management to be informed by interdisciplinary, retrospective science. In regions like New England, land managers seeking to emulate pre-contact conditions should take advantage of the naturally reforested landscape, de-emphasize the role of human disturbance and anticipate climate-driven change; those seeking to maintain important openland habitats should apply the broad range of colonial-era agricultural approaches, including grazing, mowing and cutting woody vegetation, rather than burning.

Methods

Chronological control for the sediment cores was provided by accelerator mass spectrometry ^{14}C analysis of plant macrofossils and bulk sediments, pollen evidence for European deforestation and, in some cases, ^{210}Pb analysis (Supplementary Table 2)[38]. The ^{14}C dates were calibrated with the IntCal13 calibration curve[50], and age models were constructed using Bchron v.3.2[51].

Sediment samples (1–2 cm^3) were prepared for the pollen analysis following standard procedures[52], mounted in silicone oil and analysed at ×400 magnification. Pollen percentages were calculated relative to the sum of pollen and spores of upland plant taxa. The abundances of *P. rigida* and *P. banksiana* pollen were determined following Oswald et al.[38]. For charcoal analysis, 1-cm^3 subsamples were soaked in KOH and washed through a 200-μm sieve; all charcoal fragments >200 μm were counted at ×40 magnification[53].

Site-level archaeological data for >1,800 locations across the study region (Figs. 1b and 2b) were obtained from all available cultural resource management reports from the coastal areas of Massachusetts, Rhode Island, Connecticut and New York, as well as from journal articles and other publications[25,33]. The archaeological report from each site was evaluated and then coded for the presence or absence of various subsistence activities during different time periods[33].

Data availability

The data that support the findings of this study are available from the corresponding author upon request.

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References

1. Kareiva, P., Watts, S., McDonald, R. & Boucher, T. Domesticated nature: shaping landscapes and ecosystems for human welfare. *Science* **316**, 1866–1869 (2007).
2. Ellis, E. C. et al. Used planet: a global history. *Proc. Natl Acad. Sci. USA* **110**, 7978–7985 (2013).

3. Ruddiman, W. F. The anthropogenic greenhouse era began thousands of years ago. *Climatic Change* **61**, 261–293 (2003).
4. Kaplan, J. O. et al. Holocene carbon emissions as a result of anthropogenic land cover change. *Holocene* **21**, 775–791 (2011).
5. Meggers, B. J. *Amazonia: Man and Culture in a Counterfeit Paradise* (Aldine-Atherton, 1971).
6. Denevan, W. The pristine myth: the landscape of the Americas in 1492. *Ann. Assoc. Am. Geogr.* **82**, 369–385 (1992).
7. Clement, C. R. et al. The domestication of Amazonia before European conquest. *Proc. R. Soc. B* **282**, 20150813 (2015).
8. Levis, C. et al. Persistent effects of pre-Columbian plant domestication on Amazonian forest composition. *Science* **355**, 925–931 (2017).
9. Abrams, M. D. & Nowacki, G. J. Native Americans as active and passive promoters of mast and fruit trees in the eastern USA. *Holocene* **18**, 1123–1137 (2008).
10. Askins, R. A. *Restoring North America's Birds: Lessons from Landscape Ecology* (Yale Univ. Press, 2000).
11. Poschlod, P. & WallisDeVries, M. F. The historical and socioeconomic perspective of calcareous grasslands—lessons from the distant and recent past. *Biol. Conserv.* **104**, 361–376 (2002).
12. Dunwiddie, P. W. & Caljouw, C. in *Ecosystem Management: Rare Species and Significant Habitats* (eds Mitchell, R. S. et al.) 271–275 (New York State Museum, 1990).
13. Valko, O. et al. Supporting biodiversity by prescribed burning in grasslands—a multi-taxa approach. *Sci. Total Environ.* **572**, 1377–1384 (2016).
14. Dunwiddie, P. W. & Sferra, N. Loss of rare butterfly and plant species in coastal grasslands. *Nat. Areas J.* **11**, 119–120 (1991).
15. Dengler, J., Janisova, M., Torok, P. & Wellstein, C. Biodiversity of Palaearctic grasslands: a synthesis. *Agric. Ecosyst. Environ.* **182**, 1–14 (2014).
16. Mann, C. C. *1491: New Revelations of the Americas before Columbus* (Knopf, 2005).
17. Marris, E. *Rambunctious Garden: Saving Nature in a Post-wild World* (Bloomsbury, 2011).
18. Pyne, S. J. *Fire in America* (Princeton Univ. Press, 1982).
19. Day, G. M. The Indian as an ecological factor in the northeastern forest. *Ecology* **34**, 329–346 (1953).
20. Cronon, W. *Changes in the Land: Indians, Colonists, and the Ecology of New England* (Hill & Wang, 1983).
21. Poulos, H. Fire in the Northeast: learning from the past, planning for the future. *J. Sustain.* **34**, 6–29 (2015).
22. Abrams, M. D. & Nowacki, G. J. Exploring the early Anthropocene burning hypothesis and climate-fire anomalies for the eastern U.S. *J. Sustain.* **34**, 30–48 (2015).
23. Foster, D. R. & Motzkin, G. Interpreting and conserving the openland habitats of coastal New England: insights from landscape history. *Ecol. Manage.* **185**, 127–150 (2002).
24. Foster, D. R. & Aber, J. D. *Forests in Time: The Environmental Consequences of 1,000 Years of Change in New England* (Yale Univ. Press, 2004).
25. Foster, D. R. *A Meeting of Land and Sea: Nature and the Future of Martha's Vineyard* (Yale Univ. Press, 2017).
26. Dincauze, D. F. in *The Pequots in Southern New England: The Fall and Rise of an American Indian Nation* (eds Hauptman, L. M. & Wherry, J. D.) 19–32 (Univ. Oklahoma Press, 1990).
27. Patterson, W. A. III & Sassaman, K. E. in *Holocene Human Ecology of Northeastern North America* (ed. Nicholas, G. P.) 107–135 (Plenum, 1988).
28. Robertson, K. M., Poulos, H. M., Camp, A. E. & Tyrrell, M. Introduction to fire ecology in the Northeast: restoring native and cultural ecosystems. *J. Sustain.* **34**, 1–5 (2015).
29. Sugita, S. Pollen representation of vegetation in Quaternary sediments: theory and method in patchy vegetation. *J. Ecol.* **82**, 881–897 (1994).
30. Higuera, P. E., Peters, M. E., Brubaker, L. B. & Gavin, D. G. Understanding the origin and analysis of sediment charcoal records with a simulation model. *Quat. Sci. Rev.* **26**, 1790–1809 (2007).
31. Thompson, J. R., Carpenter, D. N., Cogbill, C. & Foster, D. R. Four centuries of change in northeastern U.S. forests. *PLoS ONE* **8**, e72540 (2013).
32. Foster, D. R. Thoreau's country: a historical-ecological perspective to conservation in the New England landscape. *J. Biogeogr.* **29**, 1537–1555 (2002).
33. Duranleau, D. L. *Flexible Sedentism: The Subsistence and Settlement of Coastal New England and New York*. PhD thesis, Harvard Univ. (2009).
34. Munoz, S. E., Gajewski, K. & Peros, M. C. Synchronous environmental and cultural change in the prehistory of the northeastern United States. *Proc. Natl Acad. Sci. USA* **107**, 22008–22013 (2010).
35. Shuman, B. N. & Marsicek, J. P. The structure of Holocene climate change in mid-latitude North America. *Quat. Sci. Rev.* **141**, 38–51 (2016).
36. Keeley, J. E. Fire intensity, fire severity and burn severity: a brief review and suggested usage. *Int. J. Wildland Fire* **18**, 116–126 (2009).
37. Chilton, E. S. & Hardy, M. D. in *The Cambridge World Prehistory* (eds Renfrew, C. & Bahn, P.) 1293–1308 (Cambridge Univ. Press, 2014).
38. Oswald, W. W. et al. Subregional variability in the response of New England vegetation to postglacial climate change. *J. Biogeogr.* **45**, 2375–2388 (2018).
39. Faison, E. K., Foster, D. R. & Oswald, W. W. Early Holocene openlands in southern New England. *Ecology* **87**, 2537–2547 (2006).
40. Doucette, D. L. *Unraveling Middle Archaic Expressions: A Multidisciplinary Approach towards Feature and Material Culture Recognition in Southeastern New England*. PhD thesis, Harvard Univ. (2003).
41. Chilton, E. S. in *Ancient Complexities: New Perspectives in Pre-Columbian North America* (ed. Alt, S.) 96–103 (Univ. Utah Press, 2010).
42. Ritchie, W. A. *The Archaeology of Martha's Vineyard: A Framework for the Prehistory of Southern New England. A Study in Coastal Ecology and Adaptation* (Natural History, 1969).
43. Doucette, D. L. & Herbster, H. *Intensive Archaeological Survey of the Red Gate Farm-Lot 1 Project Area, Aquinnah, Massachusetts* (Public Archaeology Laboratory, 2005).
44. Ledig, F. T. & Fryer, J. H. A pocket of variability in *Pinus rigida*. *Evolution* **26**, 259–266 (1972).
45. Motzkin, G., Orwig, D. A. & Foster, D. R. Vegetation and disturbance history of a rare dwarf pitch pine community in western New England, USA. *J. Biogeogr.* **29**, 1455–1467 (2002).
46. *Sandplain Grassland Network* (Woods Hole Research Center, 2019); http://sandplaingrassland.net
47. Foster, D. R., Motzkin, G., Bernardos, D. & Cardoza, J. Wildlife dynamics in the changing New England landscape. *J. Biogeogr.* **29**, 1337–1357 (2002).
48. Wofsy, S. C. et al. Net exchange of CO_2 in a mid-latitude forest. *Science* **260**, 1314–1317 (1993).
49. Donahue, B. et al. *A New England Food Vision* (Univ. New Hampshire, 2014).
50. Reimer, P. J. et al. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* **55**, 1869–1887 (2013).
51. Haslett, J. & Parnell, A. A simple monotone process with application to radiocarbon-dated depth chronologies. *J. R. Stat. Soc. Ser. C* **57**, 399–418 (2008).
52. Fægri, K. & Iversen, J. *Textbook of Pollen Analysis* (John Wiley & Sons, 1989).
53. Whitlock, C. & Larsen, C. in *Tracking Environmental Change Using Lake Sediments* (eds Smol, J. P. et al.) 75–97 (Kluwer, 2001).
54. *Daily Temperature Accumulations – 32 Base Temp* (USA National Phenology Network, 2019); https://doi.org/10.5066/F7SN0723
55. Foster, D. & Gould, E. *Forest Change and Human Populations in New England 1600–2006* (2009); https://go.nature.com/2T3wyw3

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W.W.O., D.R.F., B.N.S., E.S.C., D.L.Doucette and D.L.Duranleau designed the project and participated in fieldwork, laboratory work and/or data analyses. W.W.O. and D.R.F. wrote the first version of the paper. W.W.O., D.R.F., B.N.S., E.S.C., D.L.Doucette and D.L.Duranleau contributed to the final version.

Competing interests

The authors declare no competing interests.

Additional information

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