Collaborative Research: Interacting influences of climate, land use and other disturbances on regime shifts in forest ecosystems: Holocene dynamics in the northeastern US. *PI*: David R. Foster; Lead: Harvard Forest, Harvard University (Dianna Doucette, Wyatt Oswald); *Collaborative Institutions*: University of Massachusetts Amherst (Elizabeth Chilton) and University of Wyoming (Bryan Shuman).

RESULTS FROM PRIOR RESEARCH

DEB-0815036, DEB-0816731; Collaborative Research: Ecosystem Responses to Progressive and Rapid Climate Change During the Holocene in New England, $500,000 to D Foster, W Oswald, B Shuman and Y Huang (2008-2011). The first phase of this project was highly successful in producing δD and lake-level records of century-scale climatic variability in New England (Gao et al. 2012, Marsicek et al. 2012, Oswald and Foster 2012). Comparison with other data suggests that these variations were driven by orbital changes and ocean-atmosphere responses (Shuman et al. 2012). Our detailed pollen and charcoal records indicate that these abrupt climatic changes were associated with regime shifts in forest ecosystems comparable in rate and magnitude to European land clearance (Shuman et al. 2009a). Several records exhibit dynamics distinct from the well-known hemlock decline at 5500 BP: northern sites display a major hemlock decline at 6000 BP (Oswald and Foster 2011); a restricted coastal area exhibits a collapse in oak and increase in beech at 5500 BP (Foster et al. 2006, in prep.); and in southwest CT a sharp decline in oak and fire occurs at 4200 BP (Foster et al. in prep). Results define the rate and magnitude of ecosystem change associated with climate variability (Williams et al. 2011), but raise major questions concerning thresholds for abrupt change, causes of variation in the magnitude and persistence of these changes, and interactions between climate and disturbance. We provided interdisciplinary training to graduate students (J. Marsicek, Wyoming; L. Gao, Brown) and undergraduates (Emerson students Adriana Marroquin, Allison Gillette, and Lindsay Day) in the Harvard Forest REU program, and generated many publications and a documentary film screened at Boston's Museum of Science and aired on the Vermont Access Network [www.cctv.org/watch-tv/programs/secrets-mud-hemlock-mystery].

Gao L, Shuman BN, Oswald WW, Foster DR, and Huang Y (2012) Interplay between the Laurentide Ice Sheet and insolation on Holocene climate of the northeastern United States. *Geology*. Submitted.

Marsicek JP, Shuman BN, Brewer S, Foster DR, and Oswald WW (2012) Quantifying climatic changes associated with the mid-Holocene *Tsuga* decline at ca. 5.5 ka in the northeastern United States. *Quaternary Science Reviews*. Submitted. (Based on a completed thesis by JP Masicek)

Oswald, WW and DR Foster (2011) Middle-Holocene dynamics of *Tsuga canadensis* (eastern hemlock) in northern New England. *The Holocene* in press.

Oswald WW and Foster DR (2012) A record of late-Holocene environmental change from southern New England. *Quaternary Research* in press.

Shuman B, Donnelly JP, Newby P (2009) Abrupt climate change as an important agent of ecological change in the Northeast U.S. over the past 15,000 years. *Quaternary Science Reviews* 28, 1693-1709.

Shuman B, Marsicek J, Newby P, Carter G, Hougardy D, Brewer S, Donnelly J, Foster D, and Oswald WW (2012) From causes to impacts of Holocene moisture variation in mid-latitude North America. *Nature Geosciences*. Submitted.

Williams JW, Blois JL, and Shuman B (2011). Extrinsic and intrinsic forcing of abrupt ecological change: case studies from the late Quaternary. *Journal of Ecology* 99: 664-677.

DEB-0952792; RAPID: Ecological Patterns and Consequences of Catastrophic Mortality of a Foundation Species due to Abrupt Climatic and Biotic Stress $136,510 to D Foster, D Orwig, A Ellison, J Thompson, W Oswald, A. Barker (2009-2010). The catastrophic and ongoing mortality of oak trees and stands in coastal New England (and increase in beech) following multiple insect infestations and severe drought provides a modern analogue for the 5500 BP event and an opportunity to contrast the modern declines of oak and hemlock (from the hemlock woolly adelgid). RAPID funds supported ecosystem, remote sensing and dendrochronological studies of patterns of mortality and forest dynamics and resulting changes in microenvironments, nutrient cycling and N availability. The project is strongly integrated with our paleoecological studies, LTER program of large experiments and the Harvard Forest Summer Research (REU) Program in Ecology.

INTRODUCTION

With escalating climate and land-use change, the rate and magnitude of ecosystem dynamics will likely increase with major effects on critical services to humankind. In particular, the frequency and extent of abrupt and irreversible transitions in ecological systems may increase as global-change processes accelerate (CCSP 2009). Many factors enhance the challenge of forecasting potential ecosystem changes (Bestelmeyer et al. 2011): multiple variables can force changes (Fig. 1) including a range of climatic and anthropogenic *drivers* or disturbance *triggers* such as extreme droughts, fire, or pest/pathogen outbreaks; interactions among drivers and triggers may generate unexpectedly rapid, large or persistent changes; and abrupt transitions or *regime shifts* may occur. Among possible dynamics, regime shifts are the most interesting, worrisome and challenging to anticipate as the science for detecting, interpreting, and forecasting them remains poorly developed for all but a few ecosystems (cf., Carpenter et al. 2011). Consequently, the manner in which climate change, land-use and disturbances interact to generate regional-scale regime shifts remains a critical area of research for science and society.

Several studies have sought to improve the ability to understand and anticipate abrupt changes in diverse systems, including a recent comparative effort (Bestelmeyer et al. 2011) introducing a broadly applicable conceptual approach. This work concludes that few studies have the following important characteristics:

- <u>Adequate time series</u> with a temporal resolution within the lifespan of key organisms and the temporal depth to explore multiple dynamics;
- <u>Comprehensive contextual data</u> including the geographical shape of ecological responses across environmental and disturbance gradients; and
- <u>Relevant scale and scope</u> consistent with the global-change drivers, triggers and responses anticipated in coming decades.

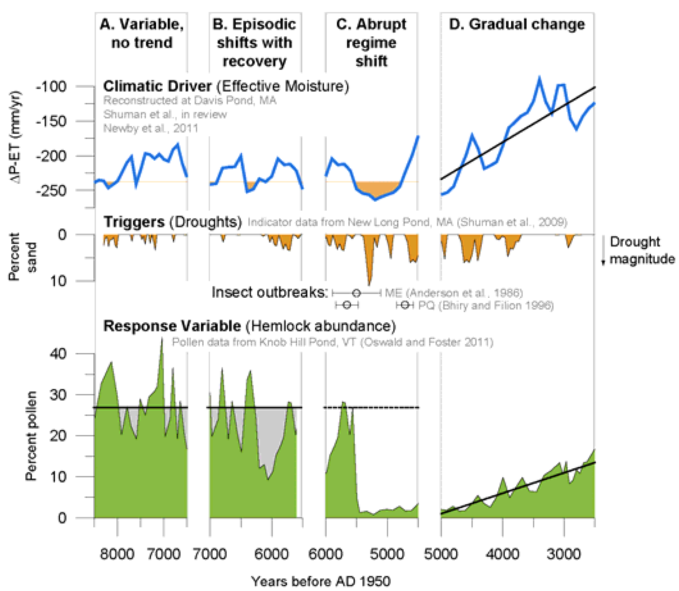

Figure 1. *Our ongoing work uses detailed multi-millennium time series to place a range of forest ecosystem responses (in terms of the abundance of hemlock pollen in a lake sediment core from Vermont) in the context of drivers and triggers. Responses can be quantitatively characterized as e.g., A) stationary, B) shifts and recovery, C) abrupt regime shifts, and D) gradual. Responses follow changing climatic drivers (e.g., effective moisture levels as reconstructed from sedimentary evidence of lake-level change) and triggers (e.g., brief droughts identified by discrete sand layers; insect outbreaks recorded from sediments in Maine and Quebec).*

We propose to advance the understanding of how climate change interacts with disturbances and land use to generate ecological responses and regime shifts by synthesizing and expanding a rich array of paleoecological, paleoclimatic, and archaeological research that address the limitations above. Our research platform is comprised of many 13,000-yr time-series featuring diverse ecological responses and potential regime shifts; regional context of environmental and cultural gradients and species distributions; and quantitative information on potential drivers and triggers that include many factors of interest today. These include known and purported episodes of rapid climate change, climate perturbations (droughts), insect outbreaks, changing human-population and land-use regimes (deforestation, fire, horticulture) and interactions among these. We will discriminate and compare ecological dynamics characterized by: (i) little directional change, (ii) slow progressive change, (iii) abrupt change followed by partial or complete recovery, and (iv) abrupt persistent changes to alternative states (Fig. 1). Using cutting-edge methodologies (Bestelmeyer et al. 2011) to analyze these dynamics with independent information on climate, disturbances and human activity, this research will investigate ancient regime shifts to determine potential mechanisms, interactions and consequences for the future.

While regime changes have been examined in individual ecosystems, we will evaluate regional-scale dynamics, spatial variation in ecosystem responses and drivers, and contextual information to interpret causes and consequences. We will consider three hypotheses regarding regional responses: (a) localized threshold responses to gradual drivers that relate to local triggers; (b) widely synchronous shifts following abrupt shifts in regional drivers; and (c) an asynchronous mosaic of regime shifts resulting from spatially asynchronous drivers and triggers (Fig. 2).

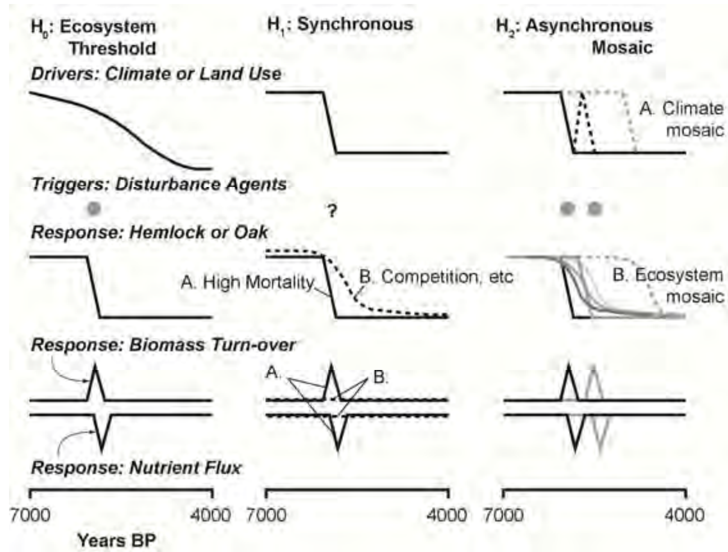

Figure 2. *Three hypothesized manifestations of regional-scale regime shift in forest ecosystems involving contrasting dynamics of drivers (i.e., climate) and triggers (i.e., fire, insect outbreaks, or droughts) and responses as documented in standing biomass, hemlock or oak abundance (and pollen representation) and nutrient fluxes. In H_1 and H_2, the rates of vegetation response, biomass turn over, and biogeochemical change may vary across space depending on the local importance of a triggering events (important, A; not important, B). In H_2, the drivers may have spatially-varied differences in timing (A), which can produce mosaics of ecosystem response (B).*

To evaluate the alternatives, we will quantify ecosystem response in terms of structure, composition and nitrogen cycling: (i) regionally in the context of climatic, cultural and disturbance gradients and (ii) in three contrasting landscapes (Fig. 3) where syntheses of rich cultural data will further inform the analyses. The three landscapes comprise coastal, near-coastal wetland, and inland-riverine areas with different ecological and climatic histories and cultural contexts (Bragdon 1996). We will examine dynamics during periods of slow, variable, and abrupt climatic change and will target rapid ecosystem changes characterized by sharp declines in oak and hemlock at ca. 6000, 5500, and 4000 yr BP (Fig. 4) and European settlement. We will fill critical gaps in the understanding of climatic change, fire, insects and human activity to assess potential drivers and triggers. In particular, the overriding importance and complexity of the human component (as both driver and responder to ecological change) warrants full evaluation of direct (archaeological) and indirect (fire, deforestation and agriculture) cultural evidence.

Study Framework: Ecological Dynamics and Regime Shifts

We consider *ecological responses* (i.e., taxon abundance and distribution; ecosystem function) state variables that describe system responses and alternative states. These variables respond directly or indirectly to changes in climatic, cultural or biotic *drivers* that can alter microclimates, resource availability, population parameters, and other features of the environment; or, perturbation *triggers* such as fire, drought, land use or pests that directly impact ecological systems. Ecological responses and drivers are presented as concurrent time series with triggers noted as discrete events or episodes (see Fig. 1 for examples from our studies). Interactions among drivers and triggers can be important, as are *context variables* such as climate and land use gradients, and species distributions.

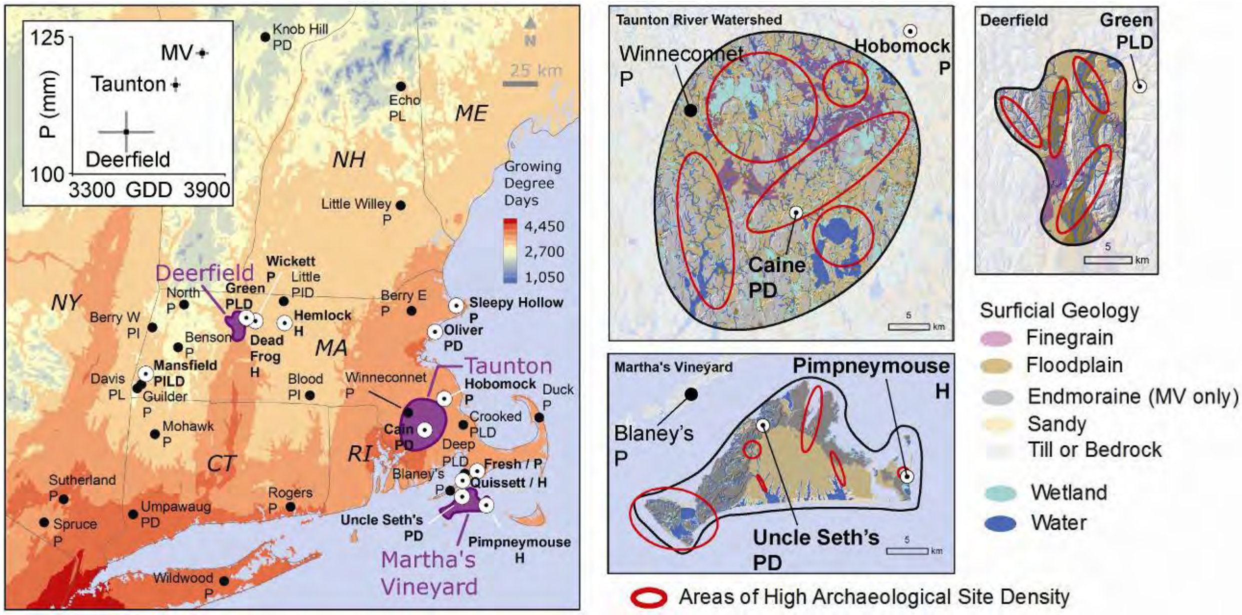

Fig 3. *Study region, three landscapes and sites: pollen records (P); lake-level reconstructions (L); hydrogen isotope analyses (I); disturbance (D) and small hollow studies (H). Proposed sites (white symbols) largely target the three landscapes of ecological and cultural interest (Deerfield, Taunton, Martha's Vineyard) that are distributed across the regional gradients in growing-degree days (GDD; regional map shading) and precipitation (P; inset). Landscape maps (right) indicate surface geologies and their great archeological site densities (red circles).*

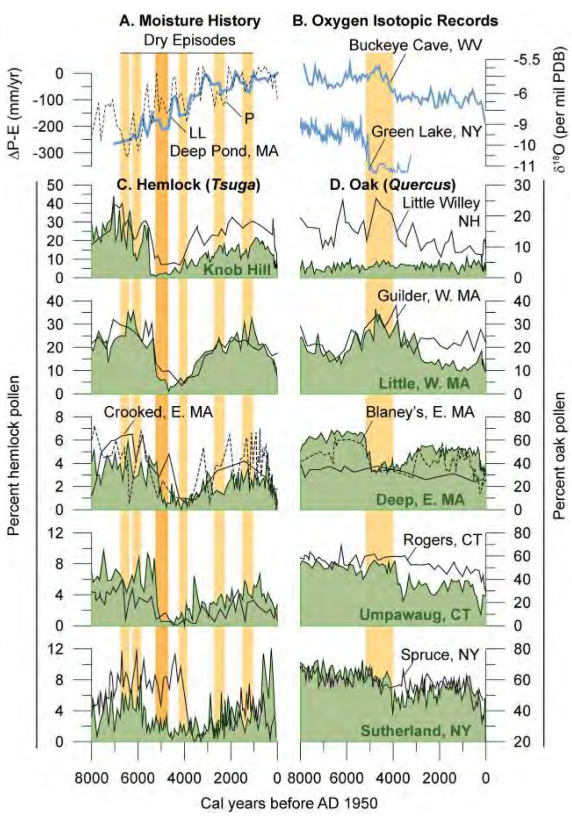

Figure 4. *Paleoclimate reconstructions (A) and indicators (B) show evidence of climatic variability and rapid state shifts that may have contributed to rapid changes in the abundance of (C) hemlock and (D) oak populations across New England. Fossil pollen datasets from northern New England, western and eastern Massachusetts, Connecticut, and the Hudson Highlands of New York illustrate the extensive decline of hemlock populations ca. 5500 yrs BP, but also the potential variance in the timing and rate of this decline (e.g., Crooked; Spruce; both closely dated), earlier episodes of hemlock decline and recovery (e.g., Knob Hill), and similar declines in oak populations at the same time (e.g., Blaney's; Deep) and later (e.g., Guilder; Umpawaug; Sutherland). Yellow bars mark periods of climatic change. Fig. 4 shows site locations. See text for data citations.*

Over 20 vegetation records spanning >13,000 yr indicate that ecological responses will fall into four general patterns (Fig. 1): (1) stationary with little long-term trend with minimal change in major drivers or triggers; (2) abrupt changes in major taxa with recovery; coinciding with triggering events; (3) abrupt species replacement due to mortality of the dominant species rather than competition; and (4) gradual change with e.g., progressive change in climate or land-use drivers or in disturbance frequency; or lagged response to more abrupt change (cf., Davis and Botkin 1985).

However, the pattern of ecological response does not convey the underlying mechanism as identical dynamics may have different causes; e.g., enduring changes may result from persistence in a driver/trigger or hysteresis (irreversibility). Consequently, entire systems of drivers, triggers, and responses must be analyzed in an integrated fashion using a system-dynamics approach to determine process and advance the theory of ecosystem regime change (Carpenter et al. 2011). To address past regime shifts we will utilize the sequential protocol developed for diverse systems by Bestelmeyer et al. (2011): (i) identify responses and transitions (Rodionov 2004); (ii) distinguish abrupt from gradual transitions (Anderson et al. 2009); (iii) identify leading indicators of abrupt changes (Carpenter and Brock 2006; Scheffer et al. 2009), and (iv) match observations to mechanistic models (Scheffer and Carpenter 2003; Heffernan 2008).

RESEARCH OBJECTIVES

The proposed work seeks to advance the broad understanding of ecosystem dynamics and regime shifts in the face of substantial global climate change by addressing major questions concerning the rate, magnitude, geographic characteristics and forcing factors associated with past ecological dynamics.

A. Evaluating Holocene Ecosystem Dynamics Across Time and Space

Employing the ecosystem regime shift framework, we ask focused questions at the ecosystem (local and landscape) to regional scales in New England (Fig. 3). All questions will be addressed by producing highly-resolved, extremely well-dated time series of fossil pollen percentages from lake sediment cores. The results from this portion of the project will enable us to evaluate specific hypotheses about regime changes in forested ecosystems described below with respect to drivers and triggers (see also Fig. 2).

1) **Have past ecosystem transitions been abrupt or smooth?** Holocene ecosystem transitions include rapid species declines (Fig. 4), but existing data limit our ability to determine whether these represent extensive canopy mortality events in the lifespan of individual trees or slower canopy turnover. The range-wide decline of hemlock 5500 yr BP is well studied (Webb 1982; Foster and Zebryk 1993; Hall and Smol 1993; St. Jacques et al. 2000) and yet its geography and cause remain enigmatic. Davis (1981) proposed that it represented hemlock mortality from a pathogen due to its apparent species specific, range-wide and synchronous nature (Webb 1982; Bennett and Fuller 2002). However, subsequent research indicates that it coincided with regional climate dynamics (e.g., Yu et al. 1997; Haas and McAndrews 2000; Shuman et al. 2004; Zhao et al. 2010) and an abrupt decline in oak near Cape Cod (Foster et al. 2006). An annually laminated core from NH suggest that the decline took <10 years (Allison et al. 1986), but few studies have the resolution to explore the timing and rates of this and other dynamics in hemlock and oak. Enhanced chronological control and quantitative analyses are needed to define and compare the many rapid declines in these taxa in time and space (Blaauw et al. 2003, 2004).

2) **Do abrupt transitions show evidence of leading indicators?** Studies of paleoclimates (Dakos et al. 2008) and modern ecosystems (Carpenter et al. 2011) show that increases in autocorrelation or variance and shifts in data spectral properties can signal imminent regime shifts. Hemlock and oak declines (Fig. 4) provide an opportunity to examine such indicators in forest ecosystems, which have not been previously analyzed because of the long time-scales required. Our data allow us to conduct millennial analyses and contrast many periods of abrupt change (Fig. 1C) with periods of stability or gradual changes (Fig. 1A, D). Our studies of hemlock dynamics (Fig. 1B; Oswald and Foster 2011) suggest that increases in variance and slow recoveries from modest perturbations may be leading indicators of regime shifts in these systems. Leading indicator analyses will also be examined on nitrogen isotope records that track shifts in N cycling and ecosystem function (e.g., McLauchlan et al. 2007).

3) **How do abrupt transitions in one ecosystem relate (in timing and rate) to those in other ecosystems regionally?** Our studies (Fig. 3-4) suggest that both hemlock and oak declines are more complex than initially thought and should be contrasted with other known or recently discovered

dynamics in these taxa. Our data (Fig. 4C) raise questions about the synchroneity of the hemlock decline because some sites (e.g., Crooked and Spruce Ponds) differ; indeed, the decline may comprise a regional mosaic of regime shifts with different rates, timing, and triggers (Fig. 2). Other events that yield opportunities for quantitative analysis of the regional pattern of spatial and temporal heterogeneity include: an earlier hemlock decline at 6000 yr BP (Fig. 4C; Oswald and Foster 2011; cf., Fuller 1998), the coastal oak decline (Foster et al. In prep), a second oak decline at 4200 yr BP in southwestern CT-NY (Fig. 4D) and a concurrent local hemlock decline (Foster et al. in prep; Maenza-Gmelch 1997). New analyses need to evaluate (a) the processes involved locally and regionally and (b) the factors that link, spread, or limit the spatial extent of regime shifts.

B. Evaluating the Drivers and Triggers of Ecosystem Dynamics: Disturbance, Climate and People
To interpret the mechanisms underlying the patterns of ecosystem dynamics we need to analyze the patterns in potential drivers and triggers (Fig. 1, 2, 5). Disturbance, such as an insect outbreak, provides one classic explanation for the hemlock decline (Davis 1981; Allison et al. 1986; Bhiry and Filion 1996), but this hypothesis and interactions with climate have been poorly examined. Likewise, the potential interrelationship between human and ecological history remains poorly resolved; an improved understanding needs to be integrated into ecological understanding and theory as well as current conservation policy and management. Three questions underlie this portion of the project:

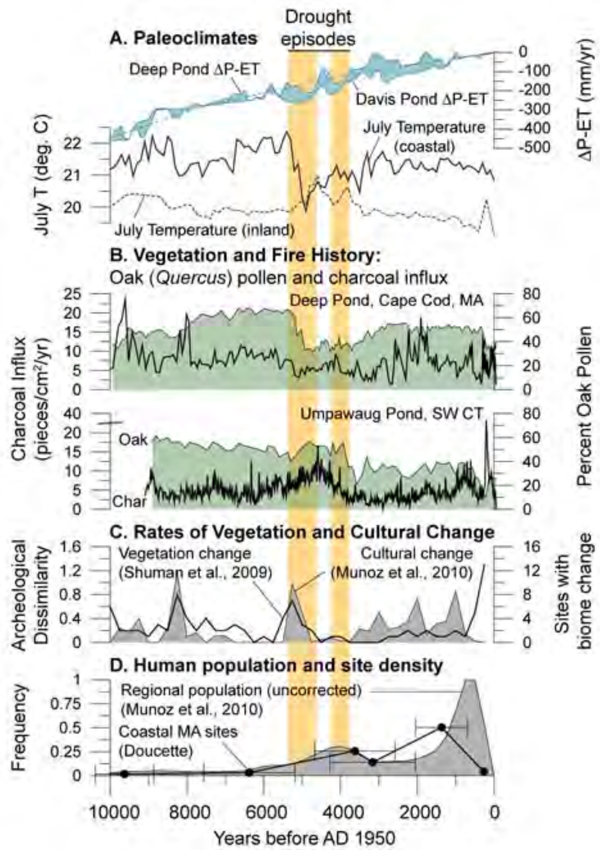

Figure 5. *Potential relationships among drivers and ecosystem dynamics. Paleoclimate drivers (A) include a long-term increase in effective moisture (precipitation minus evapotranspiration, P-ET) based on two lake-level reconstructions (Shuman et al. 2012); two drought episodes that punctuate the trend (yellow bars); and coincident coastal cooling and inland warming (Marsicek et al. 2012). Ecosystem responses (B) include rapid oak and charcoal influx declines (Foster et al. 2006; In prep) that coincide with both the beginning and end of the climatically-anomalous period (yellow bars). Rapid rates of vegetation change (C) are most frequent at ca. 8.2, 5.5, and 0.5 ka, and coincide with large archeological changes that may relate to shifts in land use. Trends in our coastal site/population data (D) are consistent with those of Munoz et al. and coincide with the climate-anomaly from ca. 5.5-4 ka.*

1) What are the patterns of Holocene disturbance in relationship to ecosystem dynamics?
Insects. Davis' (1981) proposal for a biotic driver of the hemlock decline is supported by reports of fossil remains of eastern hemlock looper (*Lambdina fiscellaria*) and chewed hemlock needles (Bhiry and Filion 1996). However, no systematic analysis of insect remains has been conducted (cf., Anderson et al. 1986).

Fire. Our high-resolution analyses of macroscopic charcoal at four sites (Foster et al. In prep) exhibit stratigraphic changes in background levels and the frequency of charcoal peaks suggesting that fire was regionally heterogeneous (Fig. 5). For example, charcoal levels for Blaney's Pond on Naushon Island and Duarte's Pond on Martha's Vineyard are high during the late glacial and early Holocene and drop during the mid to late Holocene, perhaps due to the isolation of these islands with rising sea-level. Both Deep and Umpawaug Ponds feature declines in charcoal influx with major oak declines, despite the varied timing of these events (i.e., 5500 yr BP at Deep and 4200 yr BP at Umpawaug; Fig. 5).

Nitrogen Cycling. The abrupt alteration of an ecosystem's N cycle by disturbance (e.g., Vitousek and Reiners 1975) may be detected by measuring $\delta^{15}N$ in lake sediments, as demonstrated by our collaborative work on land-use impacts (McLauchlan et al. 2007) and primary succession (Shuman et al. in prep). We propose to measure $\delta^{15}N$ across high resolution sediment records to examine the magnitude of biogeochemical responses to rapid vegetation change. Based on our ecosystem studies on modern hemlock and oak declines (from hemlock woolly adelgid and fall cankerworm respectively; Orwig et al. 2008) we expect that rapid tree mortality will produce transient $\delta^{15}N$ shifts as nitrate and ammonium are mobilized and leached from the system (Vitousek and Reiners 1975; McLauchlan et al. 2007). In contrast, we expect no disruption of N cycling when forests change gradually through species replacement (Jeffers et al. 2011). In association with our analyses of rates of change, insects, fire, and land use, the $\delta^{15}N$ data should distinguish between these contrasting processes (cf., Robinson 2001) and improve our mechanistic understanding of the declines.

New datasets regarding insects, fire and nitrogen could be used to evaluate three hypotheses (Fig. 2) about Holocene ecosystem transitions:

H_0 – Ecosystem regime shifts that are as fast or faster than associated climatic changes require an additional trigger, such as insect defoliation or fire. This hypothesis (Fig. 2) is widely accepted, but should be tested by comparing evidence from insect remains, sedimentary charcoal, and $\delta^{15}N$ shifts with the locations, timing, and rates of vegetation change. (Five closely-spaced ^{14}C ages with-in each core with detailed pollen analyses will constrain rates and timing of changes; Blauuw et al. 2004).

H_1 – Some ecosystem regime shifts may not require additional triggers. Even in cases of regionally synchronous regime change (i.e., the classic hemlock decline) the transition may have not required additional triggers (Fig. 2 – H_1 B). Compositional change in the vegetation may have been facilitated by climate or land-use drivers via canopy turnover and thus may also not be associated with strong signals in sediment biogeochemistry.

H_2 – Mosaics of ecosystem change with spatially varied rates, timing, and magnitudes may result from a spatial mosaic of triggers. Disturbances such as insect outbreaks and fires produce spatially heterogeneous effects. Consequently, if triggers were required to produce ecosystem regime changes, the timing of the changes may vary even across sites with similar climatic histories (Fig. 2 – H_2 B). In this case biogeochemical changes would also not be synchronized across sites.

Tests of these hypotheses will require analyses of the following:
Sedimentary insect remains. We will quantify insect remains in lake sediments and in four small hollows (i.e., two inland and two on the coast; Foster and Zebryk 1993) where hemlock or oak was abundant; these small basins should collect insects from nearby trees.
*Sedimentary charcoal***.** We will increase the density of charcoal analyses and analyze contiguous sediment samples to quantify fire-return intervals (cf. Long et al. 1998) for 10 lakes in association with high-resolution pollen and closely-spaced radiocarbon analyses.
Nitrogen isotopes. We will analyze closely-spaced sediment samples from 10 lakes (approximately 100 samples per lake across major transitions; cf., McLauchlan et al. 2007; Jeffers et al. 2011), and will conduct a limited number of compound-specific analyses to ensure that diagenesis and complex sediment composition do not complicate results (e.g., Enders et al. 2008).

2) What are the patterns of Holocene climate change in New England across time and space? Are the changes synchronous or asynchronous regionally? Do they coincide with vegetation shifts?
Our recent work has demonstrated that a series of severe droughts across New England during the middle Holocene were driven by orbital changes and ocean-atmosphere responses (Shuman et al. 2012) and

likely initiated and sustained the decline of hemlock 5500-3000 yr BP (Shuman et al. 2009a; Newby et al. 2011; Marsicek et al. 2012). However, our temperature reconstructions depict a spatially heterogeneous climate with middle-Holocene warming inland and cooling at coastal sites where oak declines and beech increases (Fig. 5; Marsicek et al. 2012). Oxygen isotope data from a New York lake indicate that an abrupt shift in atmospheric circulation 5500 yr BP may coincide with these declines (Fig. 4A; Kirby et al. 2002). Meanwhile, oxygen isotopes from a West Virginia cave suggest that atmospheric circulation over eastern North America shifted abruptly at ca. 4200 yr BP (Fig. 4B; Hardt et al. 2010) when oak decreases rapidly in the western portion of our study area (Fig. 4D). Other lake records show more gradual changes at the same time (Zhao et al. 2010).

The hypotheses (H_0-H_2) described above with respect to triggers also have expectations about ecosystem drivers, which we will analyze in terms of climate history:
H_0 – Climatic changes will have been slower than observed ecosystem regime changes.
H_1 – Abrupt climate changes or extreme climate variability drought (Fig. 1) will have coincided with observed ecosystem regime shifts and facilitated these change even in the absence of specific triggers.
H_2 – Climate changes will have had varying rates and timing across the region (Fig. 2 – H_2 A).

To evaluate these expectations concerning regional climate dynamics, we propose the following analyses:
Combined hydrogen and oxygen isotope analyses. Isotopes in natural waters can track changes in the temperature of precipitation (Dansgaard 1964). Therefore, to improve interpretability of the existing regional isotope records we will build on a duel isotope analysis by Shuman's recent Ph.D. student, Anna Henderson, which combined oxygen isotopes from lacustrine carbonates with hydrogen isotopes from specific organic compounds in the lake sediment to separate the evaporative and source water effects on individual isotope time series (Henderson et al. 2010). Lakes in a belt of marble bedrock in western Massachusetts provide an opportunity to conduct such an analysis.
Lake-level reconstructions. Lake-level reconstruction techniques employed on Cape Cod (Marsicek et al. 2012) will be used to constrain the spatial patterns of changes in moisture availability that correlate well with existing vegetation histories (Shuman et al. 2009a; 2012; Marsicek et al. 2012).

3) What is the role of human activity (fire, land clearance, horticulture) in shaping vegetation dynamics? The interpretation that prehistoric land-use played an increasing role in landscape dynamics through the Holocene is prevalent in historical, scientific and popular literature and exerts a strong influence on modern conservation practices especially the use of prescribed fire (Cronon 1983, Abrams 2002, Pyne 1982, Mann 2002) and yet there has never been a robust analysis of relevant archaeological and paleoecological data on the subject. The hypotheses (H_0-H_2) described above also have expectations about cultural drivers of ecosystem change:
H_0 – Cultural changes will have been slower than observed ecosystem regime changes.
H_1 – Abrupt changes in land-use, including the use of fire, will have coincided with observed ecosystem regime shifts and facilitated wide-spread regional change.
H_2 – Cultural changes will have had varying rates and timing across the region (Fig. 2 – H_2 A).
To test these expectations, we will evaluate both direct (archeological) and indirect (e.g., fire history) evidence of cultural changes at the regional and landscape scales as explained below (see Fig. 3, 6).

C. Testing Hypotheses about the Role of Humans and Disturbance in Ecological Dynamics
Our collaborative ecological and social research (Duranleau 2009, Foster and Aber 2004, Chilton and Rainey 2010) positions us to produce a novel regional synthesis as one critical element of the proposed study on ecological dynamics and regime shifts. This synthesis will inform basic ecological questions concerning interactions among climate, disturbance and human activity in ecosystem dynamics; provide a landscape and regional test of the hypothesis by Munoz et al. (2010) concerning the link between environmental change and cultural development in northeastern North America; position our

archaeological group to apply new ecological perspectives to their research; and inform modern land management practice by our private and public conservation partners in the region.

This proposed work is informed by perspectives emerging from our coastal and regional studies:

- New England Indians were hunter-gatherer-collectors throughout the Holocene; maize horticulture provided a minor but increasing supplement before contact (Chilton 1999, 2001, 2010; Chilton et al. 2009, Duranleau 2009; cf., McBride 1990, Little and Schoeninger 1995, Mulholland et al. 1998).
- Broad continuity and similarity in site use, activity and subsistence patterns existed across coastal New England – New York and perhaps much of New England (Duranleau 2009, Herbster and Chilton 2002, Chilton and Doucette 2002a, Chilton 2010, Doucette 2003, 2009; cf., Dincauze 1990).
- On the coast, variations in site density (and thus human population) parallel climate and vegetation changes, with peaks in the Late Archaic and Late Woodland and a trough in the Early and Middle Woodland periods (Fig. 5; Duranleau 2009, Chilton 2010). These results support the Munoz hypothesis.
- Major questions persist concerning the role of human land use and fire in structuring the vegetation (Parshall and Foster 2002, Parshall et al. 2003, Foster and Motzkin 2003, Oswald et al. 2010).

In assembling the relevant data to address our major research questions (above) and the role of humans as drivers of ecological responses and dynamics, we will also address the following hypotheses concerning the relationships between cultural development and environmental dynamics:

***H_0* - Progressive Cultural Development and Influence over the Environment**. This widely held perspective (cf., Snow 1980, Ritchie 1969, Dincauze 1975, Bragdon 1996, Day 1953, Cronon 1983, Pyne 1984, Denevan 1992, Krech 1999) holds that cultural development paralleled improving technology (e.g., for hunting, fishing, food processing, cooking), diversification of the resource base and emergence of horticulture and exotic cultigens (maize, squash, beans) and was accompanied by: increases in people, sites, sedentism and village development; regional differentiation in cultural patterns (e.g., coastal, interior wetland, riverine and upland; northern versus southern); and increasing impacts of humans on ecosystem patterns. Expected support for this hypothesis includes:

Archaeological Sites (proxy for population size): progressive increase in numbers; shift in geographic location and activity patterns ultimately leading to horticulture; increasing sedentary versus seasonal use.
Pollen (proxy for ecosystem patterns): Progressive shift from climatic to cultural control of vegetation with increasing fire, wood consumption, forest clearance and horticulture (cf., Cronon 1983). Long-term decline in fire-sensitive and mature forest trees (e.g., beech, hemlock, red maple); increasing early/mid-successional (oak, pine, birch), openland (graminoids, shrubs, ragweed, weeds) and cultivated taxa (e.g., maize, *Chenopodium*); increase in sedimentary nitrogen and erosional material.
Charcoal (proxy for fire): Progressive increase in charcoal abundance, frequency and peaks reaching a maximum during the Late Woodland period of forest clearance and increasing horticulture.

***H_A* - Cultural Continuity, Response to Environmental Change with Minimal Ecological Impact.** Recent studies assert that despite meaningful cultural and material change relatively minor shifts occur in hunter-gatherer-collector subsistence patterns, land use or human impacts through the Holocene (cf., Bernstein 1993, 2006, Chilton 2000, 2010, Duranleau 2009, Hart 2009a, Herbster and Chilton 2002, McBride 1995, Motzkin and Foster 2002, Munoz et al. 2010). Human population were responsive to climate and vegetation changes, but exerted little impact on the environment and exhibited minor regional differences in settlement and subsistence patterns. Expected evidence includes:

Archaeological Sites: continuity of site use and patterns; variation in population/site density with climate and vegetation changes (Fig. 5D; e.g., increasing 5000-3000 yr BP with greater mast species and declining when cool, moist ca. 3000-1000 yr BP); regional variation in site density related to resources, but modest variation in subsistence patterns; no evidence for intensive horticulture or villages.

Pollen: changing with climate trends including rapid dynamics with natural perturbations with regional patterns controlled by climate and soils; dominance by mature forest taxa until European settlement; no evidence for deforestation, openlands, horticulture, increasing nitrogen or erosion before contact.
Charcoal: variation with climate and vegetation; landscape and regional variation associated with vegetation and the environment not humans; no progressive increase before contact.

H_B* - *Cultural adaptation is context-specific in reaction to environmental and cultural conditions. A Darwinian perspective allowing for human agency and impact in models of ecological relationships and suggesting that humans adapt to conditions by choosing from possible alternatives (Hart 1999; see also Chilton 2005, 2010), some of which leave a stronger archaeological and ecological signal than others.

Archaeological Sites: variation in size and site use across different ecological and cultural settings; punctuated changes in site density not necessarily related to climate or vegetation; temporally and spatially variable environmental impacts.
Pollen: regional vegetation controlled by climate and soils but modified in some landscapes by human activity; localized evidence for changes in aquatic conditions and sediments with human activity.
Charcoal: charcoal abundance, frequency and peaks variable temporally and regionally with contrasting vegetation and environment and periodic human management of the landscape.

Fig. 6. *Synthesis and analysis of over 2000 archaeological sites from coastal New England-NY provide models for the proposed regional study and indicate substantial continuity in site use through the Holocene (Duranleau 2009).*

To address our complementary hypotheses about ecological and cultural dynamics requires an integrated analysis of cultural datasets at scales and resolution commensurate with the biophysical data. We will compile and analyze existing archaeological data at two scales: regionally for Massachusetts and in three contrasting cultural landscapes (Fig. 3): the *Taunton Basin*, a near-coastal lowland; *Martha's Vineyard*, a habitat-rich island; and *Deerfield Valley*, an inland river valley. Statewide analysis of approximately 5000 sites will apply the protocol from Duranleau's (2009) highly successful coastal synthesis of 2000 sites (Fig. 6) to: (i) enable cross-discipline analyses of geographical and temporal variation in site density and ecosystem patterns across biophysical and cultural gradients; and (ii) to provide a focused test of the Munoz et al. (2010) hypothesis of linked ecological-cultural dynamics. The landscape analyses will: synthesize rich site information from the three intensively studied and contrasting landscapes to (i) provide interpretations informed by the regional analysis and high resolution paleoecological records, and

(ii) support a novel intraregional comparison of cultural landscapes that contrast in climate, geomorphology, aquatic environments, vegetation, distance from the coast and resources (cf., Bragdon 1996). This two-tiered approach will answer major questions concerning relationships between land use and ecological dynamics.

The state-wide data will be compiled from the Massachusetts Historical Commission (MHC) and analyzed temporally and spatially. For the three landscapes data available to Chilton and Doucette will be integrated with all extant records from MHC, researchers, museums, CRM firms (approximately 200 sites in each). For each we will: (i) examine site and landscape attributes in terms of physical and cultural aspects; (ii) determine site function, human response and impacts through site density, seasonality and faunal and archaebotanical analysis, and (iii) identify regional cultural similarities and continuities as well as differences among groups in these contrasting environments (Doucette 2003). All data will be inventoried by time period, entered into a GIS database, and characterized by factors above.

The three landscapes to be analyzed include:
*Taunton River Drainage Basin***.** The gentle TRDB terrain includes extensive wetlands, intervening upland habitats and small tributaries variably influenced by saltwater and tidal impacts (Fig. 3) that support diverse vegetation and resources. The TRDB has been a focus for archaeological research for the past 70 years (Thorbahn 1984; Hoffman 1991; Mahlstedt and Johnson 1982; Doucette and Mair 2000). The lower TRDB has been rich in wetland resources continuously for 10,000 years (R. Webb et al. 1993; Newby et al. 1994, 2000) and experienced relatively stable land-use through this period (Thorbahn 1984). The landscape was a significant core settlement area based on diverse resources including large runs of anadromous fish and served as a major corridor for travel and communication between coastal and inland areas. Hundreds of sites date to the PaleoIndian through Contact periods including some of the largest Archaic sites in New England: Peace Haven, Titicut, Seaver Farm, Annasnappet Pond, and Wapanucket (Athearn et al. 1980; Robbins 1967, 1980; Doucette and Cross 1997; Doucette 2003; Robinson 1996).

Martha's Vineyard. Comprised of two moraines, intervening outwash plain and large coastal ponds, the island supports diverse habitats that differ in striking ways from TRBD. Through progressive sea level rise the island's extent, configuration, groundwater table, and pond and wetland abundance have changed significantly since its separation from the mainland ca. 6000 yrs BP. The pre-contact history is well known due a century of study (Guernsey 1915, Byers and Johnson 1940, Huntington 1969, Ritchie 1969, Anthony et al. 1980, Bouck et al. 1983, Perlman 1976; Donta et al. 1993, Macpherson and Cherau 2002; Doucette and Chilton 2006; Herbster and Doucette 2006, 2008a-c, 2009; Doucette and Herbster 2008; Herbster and Flynn 2011, Mulholland et al. 1998, 1999a, 1999b; Herbster and Cherau 1999, 2002). Recent projects have advanced a close collaboration between archaeologists and the resident Wampanoag population, whose ancestors lived on the land over the entire period of human occupation.

Deerfield River Valley. This confluence of the Connecticut River Valley and Deerfield-Miller's River Valleys served as a major transportation route through prehistory (Paynter and Chilton 2009) and supported Paleo-Indian to Late Woodland and 17th century sites (Chilton et al. 2000, 2005, Chilton and Hart 2008). The Deerfield River floodplain offers rich bottomland, a more productive and warmer environment than the surrounding uplands and protection from the more flood-prone Connecticut River. The Deerfield Valley has been the locus of study of archaeologists at UMass Amherst including the archaeology Field School for the past 30 years who collaborate with many historical organizations and specialists including Historic Deerfield, Inc., and the Pocumtuck Valley Memorial Association. The rich archaeological and historical record affords a detailed synthesis of the geomorphological, botanical, and cultural histories within the state-wide record and in comparison with other landscapes.

STUDY DESIGN

This project will add strategic new records to the existing paleoecological network to define climate, vegetation, and disturbance patterns at subregional and landscape scales for comparison with each other and with our novel archeological synthesis. We will analyze sediment records from small lakes (<10 ha) in the three areas – Cape Cod and islands, coastal lowlands, and interior uplands – embracing the three archaeological landscapes (Fig. 3, 6). On the **Cape Cod and islands** we will add two lakes (Uncle Seth's Pond, Martha's Vineyard; Fresh Pond, Cape Cod; cf., Parshall et al. 2003) to the existing array (Dunwiddie 1990, Winkler 1985, Foster et al. 2002, 2006, Marsicek et al. 2012) to address the timing, rate, and landscape-scale pattern of the mid-Holocene oak decline. Analyses of two small basins (Quissett Hollow, Cape Cod; Pimpneymouse Pond, Martha's Vineyard) will reconstruct stand-scale forest dynamics and insect outbreaks. Two **coastal lowland** sites (Hobomock and Cain Ponds in the Taunton Basin) will link paleoecological and archaeological data, and together with Oliver and Sleepy Hollow Ponds in coastal northeastern MA will help define the geographic pattern of the mid-Holocene coastal oak decline and inferred cool interval. In the **interior uplands,** Green and Wickett Ponds (cf. Fuller et al. 1998; Francis and Foster 2001) near the Deerfield Valley will link paleoecological and archaeological data while two small basins (Dead Frog Pond in the Deerfield Valley, Fuller et al. 1998; Hemlock Hollow in north-central MA, Foster and Zebryk, 1993) will yield local records of forest dynamics and insect activity. Sediments from Green Pond in the Deerfield Valley and Mansfield Pond in the Berkshires of western MA will support key inland paleoclimatic analyses for comparison with our datasets generated at coastal sites on Cape Cod (Marsicek et al. 2012) and near the Taunton Basin (e.g., Shuman et al. 2001; 2009; Huang et al. 2002). The archeological syntheses at both the regional and landscape scales embedded within our paleoenvironmental data network will provide a critical context for evaluating cultural-ecosystem-climate interactions (Fig. 3, 5).

Field and laboratory methods. We will collect 1-2 sediment cores from each site and for two lake-level sites (Mansfield and Green) will use ground-penetrating radar and a transect of several additional cores to determine the position of the shallow, littoral zone at different points in time (cf. Shuman et al. 2001, 2005, 2009; Newby et al. 2009, 2011). Cores will be dated with accelerator mass spectrometry (AMS) ^{14}C analyses of plant macrofossils at approximately 1000-year intervals, but multiple dates will be obtained around the hemlock and oak declines to determine their timing and rates precisely (e.g., Blaauw et al. 2003, 2004). The ^{14}C age estimates will be calibrated to calendar years (cf., Reimer et al. 2009), and we will use established Bayesian approaches (i.e., the Bacon software; Blaauw et al. 2004) to maximize age control using closely-spaced ages. For all cores we will measure magnetic susceptibility, bulk density, and organic content (percent loss-on-ignition at 550°C) at 1-5 cm intervals; these analyses will allow us to match parallel cores and identify stratigraphic features (Shuman 2003; Shuman et al. 2005). Samples will be prepared and analyzed for pollen and spores (Faegri and Iversen 1989) at 1-10 cm intervals, with exotic spores added to allow estimation of pollen concentration and influx values. Samples (in some cases form multiple or larger diameter cores to ensure adequate material) will also be analyzed for plant macrofossils, insect remains, and macroscopic charcoal at 1-2 cm intervals after soaking overnight in 10% KOH, sieving through 200 micron mesh, and using a dissecting microscope. Charcoal influx data will be analyzed to determine peaks above long-term background trends, allowing us to calculate fire return intervals (Long et al. 1998; Millspaugh et al. 2000; Gavin et al. 2003, Higuera et al. 2010).

Stable isotope analyses. To obtain a detailed time series of paleoclimatic variation we will follow the dual isotope analyses of Henderson et al. (2010) in which $\delta^{18}O_C$ ($\delta^{18}O$ of carbonate sediment) and δD_{PA} (δD of sedimentary palmitic acid, C_{16} n-acid) are determined (cf., Huang et al. 2002, 2004, Hou et al. 2006). Analyses of δD_{BA} (behenic acid, C_{22} n-acid) will be made to validate patterns in the δD_{PA} as both acids derive from aquatic sources and retain the isotopic signature of the original lake water (Gao et al. 2012; Hou et al. 2006). We will analyze $\delta^{18}O$ and δD in dual H and O isotope space to determine how lake water isotopic values compared with the global meteoric precipitation relationship (Dansgaard 1964; Rozanski et al. 1993) and assess the magnitude of evaporative enrichment of the heavy isotopes. Local hydrologically-influenced evaporative effects will be removed by calculating the intercept point between local evaporative trends and the global meteoric precipitation line (e.g., Gibson et al. 2002, Henderson and Shuman 2009, Henderson et al. 2010; Jahren et al. 2009). $\delta^{18}O_C$ analyses will be conducted at the UWyoming Stable Isotope Facility using a GasBench and Thermo Finnigan DeltaPlus XP continuous flow isotope ratio mass spectrometer (IRMS) to provide ~50 yr resolution at Mansfield Pond. For δD_{PA} analyses, a post-doc with experience in related techniques will be engaged in the work and given the opportunity to lead on the paleoclimate analyses. The free lipid component of the sediment will be extracted; the carboxylic acid fraction will be isolated and methylated. Silica gel column chromatography will remove hydroxl acids. Compounds will be quantified using a new Thermo DSQII GC-MS acquired via NSF MRI funding (Shuman, co-PI) with a Thermo Delta V stable isotope spectrometer with on-line GC-pyrolosis for final compound-specific hydrogen isotope measurements.

To provide a biogeochemical assessment of ecosystem response, we will measure sediment organic C and N content using a Costech EA 1108 Element Analyzer that interfaces online with a Finnigan Delta Plus XP to generate analyses of $\delta^{13}C$ and $\delta^{15}N$ of the organic matter. Using this approach, Shuman et al. (In press) found a >3 per mil $\delta^{15}N$ shift in lake sediments associated with primary succession; McLauchlan et al. (2007) found a similar magnitude shift associated with historic land-clearance and abandonment.

Statistical and Analytical Approach

The analysis will begin by securing complete time series of ecological responses, drivers and triggers to quantify the dynamics including rate of change, breakpoints, and variance and provide the means for interpreting them. Response variables will be the relative abundance of major taxa at individual sites and changing abundance of N isotopes and the variation in these records across geographical, ecological, and cultural gradients. The selection of drivers and triggers includes major factors identified by previous work: climate (temperature, precipitation, relative moisture balance, droughts), indirect indicators of land use (site or population density, cultural activity) and direct indicators of land use (fire, weed and grass species, AP:NAP, maize) and insects (head capsules). While the sampling intensity for all analyses is fine resolution by most standards (<50-100 years) for the focused analyses we will strive for 10-20 year intervals to be well within the lifespan of the dominant, long-lived tree taxa.

Our analysis will follow the approach of Bestelmeyer et al. (2011), including an objective evaluation of alternative states, examination of frequency distributions of response variables, and leading indicators, and analysis of response-driver relationships. In particular they found that: (i) response-driver regressions provided a key step for discriminating among mechanistic models and identifying case-specific response mechanisms; (ii) leading indicators must be carefully scaled to the time-scale of the biological response variable (e.g., lifespan of the organism); and (iii) evaluating site context in terms of broad-scale processes and gradients provides important insights. The specific analyses will include five steps: (i) Breakpoint analysis (Zeileis et al. 2002) to detect transitions in the time series with breakpoints identified using a combination of cumulative sum (CUSUM) plots, changes in Bayesian Information Criterion (BIC) and residual sums-of-squares (RSS), and the F-statistic (Zeileis et al. 2002); (ii) Frequency histograms to evaluate the existence of alternative states with alternative states indicated by bimodal frequency distributions of biological response values (Scheffer and Carpenter 2003); and (iii) Moving window analysis of temporal variance to detect increased variance, which may precede the onset of abrupt transitions (Scheffer et al. 2009; Brock and Carpenter 2010; Carpenter et al. 2011); (iv) Changes in driver-response relationships before and after transition breakpoints to reveal whether specific cases match general mechanistic models. For example, different model parameters (such as regression slopes) prior to and following the identified breakpoint provides evidence for hysteresis (Bai et al. 2010); (v) Context for individual sites will be provided by the range of time series across the study region and insights afforded from inter-site comparisons as well as regional to broader-scale information.

INTELLECTUAL MERIT

Substantial intellectual merit derives from the investigation of regional-scale dynamics related to (i) significant climate change, including numerous severe climatic events (droughts); (ii) major cultural changes including shifts in population size, less well understood changes in hunting-gathering-collecting or horticultural practices and the abrupt shift from native to European culture; (iii) poorly resolved changes in fire regimes; and (iv) purported outbreaks of insects. These dynamics provide highly relevant analogs to many processes confronting ecosystems and society today. The proposed work will yield novel insights into the rates and magnitudes of changes in both drivers/triggers and ecosystem responses and may support proactive detection, mitigation or management strategies for managing transitions and, where possible, adjustments to drivers.

The study will apply emerging analytical approaches to examine abrupt changes and regime shifts and thereby advance this critical area of ecological theory and study. The work will also contribute substantially to answering important questions in paleoecology: (1) Was the 5500 yr BP hemlock decline generated by abrupt climate change, insect outbreaks, or a combination of factors? Are earlier and subsequent dynamics in hemlock indicative of similar dynamics? (2) What is the geographical extent and spatial pattern of response of the synchronous decline in oak? Does this parallel event represent the response to a coastal anomaly within a broader climate signal?

The vast majority of paleoecological studies have dealt with the land-use component of global change in an incidental fashion; however, land-use requires equivalent robust treatment as climate and other biophysical drivers of change. By integrating humans into this comprehensive study we will resolve looming questions concerning both long-term and abrupt dynamics observed millennia before and through the period of European settlement. For decades substantial disagreement has existed concerning the role of fire and pre-European forest clearance and horticulture in driving vegetation dynamics. While studies have argued for an active role of humans through the Holocene (Cronon 1983, Day 1953; Krech 1999; Delcourt et al. 1997), others have countered that the evidence for pre-European land use is slight. The recent paper by Munoz et al. (2010) supports prior assertions that the major changes in human activity follow rather than drive ecological dynamics, which are linked to climate. To resolve the relationships we will integrate multiple scales of understanding of both ecological and cultural dynamics, with benefits to biophysical and social science.

BROADER IMPACTS

We are committed to utilizing our strengths in ecological, biophysical and social science to advance broad impacts in three areas where we have a strong track record: (i) interdisciplinary training at undergraduate, graduate, postdoctoral and mid-career levels; (ii) communication through diverse media to broad audiences; and (iii) environmental and conservation policy. These efforts will be advanced through institutional strengths: Harvard Forest Programs in Science and Policy Integration, Program on Conservation Innovation, Summer Research in Ecology (REU), Bullard Fellowship Program and Archaeology and Paleoecology Field School; the new collaboration between the LTER Network and the MBL Logan Journalist Program; Emerson College undergraduate program in Science Communication; and graduate programs at the Universities of Wyoming and Massachusetts. These activities will be enhanced by an annual two-day summer research forum of all investigators and students at the Harvard Forest and quarterly video-based meetings of the co-investigators.

Integrated Interdisciplinary Training. For undergraduates an interdisciplinary module will be developed in the HF Summer (REU) Program for three students working at the interface of paleoecology and archaeology; this 25-year-old program for 30 students offers engaged mentoring and strong record of student publication and advancement in science. The questions, approach, results and implications from this project will also be integrated into two field seminars for Harvard undergraduates taught by Foster: *Insights from Global Change Research* and V*isualizing Past and Future Change in New England*.

Graduate students at UMass will advance the archaeological synthesis with Chilton and Doucette, will participate in research team meetings, and will assist Doucette in coordinating the six-week Archaeology and Paleoecology Field School at the Harvard Forest. Wyoming offers highly effective post-doctoral mentoring that will enable that individual to be fully integrated into that research environment and the entire project. Finally, to advance project integration and their own careers two of the co-investigators (Shuman and Doucette) will apply for year-long Harvard University Bullard Fellowships.

Outreach and Broader Communications. Commitment by the Harvard Forest and co-investigators to engage broad audiences of decision makers, managers, conservationists and the public will motivate many activities. In year one the LTER-MBL Logan Journalism program will host a dozen leading journalists for two-weeks at the Harvard Forest for hands-on exposure to research. Strong interest surrounding topics in this study (e.g., forest collapse, abrupt climate change, species loss) will encourage journalist collaboration and development of resulting media. We will build on past success integrating Emerson College film/media majors in our summer program to develop additional video products for the project (*see* Secrets of the Mud – The Hemlock Mystery; http://www.cctv.org/watch-tv/programs/secrets-mud-hemlock-mystery). Harvard Forest is working with two professional videographers to develop short videos highlighting current research and will plan at least one sequence on this project. Finally, Foster, and Oswald have a contract with Yale University Press for *Hemlock: A Forest Giant's Life in the Shade and on the Edge,* a volume on the history, ecology and future of hemlock that will integrate this research.

Science—Policy Linkages. The project has major relevance to many modern concerns regarding invasive pests, fire and its management, species loss, and global change. Consequently, we are advancing at least four avenues of communications and engagement with policymakers, decisionmakers and managers in collaboration with colleagues Kathy Lambert and Jim Levitt of the Harvard Forest Programs on Science & Policy Integration and Conservation Innovation: (i) The LTER project on Future Scenarios of Climate and Land Use Change, which is engaging diverse stakeholders (e.g., local land managers, regional/national conservation leaders, and state environmental secretaries) in modeling New England-wide scenarios for 2015-2065; (ii) the Wildlands and Woodlands Policy group of major environmental, land conservation, natural resource production and recreational groups; (iii) the Northeastern Science and Policy Consortium being advanced by the Cary Institute of Ecosystem Studies, MBL Ecosystems Center, Hubbard Brook Research Foundation and Harvard Forest; and (iv) leading conservation organizations (The Nature Conservancy, The Trustees of Reservations) where Foster is a board member. In each venue we will communicate insights from this study to advance policy, decision-making and action.

OVERVIEW OF RESEARCH RESPONSIBILITIES AND SCHEDULE

Foster will serve as project PI and will coordinate all components of the research in association with the administrative, research and education teams at the Harvard Forest. He will organize bimonthly teleconferences and annual workshops for the collaborators to ensure completion of all research tasks. He will also integrate the project with related studies at Harvard Forest (HF) and other institutions, and will actively apply the resulting information to regional and national needs in global-change policy, restoration ecology, and conservation design. Foster, Oswald, Shuman and students will participate in field sampling during Years 1 and 2. Shuman and his post-doc will have primary responsibility for the paleoclimate component of the study, including analysis of δD, $\delta^{18}O$, $\delta^{15}N$ and core-transect samples (Years 1-3). Oswald will provide oversight for the paleoecological analyses conducted at HF, including pollen, organic content, charcoal, and insects (Years 1-3), and will oversee Emerson College undergraduates working on this project via the HF REU program; we intend to seek supplemental funding to support those positions. Doucette and Chilton will assemble the regional and subregional archaeological data (Years 1-2), supervise the UMass graduate students participating on the project, and lead the analysis and interpretation of the resulting dataset (Year 3). All collaborators will be involved in data syntheses at annual workshops and preparation of manuscripts (Years 2-3).