NEW SCIENCE, SYNTHESIS, SCHOLARSHIP, AND STRATEGIC VISION FOR SOCIETY

HARVARD FOREST LTER V 2012 – 2018

David R. Foster, Principal Investigator
Harvard Forest, Harvard University

Co-Investigators

Emery Boose Elizabeth A. Colburn Elizabeth E. Crone Aaron M. Ellison Clarisse Hart Kathy Fallon Lambert David A. Orwig Julie Pallant Pamela M. Snow Kristina A. Stinson	Harvard Forest, Harvard University
Dianna L. Doucette	Peabody Museum of Archaeology & Ethnology, Harvard University
Paul R. Moorcroft Andrew D. Richardson	Organismic & Evolutionary Biology, Harvard University
J. William Munger	Engineering & Applied Sciences, Harvard University
Adrien C. Finzi Lucy Hutyra Anne Short	Boston University
Brian Donahue	Brandeis University
Christopher A. Williams	Clark University
William V. Sobczak	College of the Holy Cross
W. Wyatt Oswald	Emerson College
Edward K. Faison	Highstead
Jerry M. Melillo	Marine Biological Laboratory
Jonathan R. Thompson	Smithsonian Institute
Jeffrey L. Blanchard Elizabeth S. Chilton Kristen M. DeAngelis Stephen DeStefano David B. Kittredge	University of Massachusetts
Serita D. Frey Scott V. Ollinger	University of New Hampshire
Eric A. Davidson	Woods Hole Research Center

Project Summary

Harvard Forest LTER (**HFR**) is a two decade-strong, integrated research and educational program investigating responses of forest dynamics to natural and human disturbances and environmental changes over broad spatial and temporal scales. HFR engages >30 researchers, >200 graduate and undergraduate students, and dozens of institutions in research into fundamental and applied ecological questions of national and international relevance. Through LTER I–IV, HFR has added historical perspectives, expanded its scope to the New England region, integrated social, biological, and physical sciences, and developed education and outreach programs for K-12, undergraduate, and graduate students, along with managers, decision-makers, and media professionals.

Intellectual Merit. The goal of HFR LTER V is to apply its site to regional-scale strengths in research, education, and outreach to address a fundamental research question: ***What will be the multiple and interactive effects of climate change, natural disturbances, biotic interactions, human land-use, and forest dynamics on landscape-scale ecosystem dynamics, processes, and services over the next 50 years***? This research will be pursued by applying long-term data from ongoing and new measurements and experiments through integrated scenarios analyses, which provide scientists and decision makers with a structured framework for understanding a complex world. Using models to link a range of scenarios describing plausible future conditions with external socio-ecological and environmental drivers, and endogenous constraints, the consequences of the interactive effects of multiple stressors on forest dynamics and ecosystem processes will be evaluated in terms of their effect on ecosystem services. This research is part of a larger effort, led by HFR, to incorporate regional land-use scenarios at all LTER sites. Advancing this agenda requires evaluating scenarios with: (i) A thorough understanding of historical, current, and potential human and natural processes that shape landscapes; (ii) A mechanistic understanding of biophysical drivers and ecological processes that couple these dynamics with ecosystem responses; (iii) A deliberative process for engaging stakeholders in the development of land-use scenarios; (iv) Simulations of changes in ecosystem structure, function, and pattern based on these scenarios that condition important ecosystem services; (vi) Evaluation of the simulations and reassessment of model results with long-term measurements and experiments and new observations; and (vii) Syntheses in publications and other media that fill critical knowledge gaps and address societally relevant questions.

Broader Impacts. HFR educational, outreach, and service activities form an integral part of the site's mission and research program. HFR's nationally recognized *REU-Based Summer Program* annually draws ~35 undergraduate participants (one-third from traditionally underrepresented groups) from > 600 applicants to provide individual mentoring in team-based interdisciplinary projects that regularly yield theses and peer-reviewed articles. The *Schoolyard LTER Program* offers teacher-development workshops in data analysis and field techniques and engages > 3,000 K-12 students from 56 schools in year-round, hands-on research projects developed by HFR. LTER cross-site collaboration is advanced through: (i) Annual g*raduate and post-doctoral student* summits across the four northeastern LTERs; (ii) The *LTEaRts* program that is engaging students and a broad public in the appreciation of ecological science; and (iii) The Northeast Science Policy Consortium initiated by Harvard Forest, The Cary Institute, Hubbard Brook Research Foundation, and MBL Ecosystem Center. The *Harvard Forest Science & Policy Integration Project* and Communication Manager build connections and promote the exchange of science insights among researchers, decision makers, media professionals, and students of all ages.

HFR LTER V: New Science, Synthesis, Scholarship, and Strategic Vision for Society

I. Results from Prior LTER Support (with 10 notable publications highlighted in blue; see http://harvardforest.fas.harvard.edu/notable-hfr-publications-lter-4 for details)

Harvard Forest LTER (**HFR**) is a two decade-strong, integrated research and educational program investigating responses of forest dynamics to natural and human disturbances and environmental changes over broad spatial and temporal scales (Fig. 1). HFR's observations and experiments test fundamental ecological hypotheses; long-term studies continually illustrate that hypotheses derived from short-term studies, experience, or intuition are often rejected as unanticipated factors, events and processes alter trajectories of ecological dynamics. HFR engages >30 researchers, >200 graduate and undergraduate students, and dozens of institutions in research into fundamental and applied biophysical and ecological questions of national and international relevance. HFR generates synthetic publications, cross-site collaborations, and effective outreach to decision-makers that profoundly affect ecological and conservation thinking.

Major findings from LTER I-IV that will guide LTER V include:

- Historical legacies of land use and biotic conditions interact with long-term environmental change, and natural and human-induced disturbances to condition ecological patterns and processes (Fig. 2);
- Climate change and disturbance together can trigger abrupt ecological shifts by causing the loss of foundation species that control biotic and environmental conditions and ecosystem processes;
- Ecosystem trajectories have large inter-annual variability (Fig. 3);
- Strong biogeochemical resiliency to disturbance maintains ecosystem functions despite disturbance-induced changes in system structure (Fig. 4);
- Effective ecological interpretation and management depend on integrated research of human/natural systems through retrospective study, decadal measurements, experiments, and modeling; and
- Scientists must engage early with decision-makers to span the science and policy boundary.

In addition to making significant strides toward a multi-level understanding of forest ecology in New England, HFR has played a major role in LTER leadership, strategic planning, and network-wide studies; NEON and ULTRA planning; and state, regional, and national policy development.

Details

HFR LTER I (1988-1994) initiated site-based measurements of forest pattern and process and long-term experiments contrasting ecosystem responses to natural disturbance (hurricanes) and anthropogenic stressors (N deposition, climate change). **LTER II** (1994-2000) added historical, paleoecological, and landscape-scale analyses of land-use and natural disturbance, and incorporated inter-annual variation in experimental interpretations of forest, carbon, and nitrogen dynamics. **LTER III** (2000-2006) explored mechanistic understandings of inter-decadal dynamics of key ecosystem and atmospheric processes that control C and N cycling; identified how interactions among biotic agents (humans, pests, pathogens, plants, ungulates, and soil microbes), climate change, and disturbance can control forest structure and function; synthesized 15 years of results in a site volume and major publications; formed partnerships with local, national, and international public agencies and NGOs that develop policies for climate change and conservation; and integrated our education and research programs. **LTER IV** (2006-2012) expanded site and historical efforts with new observational, experimental, and modeling studies of site- and regional-scale dynamics related to forest harvesting and conversion, exotic organisms, and wildlife.

A. Decadal Large Experiments have compared responses to, and interactions among, natural and human disturbances and stressors to yield insights into ecosystem patterns and mechanisms. Biogeochemical resilience to experimental hurricane manipulation, soil warming, and N additions rejected the hypothesis that changes in forest structure are a good indicator of changes in ecosystem function[1]. This conclusion has been reinforced with measurements and experiments on hemlock decline due to the hemlock woolly adelgid (*Adelges tsugae*; hereafter "HWA") and harvesting[2]. Data from these long-term natural and manipulative experiments underpin studies proposed for LTER V of microbial, plant, and abiotic controls on ecosystem processes; model parameterization; and development of future land-use scenarios.

The *Hurricane Manipulation* rejected broadly accepted hypotheses of forest dynamics and "gap dynamics theory"[3] and emphasized the role of biological legacies in ecosystem recovery (Fig. 5). Despite 80% canopy damage 20 years ago, the survival of uprooted and damaged trees conferred resilience in composition, process, and environments in the hurricane simulation[4]; the dominant oak, mid-story red maple, and new cohorts of black birch should reach pre-disturbance level of basal area by year 30 and yet lag behind the dynamic control for decades[5]. This hypothesis will be tested during LTER V.

Chronic N Addition Plots simulate anthropogenic nitrogen deposition. 20 years of N additions increased forest floor and organic matter in hardwood soils; decreased microbial biomass and fungal:bacterial biomass in conifer and hardwood plots; showed higher ^{15}N recovery in soils than trees; and revealed microbial responses including decreased soil respiration and litter/wood decay[6],[7].

Soil Warming Experiments explore climate change impacts and feedbacks by raising soils 5° C above ambient and tracking C and N dynamics in six 5×5m plots (est. 1991) and one 30×30m "mega-plot" (est. 2003). Initial increases in soil organic matter (SOM) decay and CO_2 fluxes were transient[8],[9] due to a small labile C pool[10] and apparent adaptation of microbes.[11] Surprisingly, over five years, SOM decay rates and CO_2 fluxes have accelerated (Fig. 6a), with changes in the microbial community being one possible explanation. Increased C storage has been observed in the vegetation (Fig. 6b) and attributed to warming-induced increases in N availability (**Melillo *et al.* 2011**)[12],[13],[14]. We test these hypotheses in LTER V.

A *Soil Warming × N Addition Experiment* found season-specific responses of respiration and N mineralization that increased with both N and warming[15]. Overall, warming moderated negative effects of N on respiration and microbial biomass. N additions suppressed wood decay, warming had no effect, and the combination was synergistic. No change in the wood decay fungal community paralleled the lower decay rates in fertilized plots[16]. During LTER V, we will use this experiment to integrate results from the Chronic N Addition experiment and the Soil Warming experiments and to develop a more detailed mechanistic understanding of the long-term changes observed in these single-factor experiments (*cf.* **Finzi *et al.* 2011**)[17].

B. System-wide effects of the **Loss of Foundation Species** have been identified through integrated historical studies, natural experiments, canopy manipulations, and modeling. *Paleoecological Reconstructions* identified spatially and temporally heterogeneous patterns of regime shifts involving hemlock and oak, supporting a hypothesis that foundation species loss can be triggered in complex ways by rapid climate change interacting with biotic agents such as insects or pathogens (Fig. 2)[18],[19].

We *Mapped and Sampled Hemlock* across 86,000 ha and documented that regional declines from HWA are shaped by landscape conditions, climate, and logging[2]. Long-term plots show increasing deterioration and mortality in southern New England, but further north, HWA-infested forests remain healthy as cold temperatures have slowed HWA's spread and growth. Hemlock mortality was accompanied by a shift to black birch and red maple, and increased N availability and herb/shrub richness. Following logging, N mineralization rates and capture (NH_4, NO_3) were 3 – 20× higher in urban sites than in rural sites[20]. During LTER V, the CT-MA transect will be extended into southern Vermont and New Hampshire to document the range expansion of HWA as the regional climate warms (Fig. 1).

The *Hemlock Removal Experiment* (*est.* 2003; **Ellison et al. 2010**)[21] has documented strong consequences of hemlock loss including more variable air and soil temperatures that are warmer in summer and cooler in winter[22]. N losses increase, but not as rapidly as in urban hemlock stands[20]. The seed bank poorly reflects understory vegetation composition[23], but continual seed rain contributes much more to forest regeneration following hemlock loss than does the existing sapling bank[24]. C and N dynamics changed rapidly in logged plots but converged with girdled (HWA simulation) plots within seven years[25]. HWA infested the control plots in 2010; consequently in LTER V, the Hemlock Removal Experiment will allow us to explore the interactive effects of HWA and canopy damage[21].

Regional Modeling of HWA investigated: (1) past spread as a function of climate, geography, and insect dynamics (Fig. 7[26],[27]); (2) future spread with climate change[28]; and (3) impacts on regional C dynamics (Fig. 8; **Albani *et al.* 2010**)[29]. LTER V will use these results in future scenarios simulations.

Coastal Oak Mortality from defoliation and drought was investigated with NSF-RAPID funding using paleoecological methods, remote sensing, and permanent plots. Landscape-scale variation in damage was controlled by interactive effects among insects, forest type, edaphic factors, and land-use history. N capture in resin bags increased sharply in plots with > 60% oak mortality[30]. The dramatic mid-Holocene oak decline provided a good analog for this event, with regional mortality varying with substrate and climate (Fig. 2). The decline of foundation species like oak and hemlock by interactions between climate change and physical disturbances including insects, fire and humans will be explored further in LTER V.

C. Invasions and Range Expansions of native (*e.g.,* ungulate) and non-native species (*e.g.,* garlic mustard [*Alliaria petiolata*] and HWA) have been observed, manipulated, and modeled (Fig. 8). A long-term collaboration with USGS and UMass researchers showed that recolonization by moose and increases in deer are altering ecosystems more than any time in the past 250 years, with moose exerting a stronger impact on forest structure, tree growth and recruitment[31]. A graduate thesis and undergraduate project showed that history and land-use are better predictors than climatic or edaphic factors of the distribution and abundance of invasive plants[32],[33]. LTER V will incorporate different forecasts of range expansion and different scenarios of invasive species control into simulations of forest landscape change.

D. Multi-decadal Permanent Plots play a key role in documenting forest dynamics and biotic invasions, ground-truthing eddy flux and remote sensing studies, and validating models. Re-censuses of plots in Harvard Forest's *Pisgah Tract* extended 1920s data from old-growth forests uprooted in the 1938 hurricane and continue to provide context for interpreting results from the Hurricane Manipulation experiment. Rates of *Carbon Sequestration* (net ecosystem CO_2 exchange [NEE] and standing biomass; **Urbanski *et al.* 2007**)[34] increased in the 125-year-old EMS forest (Fig. 3) as the climate warmed, red oak biomass increased rapidly[*cf.* 35]; evergreen hemlocks extended the photosynthetically active period[36],[37]; and warmer temperatures lengthened the deciduous canopy season (documented by human and camera-based phenology records[38]). The 200+ year-old hemlock stand exhibited C uptake rates 65-100% of EMS, with greater photosynthetic capacity and NEE in spring and autumn and lower in summer[39],[40]. The fifth census of a 3-ha 100-year-old oak forest (est. 1969) revealed linear biomass increases, paralleling the flux records (Fig. 3). The flux and permanent plot data are widely used to constrain ecosystem models[41],[42]; simulation of C storage with a simplified process model led to the hypothesis that observed increases in uptake represent a fundamental ecosystem shift that includes higher C allocation below-ground[43]. Models also suggest that hourly to diurnal environmental variability has a marked effect on C and ecosystem dynamics[44]. These long-term plots and tower measurements will provide critical tests of hypotheses and evaluations for future scenario modeling in LTER V.

E. Automated Meteorological and Hydrological Stations continue to yield data that are critical for LTER syntheses[45] and illuminate complexities in water fluxes in headwater streams (Fig. 9). Investigations of the *Mobilization and Transport of Soil Dissolved Organic Matter* (DOM) showed that temperature changes and drought affected the mass and structure of DOM during soil–water infiltration, whereas rainfall intensity and frequency affected only the mass. C:N ratios of effluent DOM declined during successive events and drought. Lability incubations run concurrently with measurements of discharge, nutrient concentration, DO^{13}C, and DOC/DON showed that: dissolved organic nutrient concentrations increased long-term but not short-term consumption rates; there was no relationship between rate and DOC source or quality; there is a large recalcitrant DOC pool; and a large fraction of the DOC pool is exported downstream. A two-region model closely describes these time-series data[46].

The *HFR Meteorological* and *Phenology* datasets are most often downloaded and used by outside researchers (*e.g.*, **Richardson *et al.* 2006**)[47]; ULTRA, SIGEO and LTER V studies will utilize both extensively along with stream discharge data. Continuously collected meteorological data are posted to the HFR website in (near) real time via a field wireless network (Fig. 10), and submitted monthly to LTER ClimDB. Four stream and two wetland gages in two small watersheds provide continuous measurements of water level, discharge rate, and temperature, which are posted online and to HydroDB bimonthly. The HFR Snow Pillow (2009) measures water content of the snow pack. Hydrological sensor measurements continue to provide a motivating example for our Analytic Web project, which seeks to ensure reproducibility in scientific data analyses through the use of provenance metadata[48],[49].

F. HFR led the 2008 LTER **Future Scenarios of Landscape Change Working Group** to advance both LTER-wide synthesis and coupled human/natural studies at HFR. Follow-up activities included a HFR workshop (April 2009) for scientists from 16 LTER sites; a Science Council workshop (May 2009) to develop a LTER Scenarios Prospectus; an All-Scientist Meeting forum (September 2009) for 60 scientists; Science Council designation as a flagship LTER-wide project; a paper in the LTER 30-year BioScience issue[50]; two ESA symposia (August 2011); a HFR workshop for cross-site (HFR, CWT, NTL, HJA, BNZ) modeling of scenarios in major US forest regions (November 2010); two national stakeholder dialogues on socio-economic and biophysical drivers of US forest change (Heinz Center; National Council for Science and the Environment, February and March 2011); and NSF support to advance regional cross-site modeling. Modeling results from this synthesis for Massachusetts over the next 50 years indicate that land-use legacies and forest growth increased standing forest biomass by 49-112%; conversion and harvest reduced biomass by 18% and 4%, but climate change increased it by 13.5% (**Thompson *et al.* 2011**; Fig. 11)[51]. In November 2011, we met with leaders from the Massachusetts Office of Energy and Environment and regional NGOs to identify state-level scenarios for further exploration in LTER V.

G. A HFR team studied the **Attitudes, Behaviors and Decisions of Private Forest Owners** who own most of the forested land in the eastern U.S., including > 40,000 individuals in Massachusetts whose decisions on harvesting, development, and conservation strongly control forest dynamics[52]. Key findings include: resident and absentee landowners differ significantly in attitude[53], and informal sources of information (peer landowners, friends, family members[54]) are more important than professional sources, both locally[55] and nationally[56]. This work suggests that greater improvements in forest conservation and management will result from expanding existing social networks through investments e.g., in land trusts[57],[58],[59],[60] than through conventional outreach that relies on public and private professionals for technical assistance.

H. Regional Modeling and Remote Sensing. Building on LTER III hypotheses that relationships between foliar N and aboveground NPP are an extension of leaf-level photosynthesis-N relationships, we combined field measurements at LTER and Ameriflux networks with a new N detection algorithm[61] to show a positive relationship between canopy %N and maximum C assimilation rate, and between these variables and shortwave canopy albedo (**Ollinger *et al.* 2008**) [62],[63]. To interpret underlying mechanisms (which hold different implications for future global change) the C-N-albedo relationship was examined at local-to-regional scales through analysis of leaf- and canopy-level reflectance with variation in N and CO_2 (refs.64, 65), and by combining field data and a canopy radiative transfer model (SAIL-Prospect) to examine leaf, stem, and canopy traits influencing canopy spectral properties.[66] Motivated by high N retention in the N Addition Plots the *PnET-CN Model* was expanded to link C, N, and water cycles; vegetation physiology; and climate to analyze climate-change effects in the northeast (Fig. 11)[67]. Model development included a new SOM sub-model and improved simulation of trace gas emissions by coupling with the DNDC soil biogeochemistry model and incorporating isotopic ^{15}N fractionation. PnET-CN will be incorporated in the landscape simulations proposed for LTER V.

I. New research infrastructure developed during HFR LTER IV to be integrated into LTER V include:

- *35-ha SIGEO Forest Dynamics Plot* (all stems >1cm tagged), which encompasses the footprint of two eddy flux towers, hydrological and meteorological stations, and the NEON FIU and FSUs (Fig. 10);
- *High-capacity Field Wireless Network* (Fig. 10) and primary electricity to major experiments and towers;
- The renovated (in 2009-2010) *Torrey Analytical Laboratory* with a new, full-time lab manager.

J. Information Management and Technology. During LTER IV significant upgrades to the HFR information management system were completed (details in **§VIII.B. Information Management and Technology**) and the field wireless network to experimental sites was created.

K. Broader Impacts. HFR's nationally recognized *REU-Based Summer Program* annually draws ~35 undergraduate participants (one-third from traditionally underrepresented groups) from > 600 applicants. Students are individually mentored in team-based interdisciplinary projects that combine field and laboratory analysis with modeling. Social media encourage peer networking and long-term engagement with HFR among students, mentors, and alumni. Students regularly author theses and peer-reviewed articles from summer data. The *Schoolyard LTER Program* engages > 3,000 K-12 students from 56 schools in three year-round, hands-on research studies with protocols developed by HFR ecologists (Fig. 1). The program offers teacher-development workshops in data analysis and field techniques throughout the year. Participants regularly present at professional conferences[68], publish articles[69], and leverage additional grants from their Schoolyard work. *Graduate and post-doctoral student* involvement and cross-site collaboration in LTER increased through movement among labs and an annual gathering of the three New England LTER sites, which began at HFR in 2009. As part of the *LTEaRts* cross-site effort, four visual artists were hosted at HFR in LTER IV. Products include ecological art exhibitions for students and the public, a forthcoming book of photography, a series of video webcasts documenting long-term research, and exhibitions at the NSF, Ecological Society of America annual meeting, and LTER ASM.

Major policy synthesis documents were completed including the conservation outline "Wildlands and Woodlands: a Vision for the New England Landscape" and a set of regional policy recommendations for New England forests (**Foster *et al.* 2010**) [70],[71]. The Harvard Forest teamed up with Highstead, a CT-based environmental non-profit, many regional conservation organizations, and state and federal agencies to advance science-based conservation across New England. Scientists affiliated with the Harvard Forest, Cary Institute, MBL Ecosystems Center, Hubbard Brook Research Foundation, and four northeastern LTER sites formed the Northeast Science & Policy Consortium to facilitate similar work across the region. Expanded communications efforts led to strong public visibility for HFR research through earned media features in national outlets (e.g. *New York Times*, *Boston Globe*), a permanent exhibit and event series at the Harvard Museum of Natural History, and multiple online video projects[72]. Workshops and ongoing support for researchers interested in broadening their impacts resulted in strong growth in media contact and Congressional briefings by staff scientists and developed associated programs in Outreach and Education, Conservation Innovation, and Science & Policy Integration.

HFR scientists played leading roles in LTER and related national science efforts: LTER Executive Board (Foster, Boose), LTER Strategic Planning Committee (Foster, Frey), LTER Communications Strategic Plan (**Lambert 2010**)[73], LTER IM Executive Committee (Boose), LTER Education Executive Committee (Hart, Snow), Cross-site Synthesis Workshops (Ellison, Thompson, coordinators) and BioScience LTER Synthesis Issue (Foster, editor; Lambert, Thompson, Melillo, Boose, Hart, Kittredge, authors); NEON (HFR is the Northeast core site; Melillo and Ollinger, NEON Board; Frey, Chair, Northeast Science Advisory Committee; Frey, Microbial Biology Workshop), and Ameriflux (Munger, Steering Committee).

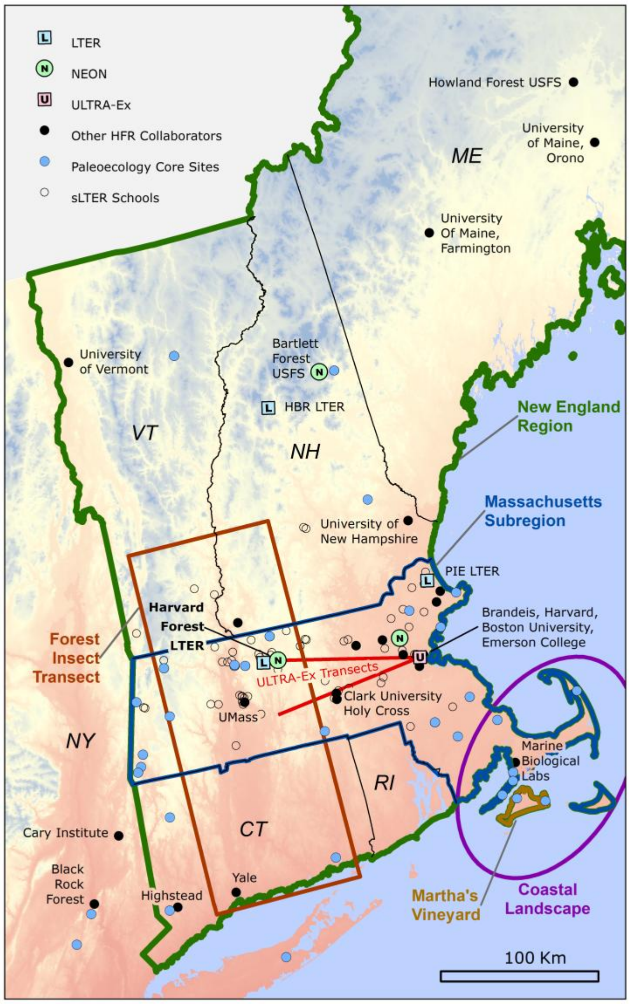


Figure 1. Elevation map depicting the location of the Harvard Forest site, coastal landscape, sub-regional (statewide and CT to VT-NH transect) and New England regional study areas. The Hubbard Brook and Plum Island LTER sites, major collaborating institutions and NEON relocatable sites are shown along with paleoecology coring sites and the 56 schools participating in the HFR sLTER program.

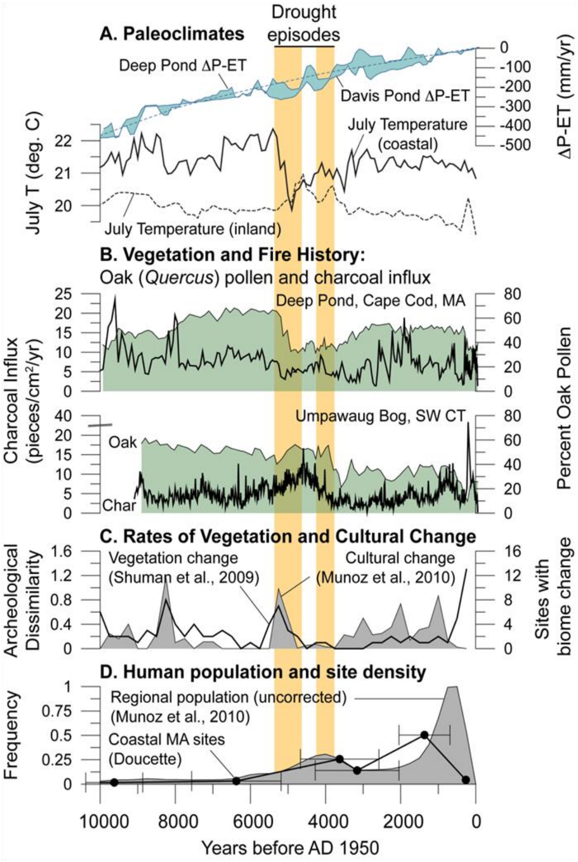


Figure 2. Potential relationships among rapid ecosystem dynamics, including the abrupt decline of oak, and paleoclimate drivers (A) including a long-term increase in effective moisture (precipitation minus evapotranspiration, P-ET) based on two lake-level reconstructions; two drought episodes that punctuate the trend (yellow bars); and coincident coastal cooling and inland warming. Ecosystem responses (B) include rapid oak and charcoal influx declines[18] 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 cultural activity and land use. Trends in our coastal site/population data (D) are consistent with those of Munoz et al.[178] and coincide with the climate anomaly from ca. 5.5-4 ka.

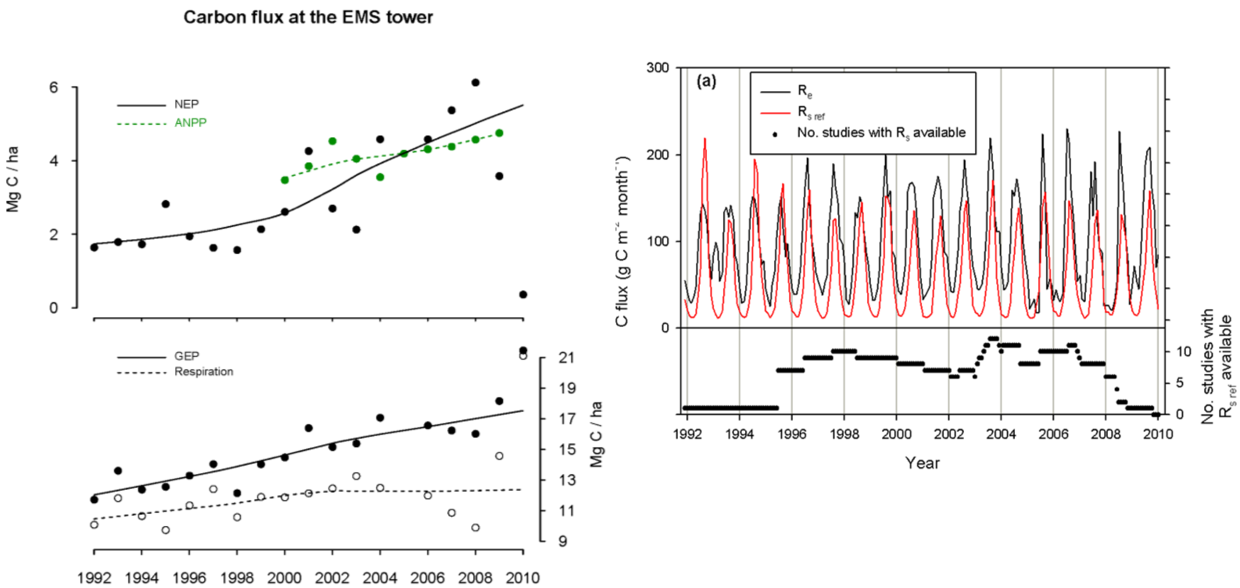


Figure 3. *Left above*: In LTER V permanent plots spanning more than six decades and the full range of edaphic, vegetation and historical settings in the HFR landscape will be used to broaden the record of carbon dynamics. Here the EMS record of annual net ecosystem production (NEP, solid line) is compared to above-ground net primary production (ANPP, green line) from plot data. *Left below*: Annual sums of gross ecosystem production (GEP) and ecosystem respiration (Re) are shown in solid and dashed lines[34]. GEP and R are estimated from measured NEP using the temperature response of nighttime NEP to fill in daytime R and summing to get annual R. GEP is the difference. *Right:* Seasonal and inter-annual variation in soil respiration (Rs) and EMS-tower derived estimates of Re. Rs is based on all measurements in control plots and observational studies at HFR. There is a consistent lag between Rs and Re in all years regardless of climate with the majority of Re accounted for by Rs in the mid- to late-growing season .

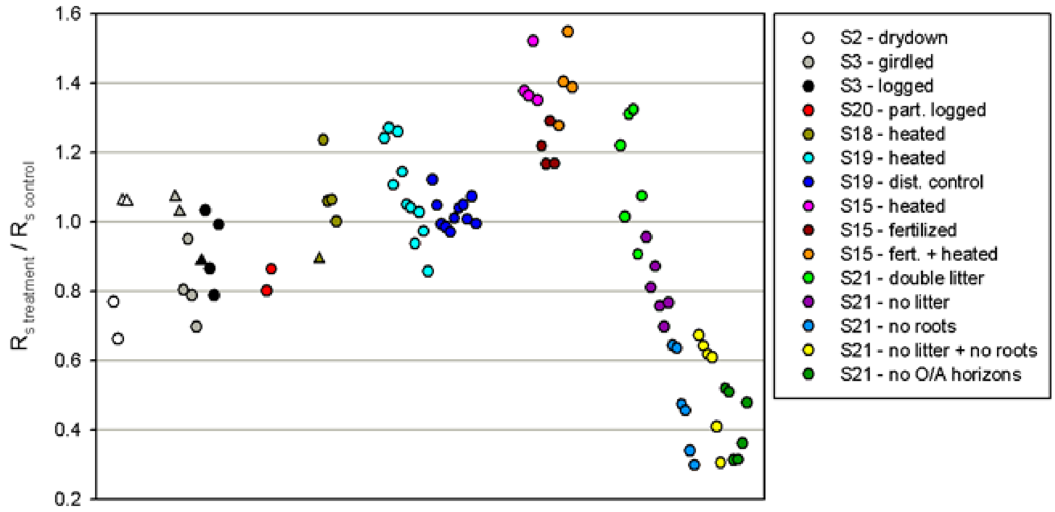


Figure 4. The response ratio of soil respiration (Rs) in treatments relative to control plots for various HFR LTER experiments. Values >1 indicate a stimulation. Values <1 indicated a repression of Rs. Experimental treatments can increase (warming, warming + N) or decrease Rs (N fertilization, dry down, girdling, logging) within about 50% of the value in the control plots.

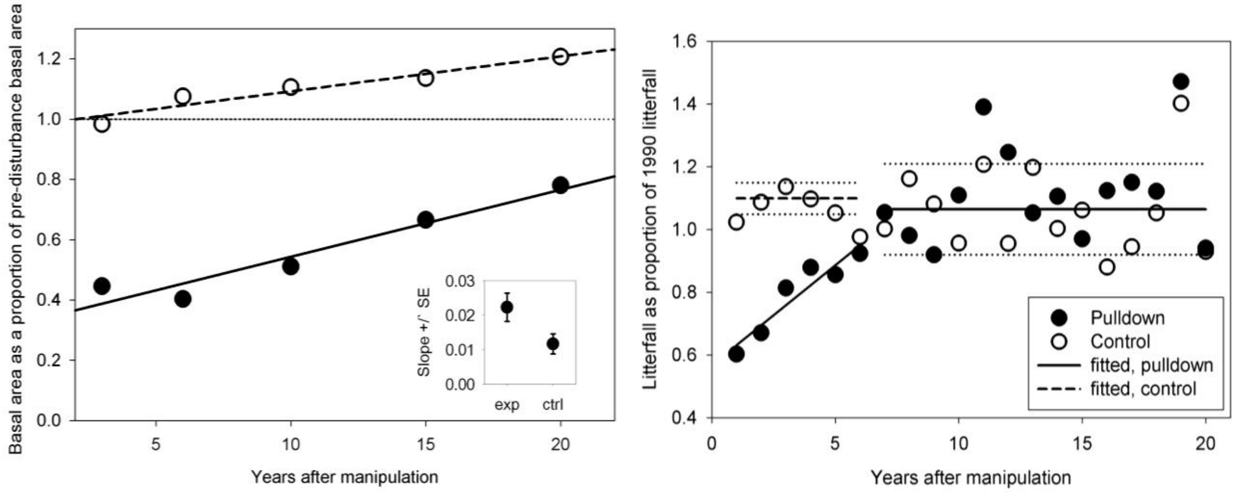


Figure 5. Twenty-year trajectories of change in basal area (*left*) and litterfall (*right*) in the hurricane manipulation (pulldown) and control. Fitted lines are significant ANCOVAs. Litterfall productivity recovered in six years, but basal area in the pulldown will lag behind the control for decades[5].

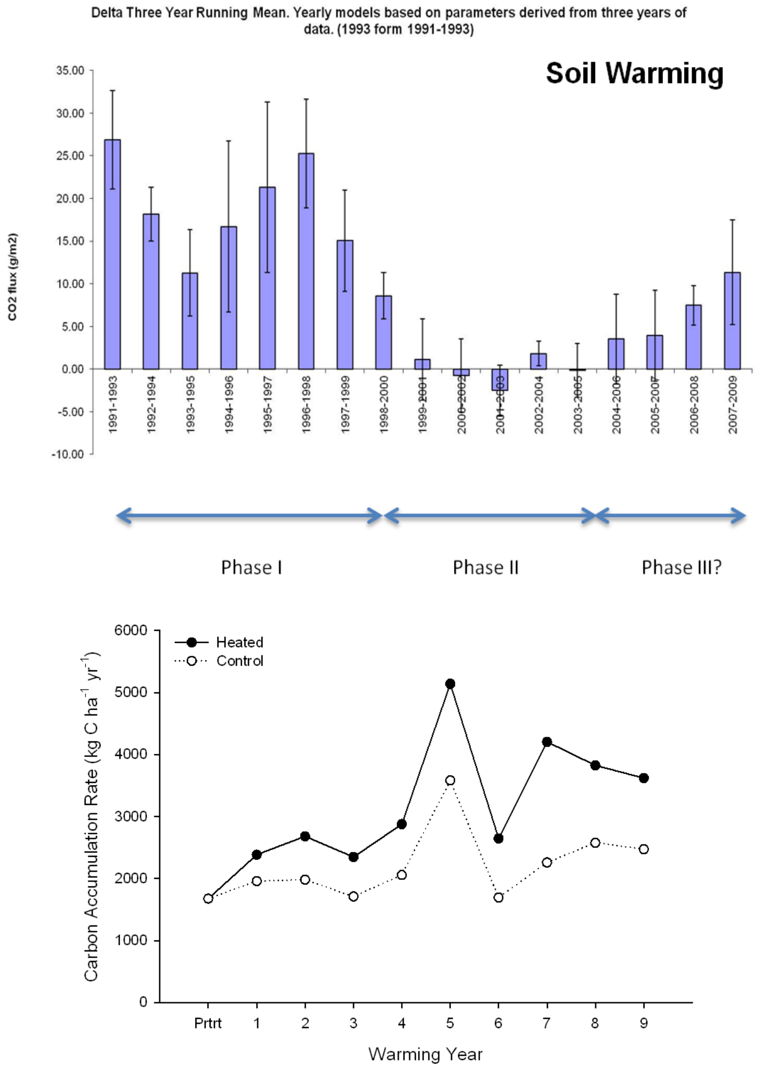


Figure 6. *Top:* Effect of warming on soil respiration at the Prospect Hill soil warming experiment over an 18-year period (1991-2009). Data are differences between respiration rates from heated and control plots represented as 3-year running means (and standard errors). Units are gC/m^2. *Bottom:* Net carbon storage in trees on the heated and control plots at the Barre Woods soil warming experiment over a ten-year period [1 pretreatment year and 9 treatment years]. Units are kg C ha^{-1} yr^{-1}.

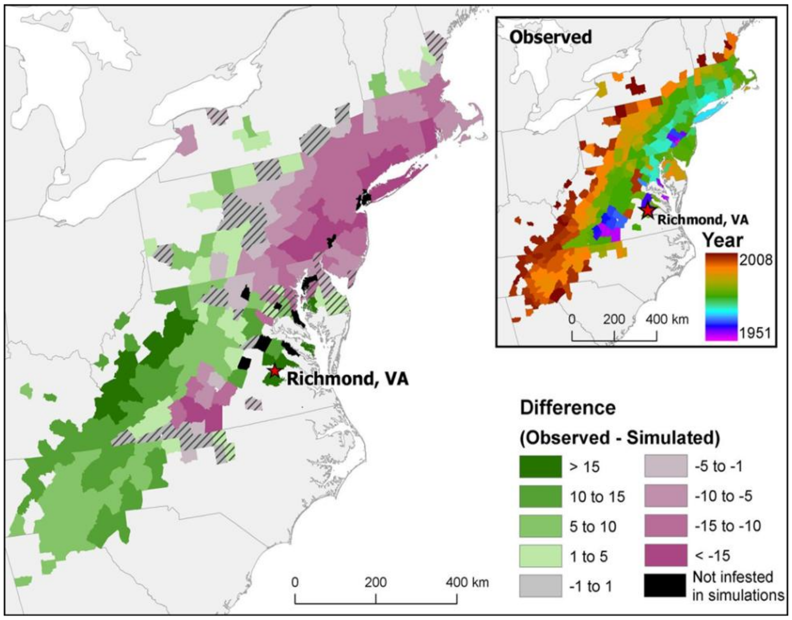
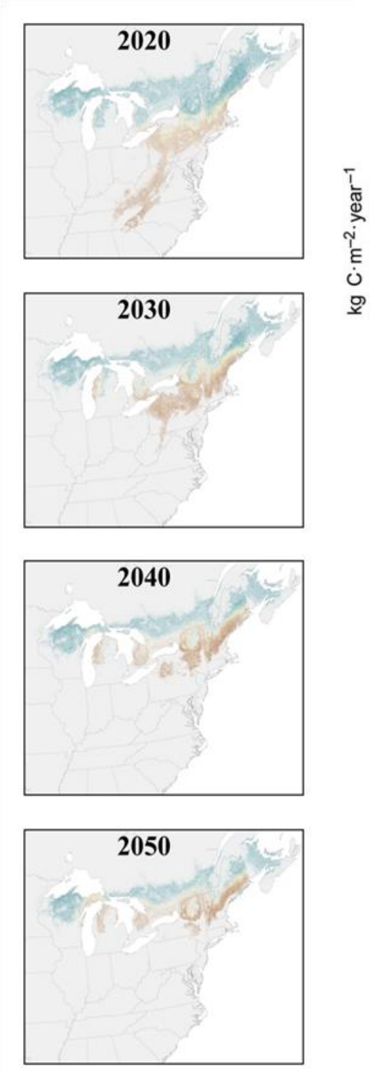


Figure 7. Difference between observed (inset) and modeled year of infestation of HWA in northeastern North America[27]. Green/purple shading indicates counties for which the model predicted a county to become infested earlier/later than was actually observed. The model predicted rapid spread to the south, followed by rapid spread to the north, but in fact, the opposite actually occurred.



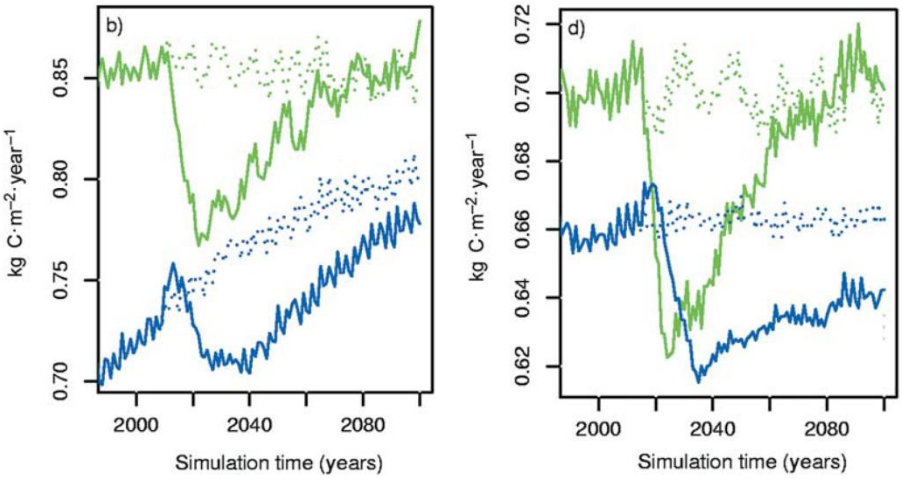


Figure 8. *Left:* Model forecasts of decline of hemlock due to HWA in eastern North America[28] (brown: dead hemlock; yellow: dying hemlock; green: live hemlock). *Above:* Model forecasts[29] of net primary productivity (NPP: green) and heterotrophic respiration (blue) if HWA causes hemlock to decline and forest structure to change as forecast (solid lines) and in the absence of HWA with hemlock persisting on the landscape (dotted lines).

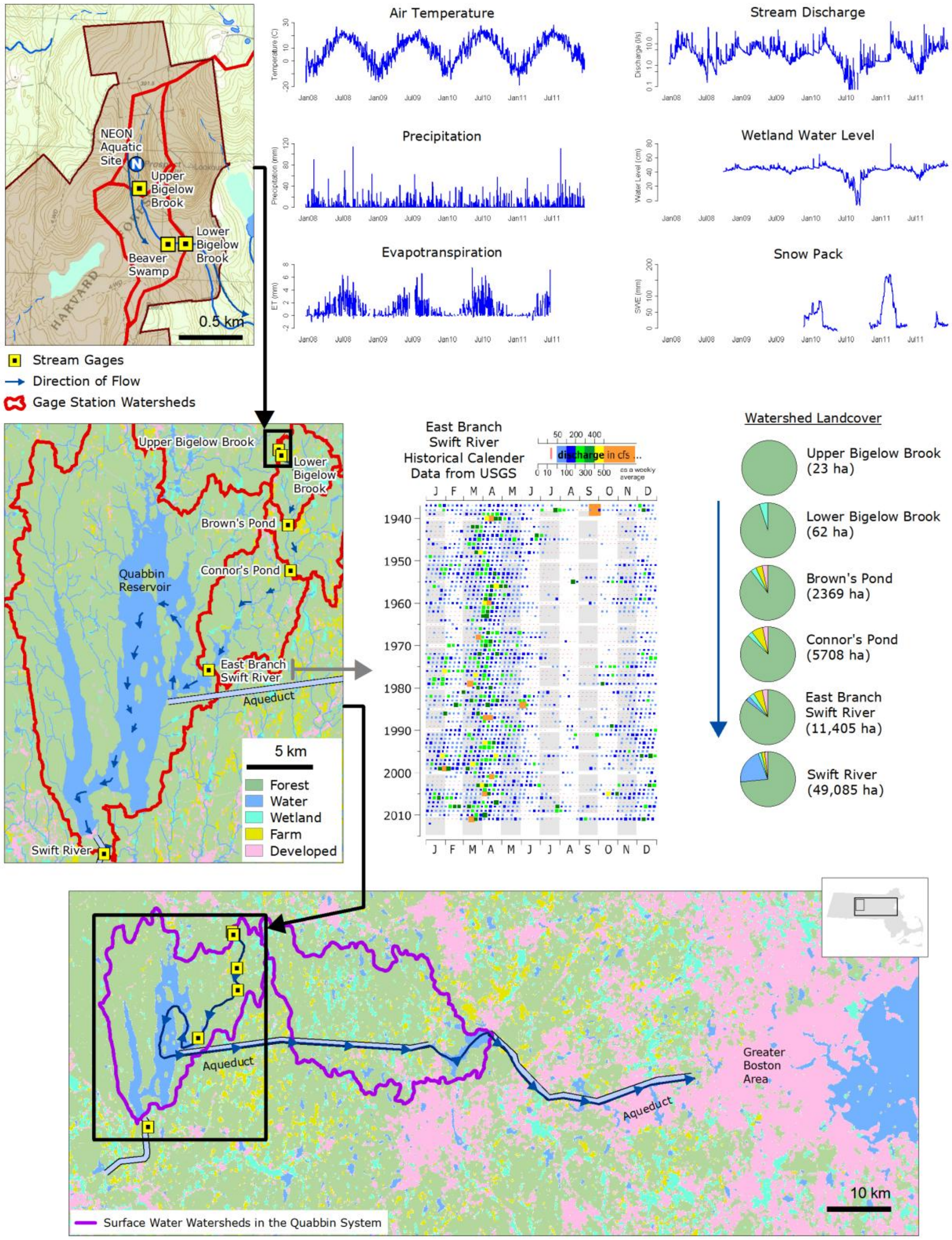


Figure 9. Hydrological studies at Harvard Forest and downstream linkages to the drinking water supply for metropolitan Boston. Maps show the headwaters of Bigelow Brook on the Prospect Hill Tract (*top left*), the watershed of the Swift River which was dammed in the 1930s to form the Quabbin Reservoir (*middle left*), and the diversion of water from the reservoir to Boston through a series of aqueducts and smaller reservoirs (*bottom*). Graphs (*top right*) show intensive measurements at Harvard Forest to support detailed studies of the water budget, including precipitation inputs, losses to evapotranspiration and surface discharge, and water storage in wetlands and winter snow pack. *Center* diagram (courtesy of Robert Sobczak) shows a long-term trend toward earlier spring melt-out at the USGS gage on the East Branch of the Swift River. Legend (*middle right*) and map colors show the shift in current land cover from upper headwaters (mostly forest) to metropolitan Boston (mostly developed).

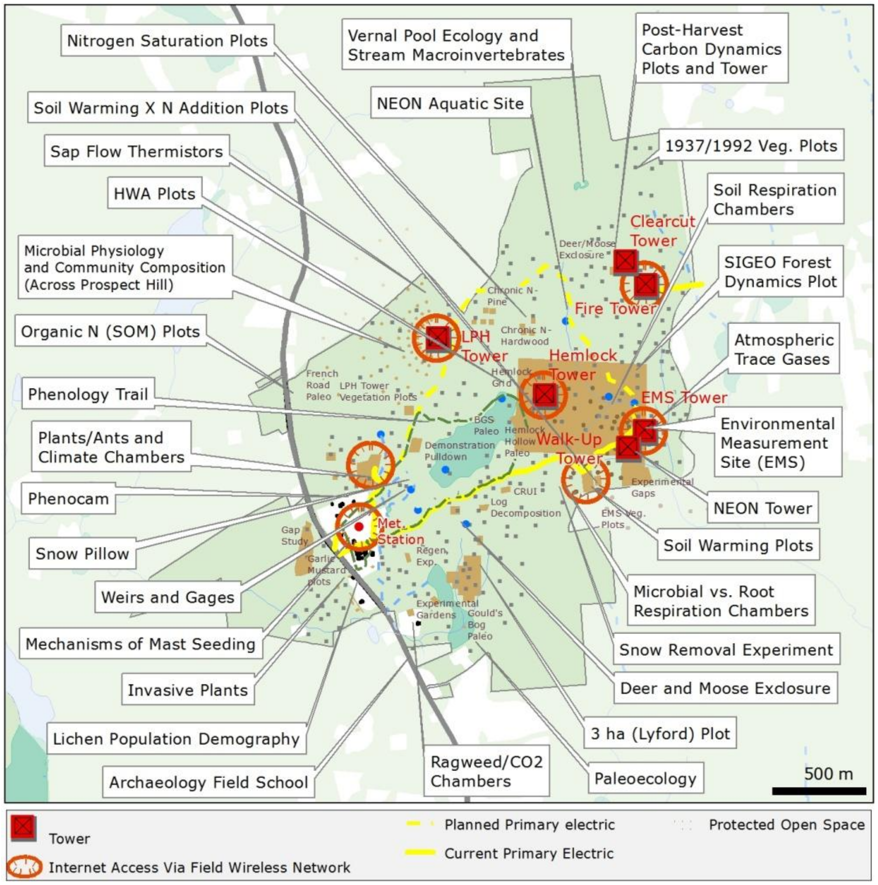
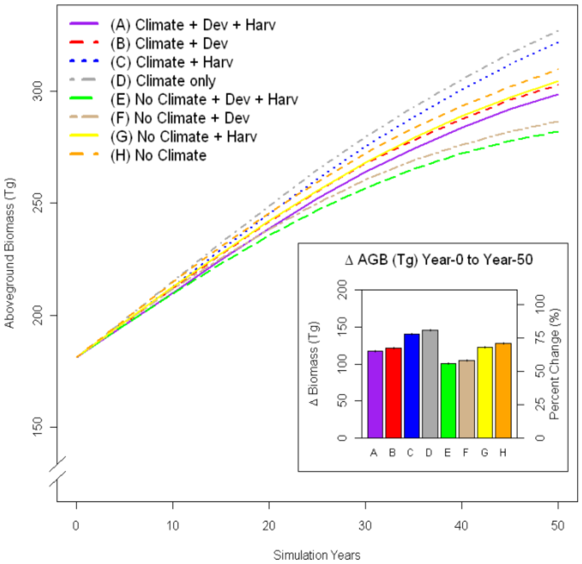


Figure 10. The Prospect Hill tract core of HFR showing major research installations and studies as well as supporting infrastructure including the field wireless, primary electric line, NEON sites, flux towers and the SIGEO forest dynamics plot. Much of the surrounding land has been protected from further development by proactive land conservation led by HFR researchers.



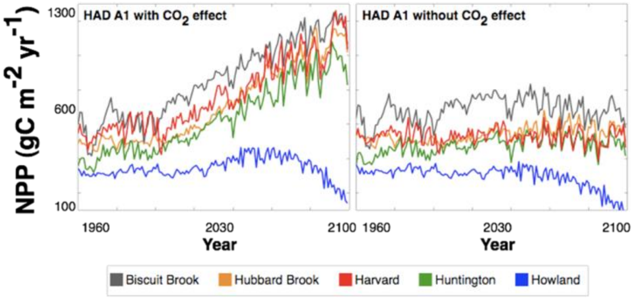


Figure 11 . *Right:* Predicted NPP from 1960 to 2100 at Harvard Forest and four other northeastern research sites generated by the PnET-CN model with future climate conditions from the Hadley general circulation model and two assumptions for the effect of CO_2 fertilization on trees[67].

Figure 11. *Left:* Average change in live aboveground biomass (AGB) for each of eight simulations, which treated climate change (Climate), forest conversion to developed uses (Dev), and timber harvests (Harv) as treatments relative to a static climate[51]. The inset histogram shows change in AGB from year 0 to year 50 for each scenario, A–H.

II. Integrated Research Plan

Synopsis – Scenarios of Future Land Use, Land Cover, and Climate Change

HFR proposes to use its strengths in fundamental science and education, and its long-standing engagement with real-world issues and the policy-making process to provide new leadership that advances ecological science and theories that are relevant to society. During LTER V, while we continue crucial long-term experiments and measurements, HFR will expand and develop work in five areas:

- **Science** that focuses on new research examining multiple scenarios of future land use and environmental change, including climate change and other disturbances and stresses, involving a cadre of new HFR scientists, institutions, and approaches [**§II.A**];
- **Synthesis** that interprets and distills existing and emerging long-term data to fill critical knowledge gaps and address societally relevant questions [**§II.B**];
- **Scholarship** that expands K-to-post-graduate educational opportunities [**§III.A, §III.B**];
- **Strategic outreach and communication** that engages decision makers, media professionals, managers, landowners, and the public to forge effective exchanges for improving the scientific basis of environmental stewardship and expanding the impact of long-term ecological research [**§III.C**];
- **Site assessment** that crafts strategic future directions for research and site management [**§VIII.D**].

Landscapes are being transformed in complex ways and at multiple scales by environmental changes, land-use and land cover changes, disturbances, and biotic processes, all of which are conditioned by legacies of past dynamics. Understanding ecological characteristics and processes that control ecosystem responses to these changes is a central challenge for scientists and decision makers (in which group we also include policy analysts, conservation professionals, resource managers, and landowners). HFR LTER V will build on the site-to-regional scale, long-term research developed through LTER I-IV to advance the understanding of the resilience and vulnerabilities of New England landscapes to global change. We will pursue this research agenda in large part through **integrated scenarios analyses**. Scenarios are qualitative descriptions about how the future might unfold, based on expert understanding of large-scale social, economic, and policy conditions and trends[50]. Scientists and decision makers use forward-looking, integrated analyses to assess and quantify the potential ecological and attendant societal consequences of interactions between future changes in land use and environmental drivers such as climate change[74,75]. The scenarios approach (Fig. 12) provides scientists and decision makers with a structured framework for understanding a complex world[76],[77],[78].

Using models to link a range of scenarios describing plausible future conditions[50] with external socio-ecological and environmental drivers, and endogenous constraints, we will evaluate the consequences of the interactive effects of multiple stressors on forest dynamics and ecosystem processes in terms of their effect on ecosystem services. This research in New England is part of a larger effort, led by HFR, to incorporate land-use scenarios into regional-scale research. This effort engages all LTER sites but is being advanced most rapidly in the five forested LTER regions – Pacific Northwest (AND), Alaska (BNZ), Midwest (NTL), Southeast (CWT), and New England (HFR,HBR, PIE)[50],[79].

Advancing this research agenda requires developing and evaluating future scenarios with:

- A thorough understanding of historical, current, and potential future suites of human activities that shape modern landscapes;
- A mechanistic understanding of biophysical drivers and ecological processes that couple human dynamics with ecosystem responses and constrain trajectories of ecosystem change;
- A deliberate and deliberative process for engaging decision makers and other stakeholders in development of narrative land-use scenarios that describe a plausible range of future human actions in a way that allows them to be incorporated into simulation models;

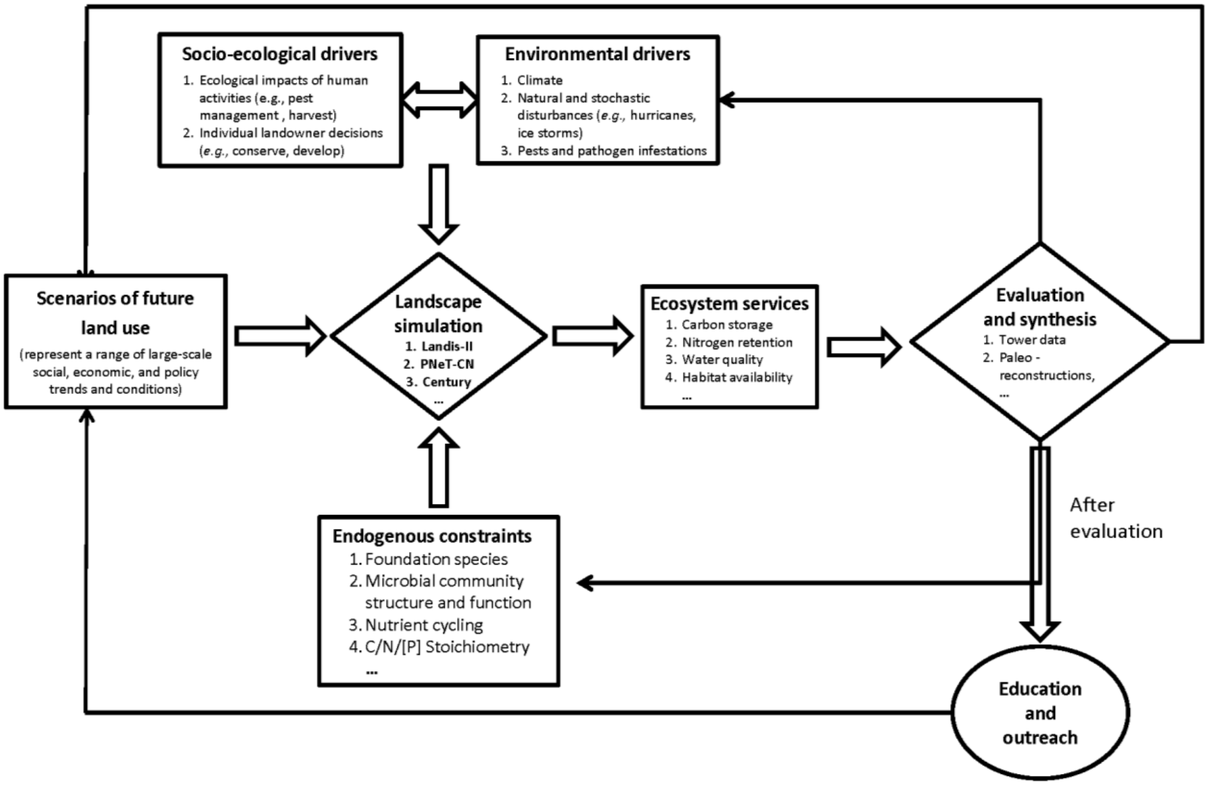


Figure 12. An overview of the Integrated Scenarios Analysis process to be used in HFR LTER V. Scenarios of future land use define the template that shape modern landscapes. In LTER V, we use a range of plausible land-use/land-cover changes and strategies for managing invasive species as socio-ecological inputs. Socio-ecological drivers describe landowner behaviors and their ecological impacts on the landscape. Environmental drivers include climate change and stochastic "natural" disturbances that are largely outside of human control over a 50-year forecasting window. Endogenous constraints are ecological dynamics and biogeochemical processes that either limit system-wide responses to human activities and environmental drivers or are used as input parameters for landscape simulations and regional analyses. Ecosystem services are outputs (quantitative predictions) from the landscape simulations and regional analyses that reflect socio-scenarios of future land use, socio-ecological and environmental drivers, and endogenous constraints. In LTER V, we focus on growth of forests and their associated carbon dynamics, water quantity and quality in headwater and 2nd-order streams, nitrogen retention in forested ecosystems, and the importance of microbial community structure in controlling many of these processes. Model output and predictions of changes in ecosystem services must be synthesized and evaluated before results are distilled and communicated to broader audiences. Long-term experiments, monitoring, and historical reconstructions will be used by LTER V to validate the models and to refine inputs into the simulations. Education and Outreach is a two-way process that (re)informs development of, and modifies, scenarios of future land use.

- Simulations of changes in ecosystem structure, function, and patterns based on these scenarios that condition, constrain, or control important ecosystem services – *e.g.*, carbon sequestration, albedo, evapotranspiration, and other forms of climate regulation, nitrogen retention, air and water purification, and availability of habitat – that reflect responses of ecological systems to coupled human-natural dynamics;
- Evaluation of the simulations with long-term measurements and experiments focused on key variables, and reassessment of model results based on new observations and results;
- Communication of results to decision makers through proven formats and delivery mechanisms.

Rationale

In 1988, researchers from Harvard, MBL, and UNH formed HFR: a new site in the then 14-member LTER program focused on comparing the effects of natural disturbance, climate change, and acid rain on Central Massachusetts' forests. At that time, NSF focused strictly on basic science, American Ecology concentrated on "natural" ecosystems and purposefully avoided human dimensions, and site-based LTER studies were unified around five core research topics: primary production, disturbance, populations, organic matter, and nutrients[80]. Through four rounds of funding over two decades and in response to new discoveries and growing interest in addressing societally relevant issues (see **§I. Results from Prior NSF Support**), HFR has added historical perspectives, expanded its scope to the New England region, integrated social, biological, and physical sciences, and developed education and outreach programs for K-12, undergraduate, and graduate students, along with land managers, environmental policy analysts, and decision-makers. Now, in 2012, the >30 HFR researchers:

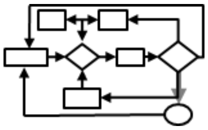
- Collaborate with students and scientists from > 100 institutions on long-term measurements, large-scale experiments, historical and paleoecological investigations, modeling, and regional studies;
- Lead programs in undergraduate research, K-12 schoolyards, and public engagement;
- Engage with national and international research networks including NEON[81], CTFS/SIGEO[82], ULTRA[83], and Ameriflux[84];
- Provide leadership for the LTER network in synthesis of scientific data, information management, communications, outreach, and science and policy integration[73];
- Advance regionally important efforts in conservation with NGO and agency partners[85];
- Leverage LTER support with awards from NSF, EPA, NASA, USFS, DOE, and private sources;
- Produce results, including >1000 articles, many books, and extensive media coverage[86],[87].

During HFR's first quarter-century, society's demands from science also have changed radically. Scientists not only must tackle questions that advance ecological theory, but also are part of the new social contract between broader society and participants in publically funded research[88]: we must focus on relevant questions and convey resulting knowledge to decision makers and the public.

Thus, **<u>the goal</u> of HFR LTER V is to apply site to regional-scale strengths in research, scenario science, education and outreach developed in LTER I–IV to understand the interactive effects of multiple socio-ecological stressors on the landscape and ecosystems of New England and to advance related training, communications, and science-based policy and management.** For example, insects and native herbivores including deer and moose are expanding their ranges and altering forest structure and function. Conversion of forests to housing, industry, transportation, and energy production (wind turbines, solar farms) is fragmenting and perforating forests, altering landscapes, and increasing demands and impacts on freshwater supplies. The intensity of forest land-use also is increasing, as wood products are used not only for timber, pulpwood, and recreation, but also for biofuels. At the same time, ecosystem services provided by intact forests (*e.g.*, carbon storage, nitrogen retention, water purification and regulation, tourism and recreation) are becoming more important than ever, while projected changes in climate and air quality pose substantial uncertainties for the future. The regional climate already is characterized by a longer growing season, greater temperature extremes, increased precipitation, changing exposure to harmful pollutants and nutrients, and tumultuous weather (*e.g.*, windstorms, drought, ice storms) that likely will increase in frequency and intensity[89]. Changes in land use and climate all are overlain on a heavily forested landscape that is still recovering from and strongly conditioned by four centuries of deforestation, reforestation, and regrowth[1],[51],[70].

The challenge for HFR scientists is to work effectively with land managers, policy analysts, decision makers and other researchers to bring our scientific understanding of multiple stressors and their interactions to bear on the critical environmental issues facing New England, the nation, and the world. Regionally, Massachusetts is part of a nine-state Regional Greenhouse Gas Initiative (RGGI)[90], a cap-and-trade program that requires states to reduce emissions by the power sector by 10% over 10 years from a 2009 baseline. If appropriately calculated, carbon sequestered in growing forests can be used to meet 3.3% of RGGI compliance requirements, with data from HFR playing a key part in these calculations[51],[91]. Nationally, Earth Stewardship is a major initiative of the Ecological Society of America[92]; the LTER 30-year review[93], Strategic Implementation Plan[94], and Communication Plan[73] all call for the 26-site LTER Network to confront the Earth's Grand Challenges and to communicate the results effectively; and NSF now supports major programs on coupled natural-human systems, urban systems, continental scale ecology, and science, engineering, and education for society[95],[96],[97],[98],[99]. HFR has been and will continue to be a key contributor to all of these efforts.

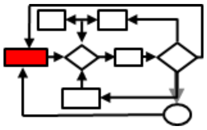
Navigation and Orientation



The New Science, Synthesis, Scholarship, and Outreach & Communication thrusts of HFR LTER V are centered on a fundamental research question: ***What will be the multiple and interactive effects of climate change, natural disturbances, biotic interactions, human land-use, and forest dynamics on landscape-scale ecosystem dynamics, processes, and services over the next 50 years***? Figure 12 illustrates, in flow-chart form, our integrated approach to this question and major components of the proposal. Each section of this Integrated Research Plan elaborates, in turn, pieces of this flow chart; the relevant piece discussed in a given section is highlighted in red.

II.A. New Science

II.A.1. Developing scenarios of future land use



Lead investigators: Foster, Hutyra, Kittredge, Lambert, Orwig, Stinson, Thompson.

People have shaped, and continue to shape, our landscape. In LTER V, HFR researchers will develop different scenarios of future land use that we will use to examine the interactive effects and relative influence of multiple drivers of socio-economic and environmental change. The nature and extent of land-use and land-cover change (LULCC) in New England is influenced by large-scale economic, social, and policy conditions that are difficult to predict but that can be bracketed by scenarios describing a range of plausible future land-use conditions[50],[51]. We will engage decision makers from state and federal agencies, and representatives from conservation organizations, academic institutions, and landowner organizations to develop an initial set of scenarios of future land use in New England over the next 50 years (**§III.B.1**). Each scenario will be translated into a set of quantitative rules describing the spatial distribution and intensity of land use and other activities to be used as inputs for subsequent simulations (**§II.A.5**)[51]. The quantitative rules will be based on extensive research and data on the impacts of human activities (*e.g,* harvesting, development, conservation) and the factors that influence landowner decision making (**§II.A.2**)[52],[53],[54].

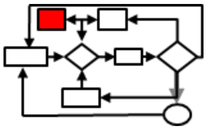
Building on discussions of national forest scenarios in LTER IV (**§III.B.1**), in November 2011 we held our first set of scenario-development workshops with stakeholders from Massachusetts and the New England region. Together, we defined three example land-use scenarios that reflect varying degrees of development, energy and resource use, and government intervention:

- *Free Market Future* – Environmental regulations are rolled back; weakened zoning laws allow for proliferating sprawl, subdivisions, and a 125% increase in development; reduced funding for conservation and divestment of public lands leads to a 25% reduction in conserved land; intensive, largely unregulated and unplanned forest harvesting occurs.
- *Resource-limited Future* – As important resources become scarce and oil prices rise, society adjusts; energy demand increases for woody biomass fuels, leading to increased forest harvesting; demand for local food increases leading to forest clearance for agriculture; development of tightly spaced, low-income housing increases, but the number of high-income lots shows little change.
- *Green Investment Future* – Development is strongly targeted towards redevelopment of small cities and old industrial towns; expansive protection of forest and farm lands is paralleled by an increase in sustainable harvesting, large forest reserves, and local sources of sustainably produced meat, vegetables, and fruit. Alternate energy capacity (primarily solar and wind) expands; aggressive carbon caps are developed and enforced; and use of biomass for fuel increases dramatically.

We emphasize that the land-use scenarios and associated modeling proposed here are not agent-based efforts[100]. Rather, we are developing these scenarios of plausible futures through interactions among scientists, decision makers, and thought leaders. The scenarios will then be used as part of larger quantitative models of ecosystem and landscape dynamics. These models do not embed human responses, nor do we plan to conduct comprehensive social-science research to elucidate the range of potential human responses. Our social science efforts are strategically focused to inform the development of land-use scenarios and to develop the quantitative rules for translating scenarios into discrete land-use and land cover actions that can be used in landscape modeling (**§II.A.5)**.

The land-use scenarios are being analyzed first in Massachusetts, using established IPCC climate-change forecasts. Other disturbances (*e.g.,* insects, pathogens, hurricanes) and stresses (N deposition, ozone) will be incorporated once the land-use + climate simulations are completed (**§II.A.5**). During LTER V, additional land-use scenarios will be developed and applied as the geographic scope expands to include northern New England (ME, VT, NH). These expanded efforts will draw on cooperation with parallel efforts in Maine and New Hampshire (supported by NSF/EPSCoR), the Hubbard Brook LTER (HBR), and the Universities of Maine, New Hampshire, and Vermont. The stakeholder engagement that supports the development of land-use scenarios and the communication of results to decision makers will be a central activity of the new Northeast Science & Policy Consortium (**§III.B.1**)[101].

II.A.2. Socio-ecological drivers: human activities and landowner decisions that shape the landscape



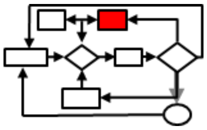
Lead investigators: Foster, Hutyra, Kittredge, Orwig, Short, Stinson, Thompson.

To understand current landscape-level dynamics and to anticipate how they may change in the future in the context of different land-use scenarios (**§II.A.1**), it is essential to understand the backgrounds, motivations, and decision-making behaviors of the tens-of-thousands of individuals, families, and institutions who own and manage New England's forests[102],[103]. In LTER V, we will advance research and apply our current knowledge on private landowner behaviors to inform the modeling of future land-use scenarios. The integration of scenarios and landscape modeling with landowner research builds on two decades of research by HFR scientists (**§I**); existing partnerships with the US Forest Service, the Family Forest Research Center[104], and the Wildlands & Woodlands partnership[85] (**§III.B.2**); and new collaborations with the Boston ULTRA-Ex[105].

Data on how landowners actually use their forest lands will be the basis for quantitative, probabilistic rules in the simulation models that describe how landowners respond to the social, economic, and policy conditions envisioned by each of the scenarios of future land use. We will develop the rules for landowner actions in three ways: (1) estimate their response based on what we currently know from our research, published studies, and the National Woodland Owner Survey (available for New England, and nationally); (2) use recent history to predict behaviors under past circumstances (*e.g.,* documented landowner behaviors when real estate prices were high in the 1980s, or during periods of high or low timber prices); and (3) conduct new qualitative and quantitative surveys of landowners about attitudes and potential behaviors under the different scenario assumptions. Important questions include: how do real-estate values or carbon and biomass market conditions affect the probability of forest harvest as parcel size changes? How are landowners likely to act in response to new infestations of non-native species such as HWA, Asian long-horned beetle (*Anoplophora glabripennis* [ALB]), winter moth (*Operophtera brumata* [WM]), or emerald ash borer (*Agrilus planipennis* [EAB])? And how might they respond to another destructive hurricane or ice storm?

We will also expand our understanding of landowner behavior by assessing sources of landowner information about ecological processes and options for land management; information flow among landowners; and the role of local governance (municipal and non-profit conservation) in shaping landowner decisions. One way to generate the answers to these questions directly from landowners is by using a Conservation Awareness Index,[106] which we developed during LTER IV and are now applying regionally in surveys and associated research across urban and rural landscapes in collaboration with the Boston ULTRA-Ex.

II.A.3. Environmental drivers: climate change and stochastic disturbances



Lead investigators: Boose, Foster, Melillo, Munger, Ollinger, Oswald, Thompson**.**

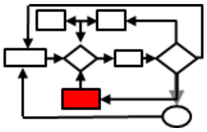
Many large-scale environmental drivers operating in the near term (50-100 years) will be difficult for humans to alter.[107] The climate will continue to change[108], and with it, regional models forecast substantial increases in temperature, precipitation, growing season, and severe storms, including hurricanes, tornadoes, ice storms, and nor'easters[89]. Climate change and other exogenous disturbances will be integrated with land-use scenarios by using a consistent set of assumptions that allow for a consideration of their relative and interactive effects. In our simulations (**§II.A.5**), we will begin by using the IPCC A1 family of emission scenarios[108] and downscaled climate model projections for the Northeast region[109] (but *cf. ref.* [110]). However, the current generation of IPCC emission scenarios is being superseded by "Representative Concentration Pathways" (RCPs), which in turn are forming the basis for analyses in the forthcoming IPCC V[111]. As RCPs are elaborated, we will match each of the stakeholder generated land-use scenarios (*e.g.,* free market, resource limited, green investment and others explored in the future) with the appropriate RCP.

Additional environmental drivers that can accentuate or offset effects of climate change include changing CO_2 concentrations, N deposition, and other pollutants including ozone. In the past, HFR modeling activities have focused on combining mechanisms related to interactions among all factors and estimating their historical influence on forest growth[112]. In LTER V, we will include future projections of changing atmospheric emissions, concentrations, and the deposition of key pollutants[113]. One critically important new step is that we will examine the interactions among, and relative importance of, climate change, atmospheric change, and LULCC as drivers of future regional ecosystem processes.

Historical evidence of the frequency, intensity, and impacts of past extreme events (*e.g.,* hurricanes, wind and ice storms, floods, droughts) will shed light on the possible future impacts of climate change as predicted by regional climate models. For example, work in LTER I-III established a detailed 380-year history of hurricanes in New England, regional gradients of past hurricane damage, and modeling techniques for predicting spatial patterns of wind and damage from individual storms[114]. These data and models will be used to generate regional patterns of predicted hurricane impacts from more general predictions of a change in hurricane frequency and/or intensity[115]. Likewise, we will base our estimates of other extreme events on long-term retrospective records.

Potential impacts of forest insects, including both their direct impacts and the human responses to them, will be incorporated as additional scenarios. We envision using at least three scenarios: (1) *Single-species impacts* – widespread decline of a single host tree species, and salvage or pre-emptive harvesting; (2) *Multi-species impacts* – widespread decline with related harvesting of many host tree species in response to, and in anticipation of, multiple insect outbreaks; (3) *Insect extirpation* – intensive chemical or biological control of target insect species across entire range. These scenarios will also reflect changes in socio-ecological drivers associated with, for example, salvage and harvesting, biological controls, chemical controls, and firewood limitations.

II.A.4. Endogenous constraints: foundation species, insects, microbes, and nutrient availability



Lead investigators: Blanchard, Davidson, DeAngelis, Ellison, Finzi, Foster, Frey, Melillo, Munger, Orwig, Oswald, Richardson**.**

Just as environmental drivers provide the biophysical context in which human actions play out, endogenous constraints define and limit responses of ecosystems to a range of future scenarios. Using a combination of retrospective studies (paleoecology, historical reconstruction, and hind-casting models), site-based experiments, site-to-regional scale observations, and modeling, we will identify key population-, community-, and ecosystem-level properties and processes active on the New England landscape. At the population and community level, we focus on foundation tree species, the insects and herbivores that strongly interact with them, and the microbial assemblages in their soils. At the ecosystem level, we focus on correlated changes in nutrient cycles and species composition.

Foundation species are species that disproportionately shape their environments and modulate key ecosystem processes. In northeastern forests, eastern hemlock (*Tsuga canadensis*), beech (*Fagus grandifolia*), and oak species (*Quercus* spp.) have characteristics of foundation species[116] and many of these are declining or have exhibited past declines due to interactions among climate change, ungulates, insects and pathogens, and LULCC. As foundation tree species decline, their conditioning of landscape dynamics will change in parallel. We will continue to use retrospective and observational studies and manipulative experiments spanning LTER I-IV to clarify the roles of foundation species in controlling population and community dynamics of associated species and ecosystem processes. One new focus is the 35-ha forest dynamics plot established in 2010 as part of the global network of large plots overseen by the Center for Tropical Forest Science (CTFS) – Smithsonian Institution Global Earth Observatory (SIGEO) focused on C dynamics and climate change. The HFR SIGEO plot is in the footprint of two eddy flux towers and the NEON FIU and FSUs, contains hydrological and meteorological stations in a small gauged watershed (**§II.A.6**), and has a large area dominated by eastern hemlock. Spatially explicit data for ~90,000 stems > 1 cm diameter collected every five years (begun in 2010) will provide an unparalleled picture of species distributions, forest age structure, and forest demography in a representative central New England forest. Subplots arrayed around the EMS and Hemlock eddy-flux towers are measured annually to capture short-term variability in biomass and vegetation dynamics.

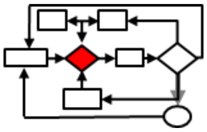
In LTER V we also will continue our *stand to-landscape scale studies on ungulates and insects* and their effects on foundation species and forest dynamics. HWA was emphasized in LTER II-IV; in LTER V we will add studies of EHS, EAB, and ALB. HWA began colonizing HF in 2010; it now occurs across the SIGEO plot and Hemlock Removal Experiment[21] and could kill hemlocks quickly unless cold winter temperatures slow the impact of HWA[2]. The co-occurring EHS has increased in density and rapidly spread across the study area, leading to novel species interactions and impacts[117],[118]. At a regional scale we will study dynamics and interactions of HWA and EHS, climatic- and stand-level drivers controlling tree mortality, and changes in energy and nutrient fluxes in hemlock stands. This work leverages USDA-

AFRI support for studies of leaf-level impacts of HWA-EHS interactions and economic analyses of hemlock loss. At permanent plots in a 7,500-km^2 transect from southern CT to northern MA we biennially sample soil N availability and vegetation dynamics and measure aboveground and belowground C stocks and fluxes in old-growth and secondary hemlock forests, stands in early and late stages of HWA infestation, and second-growth hardwood forests. In LTER V, we will extend the transect and plot network into VT, NH, and ME ahead of HWA and EHS migration. At a local scale, HWA spread and impact will be documented annually across the HFR SIGEO plot by examining HWA presence in all 875 20×20m subplots[119], monitoring changes in canopy vigor (density, color) visually and with continuous canopy imagery and physiological measurements (chlorophyll fluorescence, photosynthetic rates), measuring environmental changes (stand light, air and soil temperature, humidity profiles, and moisture), and documenting changes in ecosystem processes (respiration measured with soil chambers and integrated CO_2 and water fluxes measured at eddy-flux towers). Hypothesized causal relationships among these measurements are being tested in our 8-ha hemlock removal experiment, now entering its 10th year[21,120,20]. These data also will constrain scenarios and models of single and multiple insect impacts (**§II.A.3, §II.A.5**).

We also will expand our investigations (initially funded by NSF Ecosystems and Rapid, and USDA) of other insects altering New England's forests. Retrospective studies explore climate-insect interactions controlling abrupt pre-historic declines of both hemlock and oak. We are also studying mortality patterns, tree-ring growth dynamics, and subsequent regeneration dynamics associated with modern outbreaks of ALB surrounding Worcester, MA[121], WM, and fall canker worm (*Alsophila pometaria*) in coastal oak forests[122], and contrasting these dynamics with modern and pre-historic hemlock declines (**§II.A.6).** As the EAB enters New England from eastern New York, data from these studies will help guide new research on and define future scenarios of, impacts of, and responses to, these non-native species (**§II.A.2, §II.A.3**).

Microbial diversity and community composition are key controllers of ecosystem processes including C and nutrient fluxes. Data on microbial pattern and process are used to parameterize process-level models of belowground dynamics in forests and feedbacks between soil, vegetation, and the atmosphere (**§II.A.5**). During LTER IV, we began to assess microbial community structure in several of the long-term experimental plots at HFR. By leveraging recently-funded NSF and DOE awards we are able to sequence microbial assemblages from the 20-year N-saturation and soil-warming plots. We are describing bacterial and fungal assemblages using phylogenetic, meta-genomic, and meta-transcriptomic approaches that are coupled with culture-based studies, stable isotope analysis, pyrolysis GCMS, and nuclear magnetic resonance (NMR) spectrometry. Our overall objective with this work is to better understand the ecology and evolution of soil microorganisms in the context of abiotic and biotic change and the feedbacks between microbial community structure and microbial controls on biogeochemical cycles (**§II.A.6**).

II.A.5. Landscape simulation and regional analyses



Lead investigators: Ellison, Foster, Melillo, Moorcroft, Ollinger, Thompson

In concert with the development of future land use scenarios (**§II.A.1**) and remote sensing work to evaluate changes in surface albedo (**§II.A.6**), model simulations will enable us to contrast past and future effects of atmospheric and biotic changes with the effects of changes in the extent and distribution of different land cover types, and to provide quantitative estimates of changes in carbon storage, climate forcing, and other ecosystem services.

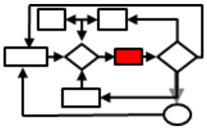
Landscape-to-regional simulations of ecosystem dynamics have been a core component of HFR since LTER-III. Past efforts have focused on the development of several models that simulate a series of inter-related ecosystem processes at different levels of complexity and spatiotemporal resolution. Collectively, the TEM, PnET, and ED models simulate carbon, nitrogen, and water cycles; and species dynamics and successional change, to examine the role of climate, disturbance, and pollution as regulators of regional-scale ecosystem processes[42],[67],[123]. PnET, along with its component sub-modules, is a well-validated site-to-regional model of ecosystem C, N, and H_2O fluxes that captures important controls on net primary productivity (NPP), C exchange and N retention using a small number of site and vegetation parameters and minimal reliance on calibration. It has been modified to predict the effects of multiple atmospheric pollutants (ozone and N deposition) and disturbance history, and has been tested against C, N, and H_2O flux data at sites across North America and Europe[124],[125],[126],[127],[128].

In LTER IV we applied LANDIS-II, which is process-driven, flexible, and well-tested (at landscape to state-wide scales) to simulate the current trends of climate change, fire, timber harvest, and forest conversion. We used PnET to simulate forest growth, while LANDIS added dynamics associated with disturbance, management, and succession. The combined framework emphasizes spatial interactions across the landscape and accounts for additive and interactive effects of multiple stressors (*e.g.*, climate change, insects, harvesting) and ecological processes (*e.g.*, succession, seed dispersal) over decades or centuries[51],[129],[130],[131],[132],[133],[134],[135],[136],[137],[138],[139],[140]. Validation exercises repeatedly have shown that PnET's ability to predict patterns of growth in forests is greatly improved by having spatially explicit measures of foliar %N, which the model uses to set photosynthetic capacity. This has prompted a parallel line of investigation designed to derive landscape-scale measurements of canopy %N using aircraft imaging spectroscopy[62],[63]. From its origins at HFR, this remote sensing work now includes multiple biomes worldwide[61] and is being integrated into the NEON aircraft observatory platform and NASA's HyspIRI satellite sensor. The combined modeling and remote sensing work places HFR research in a broader spatial and temporal context and highlights uncertainties in important mechanisms, such as those underlying long-term response to rising CO_2. Mechanistic, process-based models, including ED-2 (*ref.*[42]) may better resolve these uncertainties, but they have not yet been adapted to run multiple scenarios at regional scales.

The emphasis on *species' biogeochemical responses to climate and land-use activities* provides a valuable means of quantifying landscape responses to interactions between the environment and management that will be the focus of simulation modeling and scenario analysis in LTER V. In particular, we will incorporate the Century Succession extension for LANDIS-II, which simulates regeneration and growth of trees and shrubs, along with below-ground processes[141],[142]. The C and N cycling components are derived from the Century soil model[143],[144] and calculate net ecosystem exchange and net ecosystem production. In the model, successional dynamics of tree species are dependent upon their unique life history attributes[145], growth rates, establishment, and competitive abilities at a given location[51],[146],[147]. The ability of tree and shrub species to establish under changing climate conditions is estimated outside of the LANDIS framework, typically using an ecophysiological approach within the TACA or ED-2 models[42],[148]. In addition, we will expand our regional-scale focus by: (1) using new information on soil microbial processes and organic matter dynamics (**§II.A.4**) to improve PnET's ability to capture effects of N enrichment on belowground allocation and soil C accumulation; (2) incorporating components of the Forest-DNDC model[149] to add emission of gaseous N losses from soils; and (3) conducting regional simulations using PnET in conjunction with future land-cover scenarios (**§II.A.1**) and the LANDIS-II forest dynamics model[150],[151] to predict past and ongoing changes in climate forcing and ecosystem services.

Forest management will be simulated using the Biomass Harvesting extension for LANDIS-II (*refs.*[129],[147]), which allows complex rules to be applied based on stakeholder inputs (**§II.A.2**) and which can simulate forest conversion at intensities ranging from small partial clearings for individual homes to large permanent clearing for agriculture[51]. Management activities can be mapped as the amount of canopy, basal area, or C removed from the system. Insect outbreaks and impacts (**§II.A.3, §II.A.4**) will be simulated using the Insect Defoliation extension[152], which simulates the spread, growth, and mortality of multiple insects as a function of insect host preferences, outbreak frequency and dispersal distances, and the likelihood of defoliation given recent outbreaks within the dispersal-defined neighborhood and their frequency and duration. Recorded insect outbreak size and frequency within each landscape will be correlated with historic weather records, accounting for tree species composition. Assuming that a climatic signal can be detected, those relationships will be used with climate projections to estimate future insect outbreak frequency, intensity, and size.

II.A.6. Ecosystem services – Carbon, air, water, organisms and their habitats



Lead investigators: Boose, Crone, Davidson, DeStefano, Faison, Finzi, Foster, Frey, Kittredge, Melillo, Munger, Ollinger, Short, Sobczak, Stinson, Thompson, Williams.

Carbon storage, climate and water regulation, and nitrogen retention are key services provided by terrestrial ecosystems: belowground plant allocation of C and microbial metabolism of plant-derived organic materials contribute significantly to the large amount of C annually stored in, and released from, soil. In HFR V, we will link microbial information gained through genomics and transcriptomics (**§II.A.4**), data on biogeochemical processes (**§II.A.4** and below), and next-generation ecosystem models (**§II.A.5**) to provide a more mechanistic understanding of how soil C storage and nutrient cycling respond to plausible future scenarios of landscape and global change. Focal areas of research include: (1) interactive effects of belowground resource allocation by trees and microbial community composition/function on the decomposition of SOM; (2) coupled terrestrial-aquatic dynamics; (3) interactions and feedbacks between ecosystems and climate; and (4) the intersection of organisms and their habitats with ecosystem processes. These research foci build on long-term global change experiments at HFR, including soil warming[8],[13],[15], N saturation[6],[7], forest harvesting, and HWA[21], as well as ecosystem-scale constraints on C uptake and allocation derived from eddy-covariance observations.

Microbial Physiology and SOM Dynamics. Advances in empirical knowledge regarding decomposition and nutrient cycling have yet to make substantial inroads into ecosystem process models or earth system models[153],[154]. We know, for example, that: microbial exo-enzyme kinetics drive decomposition dynamics[155]; temperature sensitivity of SOM decomposition is a function of the activation energy of substrates being decomposed[154]; microbial communities produce specific types of enzymes based on whether their activity is C, N, or P limited[156]; and belowground C allocation by plants provides resource subsidies to microbes that fuel even greater rates of decomposition than those observed in bulk soil[157],[158]. These data[159],[160],[161] clearly demonstrate that the "standard model" for SOM decomposition – typically three soil pools roughly based on SOM turnover time with first order, temperature-dependent decay dynamics and a soil moisture multiplier – is insufficiently rooted in fundamental principles of the decomposition process. This compromises the model's ability to predict future ecosystem states because they are driven by empirical rather than fundamental relationships. During LTER V, we will use an emerging modeling framework, past data sets, and new studies to calibrate a new, mechanistically based model (DAMM-MCNIP) of SOM decomposition driven by fundamental relationships[162] .

The combined approaches of soil sampling for microbial analysis (**§II.A.4**), modeling (**§II.A.5**), and synthesis (**§II.B**) will provide new mechanistic and quantitative understanding of coupled interactions among C and N cycling processes. The models will identify potential responses of, and constraints on, the climate and biosphere to increased greenhouse gas concentrations, soil warming, and changes in precipitation patterns. As the ecosystem models we develop are scaled to the regional landscape where they are linked with the land-use scenarios, they will be evaluated using time series of CO_2 (and other trace-gas) mixing ratios as top-down constraints. Data assimilation approaches that combine transport models with remotely-sensed vegetation data and meteorological fields can predict carbon fluxes at large spatial scales[163]. Application of such inverse analysis to the tower data from HFR and other locations supported by ULTRA and NEON will enable evaluation of the landscape simulations for current conditions, thus providing added confidence in the scenario predictions.

Coupling of Terrestrial and Aquatic Systems. In small forested catchments, the terrestrial ecosystem provides critical inputs of nutrients to streams and wetlands. For HFR's three gauged watersheds (24 – 65 ha), we ask: how significant are C and N export in streams as part of the forest C and N budget; and what are the mechanisms that control mobilization, transport, and processing of dissolved organic matter (DOM) in soils and aquatic systems? In particular, what is the role played by precipitation events?

To start, more accurate water budgets are essential for assessing water availability (for plants and animals, including humans) and understanding long-term watershed responses to climate change and changes in land use and land cover. However two terms of the water budget – evapotranspiration (ET) and belowground exchange (in or out of the watershed) – are notoriously difficult to measure. In LTER V, we will improve water budgets for our gauged watersheds through (1) direct measurement of water vapor flux at three eddy flux towers and of sap-flow[164] to parameterize and evaluate simulations of ET[165]; (2) analysis of stable isotopes (^{2}H, ^{18}O) in precipitation, ground water, stream water, and plant tissues to identify sources and movement of water through the watershed[166]; (3) deployment of nested piezometers to estimate lateral soil water movement and any losses through bedrock; and (4) evaluation of soil moisture observations at multiple scales (incorporating remotely sensed estimates as available[167]) to improve simulations of soil hydrology and moisture availability in the root zone.

Water quality and quantity in river systems are directly affected by headwater processes and downstream linkages, which are particularly important for reservoirs fed by small headwater streams and small rivers such as the Quabbin Reservoir, the source of drinking water for metropolitan Boston (Fig. 9). Data from the gauged upper and lower Bigelow Brook watersheds on Prospect Hill will be combined with downstream data from the East Branch of the Swift River and the Quabbin Reservoir to examine: (1) linkages between headwater stream discharge, river flows, and reservoir water levels, especially during flood and drought events and (2) mechanisms that control inputs, transport, and processing of dissolved organic matter (DOM) from headwater stream to the reservoir. Climatic changes in precipitation, humidity, and temperature, and LULCC (*e.g.,* forest conversion, harvesting, natural disturbance, forest development) also may have major impacts on water yield. Because these changes often co-occur, it can be difficult to discern the impacts of each. Studies to inform the scenario simulations will focus on: impacts of the loss of a foundational species (eastern hemlock) from HWA on catchment microclimate, water availability, and decomposition rates (**§II.A.3**); and synthesis of long-term climate and discharge records from small catchments and river basins across North America (**§II.B**)[45,168].

Ecosystem-Climate Interactions. Ecosystems respond to climate and, in turn, have important effects on climate through regulation of C, water, and energy exchanges between the land and the atmosphere[169]. A growing body of evidence has shown that canopy albedo and other biophysical properties of vegetation can have climate effects that equal or exceed those of C storage[170]. Forests, for example, tend to have lower albedo than the land-surface, with most of the energy they absorb translated into latent or sensible heat. Hence, land use that alters the extent, structure or composition of forests can have important, but often overlooked effects on climate[171]. Several studies emerging from LTER IV show that forest albedo is positively correlated with foliar N concentrations and the maximum rate of carbon assimilation (**§I**)[62,63], suggesting that multiple mechanisms of climate regulation may be interconnected more than previously thought. Clearly, scientific and policy endeavors that address land management and climate mitigation strategies must look beyond carbon and towards more comprehensive analyses of climate forcing.

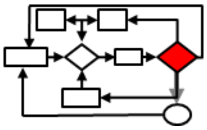
In LTER V, we will expand our site-level studies of mechanisms underlying the relationship between albedo, ecosystem carbon, and nitrogen status[65,66] in several important ways. First, we will use recent high-resolution aircraft imagery from NASA's AVIRIS instrument (Airborne Visible/InfraRed Imaging

Spectrometer) to examine how albedo responds to N deposition and forest change induced by LULCC. These data span a gradient of N deposition rates across the northeast and include forests subjected to a variety of harvesting treatments. Second, we will take advantage of the flux records at HFR to examine how carbon, water, and energy balances differ among mature deciduous, hemlock, and rapidly regrowing forests, and how these relate to radiative forcing. Third, we will use a combination of field measurements and remote sensing data from Landsat to examine relationships between mid-summer canopy albedo and albedo at other times of the year. In addition to providing a clearer understanding of ecosystem-climate interactions under modern conditions, the resulting data will be applied to past land cover (~1850 to present; historical data from LTER I-IV) and to future land-cover scenarios (**§II.A.2**).

Organisms and their Habitats on the Broader Landscape. Flourishing wildlife populations are integral components of natural communities that provide diverse recreational interests, but abundant large herbivores can diminish biodiversity, spread invasive plants, pose threats to motorists, and serve as vectors for human disease[70], [172],[173]. Populations of many native species have adapted to, and grown with, suburban development[172],[173], while the loss of natural habitats threatens other species. Understanding how animals respond to and influence their habitats within the context of increasing LULCC and climate change is thus a critical research and management concern.

In much of the eastern U.S., deer browsing, in concert with harvesting, shapes forest structure, composition, and function[173],[174]. However, in most of rural New England, browsing has not been an important factor for more than two centuries; indeed, our sampling during LTER I-III demonstrated no browsing impact. That is no longer the case. During LTER IV, two major changes were observed: deer populations grew substantially, and moose became well established in the region. Today in Massachusetts there are ≈85,000 – 95,000 deer and ≈850 – 950 moose, the latter largely in the central and western region where HFR is located[31],[175],[176]. Both species are beginning to exert pronounced impacts on forests, especially after disturbances (*e.g.,* timber harvesting, insect outbreaks, or storm damage), when regenerating seedlings and saplings are abundant[31],[176]. Because these increases in deer and moose were anticipated, HFR proactively established studies (in collaboration with USGS, Massachusetts Division of Fisheries Wildlife, and University of Massachusetts) to investigate the movement of these ungulates and their responses to landscape disturbance. In 2006, GPS-based studies funded by USGS and USFWS began on moose (and bears and bobcats) to track movements, landscape use, interactions with natural (*e.g.,* forest) and built (*e.g.,* development, roads) ecosystems, and conservation needs in large, fragmented environments. In LTER V, we will expand these studies to include landscape-scale measurements of foundation-tree regeneration in response to varying browsing pressures, harvesting, forest fragmentation and hunting pressure. We will continue to monitor a set of large exclosures that prevent browsing by moose alone, deer + moose, or neither in areas with different levels of timber harvesting (clearcut, partial harvest, and undisturbed). Finally, we have augmented our hemlock removal experiment (**§II.A.4**) with 450 m^2 deer/moose exclosures to examine ungulate interactions with HWA or salvage logging on recovering understory vegetation, associated fauna, and ecosystem processes. The results of these studies will be integrated into the scenarios of future land use (**§II.A.1**) and associated simulation modeling (**§II.A.5**). These studies are distinctive because they: (1) examine a two-herbivore system; (2) include experiments with three levels of browsing pressure rather than the simple fenced/unfenced approach; and (3) investigate the role of moose at its southern range limit in Eastern North America, in temperate oak-pine forests across a densely populated landscape[175],[177].

II.A.7. Evaluation: retrospective studies, long-term monitoring, remote sensing, and modeling



Lead investigators: Chilton, Ellison, Foster, Hutyra, Munger, Orwig, Oswald, Richardson, Thompson, Williams.

Retrospective studies. Paleoecological records provide a unique, long-term perspective that informs questions about human-environment interactions[178] (**§II.A.2**), climate change and other exogenous disturbances[179] (**§II.A.3**), losses of foundation species[18] (**§II.A.4**), and nutrient cycling[180] (**§II.A.6**). In coming decades forest dynamics will be strongly influenced by land use, rapid changes in climate, and extreme events. Forecasting potential ecosystem responses is a challenging task: multiple variables can force changes, including a range of climatic and anthropogenic drivers or disturbance triggers (*e.g.*, extreme droughts, fire, or insect/pathogen outbreaks); interactions among drivers and triggers may generate unexpectedly rapid and/or large changes; and abrupt, persistent transitions or regime shifts may occur. In LTER V, we will inform our forecasting efforts by expanding and synthesizing the rich array of paleoecological, paleoclimatic, archaeological, and historical data from New England developed in LTER I-IV to evaluate the patterns, causes, and consequences of regime shifts across a hierarchy of local, landscape, and regional scales. Records spanning the last 10,000 years feature several regime shifts, including major declines of hemlock and oak 5,500 years ago[18],[181] and sharp declines in these species and beech at the time of European arrival and land clearance (Fig. 2).[182],[183] These regime shifts also embody a range of potential drivers and triggers, including many factors of present-day interest: known and purported episodes of rapid climate change, episodic climate perturbations (*e.g.*, droughts), pathogen and insect outbreaks, changing human-population density, shifting land-use regimes (*e.g.*, sedentism, deforestation, fire, horticulture, grazing), and their interactions[178],[179],[184],[185]. At least 30,000 prehistoric archaeological sites and >100 paleoecological sites exist in New England, but most human data are unpublished and studies from neither discipline have been integrated with ecological and climatic data. We will synthesize these data for Massachusetts and conduct time-series analyses following the approach developed through a 2011 cross-LTER workshop at HFR[186] to address the following questions: (1) were past environmental and ecological transitions smooth or abrupt; (2) do abrupt transitions show evidence of leading indicators; (3) how do abrupt transitions in one ecosystem relate (in timing and rate) to those in other ecosystems regionally; and (4) how do human actions and land-use regimes shape and/or respond to episodes of rapid changes in climate and vegetation?

We will also use *long-term monitoring* to inform and evaluate our future scenarios simulations by expanding the spatial, temporal, and compositional understanding of long-term carbon dynamics employing a range of studies: the 35-ha SIGEO plot (**§II.A.4**); 3-ha Lyford plot; 0.7-ha hemlock grid; 34 plots in the EMS array where annual litter inputs, above-ground biomass increment, leaf area, and woody debris are also tracked (**§II.A.4**); 10-ha old-growth stand at Pisgah where coarse woody debris is also sampled; many experimental controls; and the more than one hundred 400-m^2 plots established in 1937 and re-measured in 1992. The 1937/1992 study provides unrivaled data across major forest types on land-use and hurricane history, soil drainage, soil chemistry, and insect impacts that allow for realistic interpretation of trends and factors associated with carbon sequestration in maturing forests[187]. Harvard Forest has been a focus for validation of remotely sensed (radar) biomass estimates that provide the basis to explicitly link these local data to regional scale patterns of carbon dynamics[188],[189],[190],[191],[192],[193]. Data from a suite of NASA-funded remote sensing projects conducted near or in the SIGEO plot will be coupled with past dendroecological investigations[194], flux tower measurements, and plot structure and composition data to better quantify carbon storage over time[194],[195],[196],[197],[198],[199].

Remote sensing. Six networked digital cameras ("webcams"), deployed as part of the PhenoCam network[200], with partial support from NSF's Macrosystems Biology program, make continuous observations of individual trees and the forest canopy[201],[202] that allow scaling from leaves to tree canopies, from canopies to satellite pixels, and from pixels to the New England region. These studies leverage: (1) radiometric measurements from continuous broadband and narrow-band measurements of incident and canopy-reflected radiation, made with an automated, directional 256 channel spectrometer, several multichannel imaging sensors, and a four-channel net radiometer recently installed at HF; (2) canopy leaf-level studies conducted by HFR REU students (**§III.A**); and (3) Webcam imagery from HFR and northeastern sites. We also will deploy a small, remote-controlled helicopter ("drone") with conventional RGB (red, green, blue) and infra-red imaging sensors to conduct more spatially extensive sampling during the growing season. The drone will cover HFR plots and provide airborne observations that complement continuous measurements from the webcams and regular over-flights by the NEON Airborne Observation Platform.

Long-term eddy-flux-tower observations of carbon, water, and energy exchange provide direct measurements of instantaneous ecosystem response (*e.g.,* canopy-scale light-use efficiency) to changing environmental conditions, constrain ecosystem models, and improve understanding of emergent properties at ecosystem scales. Merging the fast-response flux data with slower-response ecological data greatly reduces model uncertainty, and generates new and testable hypotheses based on inferred changes in model parameters needed to fit observations[42],[43]. Most importantly, flux-tower observations integrate fine-scale variability across several hectares of landscape and provide data to test predictions from scaling up individual components (*e.g.,* soil, roots, stems, leaves) and processes (*e.g.,* collar-based measurements of soil respiration), which enables a transition from describing phenomena to predicting forest-C balance, and provides a bridge from identifying plot-scale process to understanding regional outcomes.

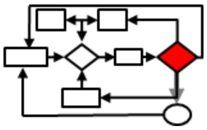
Tower observations contribute to LTER V analysis well beyond measuring carbon cycling; flux-tower observations provide the data needed to perform full carbon + climate accounting of vegetation changes. The net climate impact from ecosystem changes (*e.g.,* loss of hemlock due to HWA and LULCC) can only be understood by considering simultaneously changes in carbon uptake and release, water storage and evaporation, albedo, and boundary layer heights and wind speeds influenced by surface roughness. Coupling between these factors can be evaluated using a mesoscale modeling framework (e.g. RAMS - Regional Atmospheric Modeling System)[203],[204] that directly links to the transport modeling used to estimate regional carbon exchanges from CO_2 concentration data. Coordinated observations by eddy-flux towers of radiation balances, sensible and latent heat fluxes, and momentum exchange at the canopy interface parameterize and constrain interactive the land-surface models needed to predict the climatic consequences of vegetation change in simulated in future scenarios.

Finally, during LTER V the NEON Domain 1 tower will be installed near the existing EMS tower. Overlap of these towers for ≈5 years is required to allow NEON data to be linked with the 20 years of HFR data. LULCC studies are further informed by the Boston ULTRA-Ex project, which also incorporates social, political, and environmental sciences. The Boston ULTRA-Ex uses atmospheric measurements, energy flows estimates, advanced transportation emissions modeling, satellite measurements, and models of human activity and the built and natural environment to analyze and model spatiotemporal variation in carbon exchange across the urban-to-rural gradient from Boston to HFR.

Ongoing modeling efforts to evaluate landscape simulations will use model-data fusion based on Monte Carlo techniques to quantify and propagate uncertainties in the analytical framework[42],[44],[205],[206]. Work in LTER V will address questions related to: (1) identifying mechanisms driving the long term trends observed in ecosystem C uptake at the EMS over the last 20 years, forecasting future trends in forest ecosystem C cycling for these oak-dominated stands, and confronting model predictions with data as new observations become available; (2) testing the ability of a model calibrated at a single site to predict C uptake and storage at other regional sites (*e.g.,* Bartlett Experimental Forest, an AmeriFlux site selected as a NEON relocatable site, and integrated into the Hubbard Brook LTER); and (3) use of posterior model analyses to identify the most important sources of uncertainty in model predictions, and to target new measurements that would be of greatest value in reducing these uncertainties.

II.B. Synthesis

Lead investigators: Boose, Davidson, Donahue, Ellison, Finzi, Foster, Frey, Lambert, Melillo, Munger, Ollinger, Oswald, Richardson, Thompson, Williams.



In LTER V, we will continue to synthesize HFR's site-based, long-term data as well as lead and participate in LTER Network-wide activities that integrate research from multiple sites and advance the LTER mission. We will augment these efforts with problem-oriented syntheses coordinated through the new Northeast Science & Policy Consortium (NSPC). Synthesis products, including articles, books, and films will be distilled in a number of ways for our non-academic partners and the general public (**§III.B**).

II.B.1. Peer-reviewed synthesis articles to be produced in the next three years include:

- *Future scenarios research* using examples from the LTER network and highlighting directions for broader LTER application[50]. This is part of a forthcoming special issue of *BioScience* on LTER edited by HFR PI Foster, and including articles with eight HFR authors (lead: Lambert, Thompson) [9,45,50,207,208].
- *Analysis of past episodes of abrupt ecological dynamics* in New England forests using paleoecological, archaeological, and historical data applying new protocols for time series and threshold analyses developed for four LTER sites as part of an LTER working group[186] (leads: Ellison, Foster, Oswald).
- P*atterns and mechanistic controls of forest carbon, nutrient, and hydrological dynamics* based on analyses of the world's longest continuous record of carbon exchange, other flux records, more than 15 ha of permanent plots, climate change (warming), and N deposition experiments, and a 20-year database on soil respiration, together with snow removal and harvesting experiments . This effort will enable a robust integration and comparison of approaches, results and forest ecosystem dynamics in southern (HFR) and northern (HBR) New England (leads: Davidson, Finzi, Munger, Williams).
- *Coupled biogeochemical cycles*. HFR studies have generated a wealth of data on N cycling, stocks and inputs together with C stocks and exchanges at ambient and experimentally manipulated plots. This work will link the 20-year dataset on soil respiration and net N mineralization from many plots (harmonized with LTER IV supplemental funding; Fig. 4) and 20 years of data from the N-addition experiment in a synthesis aimed at understanding the coupling between N and C, including an evaluation of inter-annual variation and long-term trends in tower- and experiment-based C fluxes. This work will define and bound the effects of environmental drivers (temperature, precipitation, warming, N deposition, measured at the EMS) on ecosystem processes including soil C storage, NPP, and N mineralization at HFR and throughout the northeast (leads: Finzi, Frey, Melillo, Munger, Ollinger).
- *20-year synthesis of the Experimental Hurricane*, revisiting multiple hypotheses regarding forest response to disturbance (leads: Barker-Plotkin, Foster).
- *Evaluation of the Wildlands & Woodlands approach* of applying ecology and history to forest conservation for diverse LTER sites and other US regions engaged in future scenarios research (AND – Thompson, Spies; CWT – Gragson; NTL – Mladenoff, Langston; HFR – Donahue, Foster; Ozarks – Flader). This effort was launched during LTER IV at an American Society for Environmental History workshop and will be advanced with another ASEH workshop (leads: Donahue, Foster, Thompson).
- *Microbial responses to invasive plants*. HFR and related research on the direct and indirect effects of exotic plants on soil microbes, their interactions with native plants, and subsequent effects on ecosystem function. A primary focus is on phytochemical suppression of forest soil fungi by *Alliaria petiolata* as a model for similar impacts in other systems (lead: Frey, Stinson).

II.B.2. Books that synthesize HFR research, and which will be completed during HFR LTER V include:

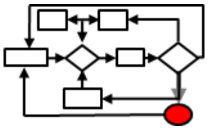
- *The role of foundation species in forest ecosystems* centered on hemlock, a species declining from HWA and warming temperatures. This volume will synthesize HFR data derived from four integrated approaches: retrospective analyses, large experiments, natural experiments, and modeling. The book will examine modern and pre-historical declines of hemlock, and contrast these with changes in other taxa including oak. Under contract with Yale University Press (leads: Foster and seven HFR authors).

- *The application of archaeology, history and ecology to conservation and future scenarios of change* based on 20 years of HFR coastal research funded by LTER and the A. W. Mellon Foundation. Under discussion with Yale University Press (lead: Foster).
- *A handbook of statistics for large-scale experiments in ecology and ecosystem science*. A synthesis volume drawn from LTER network-wide studies under contract with Sinauer Associates (lead: Ellison).

II.B.3. New mechanisms for advancing these and other synthesis activities include:

- *Northeast Science and Policy Consortium* – this new effort brings scientists from four LTER sites (BES, HBR, HFR, PIE) together with decision makers to undertake problem-oriented syntheses on regional issues of land-use and land-cover change, pest and pathogens, energy, and water quality (**§III.B.1**).
- *Bullard Fellowships* to individuals and groups (**§III.A**). Past Fellows who have advanced cross-site synthesis include: Aber and Lambert (HBR/HFR); Briggs (CAP); Brush (BES); Frey and Kittredge (HFR); Franklin, Spies, Swanson, Harmon, and Jones (AND); Knapp (KNZ); Neill (PIE); Waide, Thompson, Crowl and Brokaw (LUQ).
- *The Annual HFR LTER Research Symposium* will engage the HFR LTER (and larger) community in advancing and reviewing synthesis products. We will combine 1-3 day synthesis workshops with the full-day symposium, and use symposium sessions to get feedback on synthesis topics and products.
- *LTER-funded workshops*, as available and appropriate.

III. Education and Outreach



III.A. Training and Scholarship: K-to-Post-graduate Education

Lead investigators: Boose, Colburn, Ellison, Foster, Kittredge, Hart, Orwig, Snow, Stinson.

Our K-12 Schoolyard LTER program (sLTER) reaches >3,000 students in >50 schools each year. In LTER V, we will increase teacher recruitment, retention and engagement, and strengthen assessment. A central activity will be implementing a new workshop for experienced sLTER teachers who have completed and mastered our Level 1 Data Workshop, which emphasizes the data submission process, and Level 2 Data Workshop, an introduction to graphing project data. Like all HFR Schoolyard workshops, the Level 3 Data Workshop advances teachers' self-determined educational objectives and will be supported and mentored by Harvard Forest researchers. The Level 3 Data Workshop will focus on graphing Schoolyard data over time and making cross-site comparisons where appropriate. Additional LTER V goals for our K-12 and sLTER programs include: (1) development of a curricular module focusing on the history and future scenarios of LULCC to augment existing sLTER modules on climate change, HWA, and vernal pools, and to leverage ongoing LTER V research; (2) participation in advancing network-wide assessment strategies; (3) continued engagement of teachers in RET experiences; and (4) the placement of phenology cameras at several schools. In 2011, HFR, with support from NASA and NSF, installed the nation's first K-12 schoolyard phenology camera in the Ashburnham, MA Middle School[209]. Stand-alone analytical tools are being developed that will enable teachers and students to process camera imagery, extract phenological time series, and integrate this digital monitoring into the "Buds, Leaves, and Global Warming" sLTER module. We plan to install five more phenology cameras in K-12 schools during LTER V. We will also continue to collaborate with and advise the Kohler Environmental Center at the Choate School (9-12th grade) in CT as they develop their world class facilities and new environmental programs, field trips, and courses that tap into HFR data and facilities, and internship opportunities.

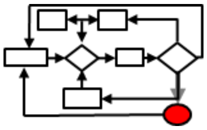
The HFR Summer Undergraduate Research Program in Ecology is entering its second quarter-century. Each year, with support from NSF REU, NASA, NEON, LTER, SIGEO, and Harvard, and through partnerships with other colleges and universities, we host ≈35 students who conduct integrated, interdisciplinary scientific research that combines field and laboratory research with statistical analysis and modeling. Student participants stay engaged with HFR, LTER, and ecological career opportunities via social networks including a Facebook group and website blog[210]. We also teach intensive courses for Harvard undergraduates, including a Freshman Seminar on Global Change Studies and an interdisciplinary January Term course, both of which extensively use LTER data, publications, and research sites. LTER V will increase the ability of Harvard undergraduates from diverse disciplines to engage with the Harvard Forest and LTER research. Finally, a summer field course in archaeology will engage 12 undergraduates in research into historical and pre-historical archaeology, paleoecology, and ecology, using HFR sites, and provide new insights on land-use history and global change.

In fall 2009, HFR began coordinating regional opportunities for *LTER graduate students and post-doctoral fellows* to forge new collaborations and syntheses. An annual gathering hosted by HFR (2010), HBR (2011), PIE (2012), or BES (2013) will allow graduate students and post-docs from each of these Northeastern LTER sites to meet, present research, and learn about each site's long-term studies.

The Bullard Fellowship Program, in its fifth decade, annually supports up to eight mid-career scientists, conservation professionals, historians, artists, and others who spend 6 – 12 months at HFR. Fellows interact with HFR researchers and bring new perspectives to bear on LTER research and its relevance to regional landscapes and policies. In LTER V, we will use this program strategically to advance cross-site activities by encouraging individuals or teams of 2 – 3 colleagues from LTER sites to collaborate on synthetic studies.

III.B. Strategic Outreach and Communication

Lead investigators: Foster, Hart, Lambert.



The Harvard Forest has made substantial commitment to outreach and communications activities that engage decision makers, the media, land managers, and the broader public to enhance the role of science in informing environmental stewardship and increase appreciation for the value of long-term ecological research. Though described as "outreach and communication," the programs are an integral component of HFR future scenarios research and problem-oriented synthesis efforts. These strategic outreach and communication efforts are designed and implemented by the Harvard Forest Science & Policy Integration Project in collaboration with partners at Highstead[211], the Northeast Science & Policy Consortium, the LTER Network Office, and the NSF Office of Legislative and Public Affairs.

III.B.1. Engaging Decision Makers

The Harvard Forest Science & Policy Integration Project seeks to address the Grand Challenges of Environmental Science[88,212,213] and strengthen the scientific basis for environmental stewardship by building stronger connections between scientists, long-term ecological research data, and decision makers at multiple levels of society. We achieve this goal by (1) engaging decision makers in the formulation of synthesis questions and narrative scenarios (**§II.A.1**); (2) convening teams of scientists to conduct policy- and problem-oriented syntheses of long-term research data (**§II.B**); (3) communicating salient findings in formats that meet decision maker needs (*e.g.*, white papers, web tools, visualizations, workshops, in-person briefings); and (4) evaluating each project to improve best practices for integrating science, policy, and education. The Wildlands & Woodlands Initiative (below) and engagement of decision makers in developing scenarios of future LULCC (**§II.A.1**) are two examples of the Project's effort[208,214]. We emphasize that the Science & Policy Integration Project is not a social science research effort; rather it applies theory and lessons from the fields of public engagement, science communication, and science and technology policy to advance many of the recommendations in the LTER Network Communication and Strategic Implementation Plans[73,94].

Wildlands and Woodlands (W&W). One of the Harvard Forest's most visible and influential science and stewardship efforts is W&W[85], which synthesized research from HFR and other sites into publications for non-scientists that call for stemming forest loss in New England and balancing wildland preservation with conservation of extensive managed woodlands[70,215]. W&W publications were developed with extensive stakeholder input and accompanied by press releases, webinars, stakeholder briefings, and a public event at Harvard University's Kennedy School of Government. W&W has contributed to important policy and management advances, including: (1) establishment of wildland reserves on Massachusetts public lands; (2) advancing conservation finance in Massachusetts to accelerate the pace of conservation; (3) launching an innovative effort to aggregate multiple parcels into a single conservation project with the goal of conserving ≈10,000-acre blocks of forest; and (4) federal conservation policy documents written by >60 regional NGOs based on W&W recommendations[71]. Since the release of W&W, HFR has forged a partnership with the non-profit organization Highstead to accelerate landscape scale conservation, host W&W events, and develop and disseminate information on relevant science, analysis, and regional conservation activities.

During LTER V, Harvard Forest will build on the success of W&W to advance future scenarios research by engaging decision makers in activities that link future scenarios with regional conservation priorities, land-use planning, and forest- and carbon-policy developments. Decision-maker engagement at the outset and throughout the development of ecologically based scenarios is critical to ensuring that the ecological research and simulations are relevant to environmental stewardship and have impacts beyond the scientific community[214,216]. Decision-maker engagement efforts began in February 2011 with two national dialogues convened by HFR in Washington DC at The Heinz Center and at the National Council for Science and the Environment. The Heinz Center dialogue included representatives from the National Wildlife Federation, the Sustainable Forestry Initiative, the National Forestland Owners Association, the Wilderness Society, and the America Forest Foundation. The dialogue at the National Council for Science and the Environment included senior federal agency representatives from the U.S. Forest Service, U.S. Geological Survey, National Park Service, and the U.S. Global Change Research Program. These dialogues established relationships with national organizations and federal agency officials, defined and clarified major national scale drivers of forest change (*e.g.,* competition for land; changing federal policy and incentives; geographic shifts in forest harvesting), and identified other regional and national scale management and policy initiatives relevant to developing future scenarios and focusing ecological research. With the national picture in mind, a group of stakeholders met in fall 2011 to define a set of narrative scenarios of landscape change for Massachusetts – the first pilot region for the future scenarios portion of LTER V (**§II.A.1**). Throughout LTER V, we will work iteratively with stakeholders to refine scenarios and develop decision rules for translating scenarios into quantitative algorithms for landscape simulations. As research advances, and in response to stakeholder needs, we will communicate results through: online simulation and visualization tools; print publications for non-scientists; media outreach; and in-person briefings to promote uptake and influence of key findings by decision makers.

Given the high proportion of Northeastern forestland controlled by private landowners, we will continue to engage landowners and local decision makers as part of both W&W and the development of future scenarios. This outreach will be guided by the findings of HFR co-I Kittredge related to landowner social networks and conservation awareness, and will include the successful *Keystone Program*, a 20-year collaboration between HFR, the University of Massachusetts, and state extension offices that educates community and regional leaders in conservation, and integrates science, decision making, and stewardship. The program annually trains 25 community leaders in a three-day intensive workshop. In return for this opportunity, participants agree to disseminate reliable information on, and educate their friends and neighbors in, relevant conservation topics. To date, there are over 250 trained volunteers in the Massachusetts-wide Keystone network who continue to serve as conservation conduits connecting people to sources of information.

Northeast Science & Policy Consortium (NSPC). In LTER V, we will extend the Harvard Forest Science & Policy Integration Project to a regional consortium that will address multiple, interactive effects of climate change and energy, water, and LULCC in the northeastern United States. Scientists from HFR, PIE, HBR, BES; additional representatives from the Cary Institute of Ecosystem Studies, the Ecosystems Center at MBL, Syracuse University, and the University of New Hampshire; and regional policy and media experts met at HFR in November 2011 to define this new consortium. The NSPC will develop new tools and expanded resources for problem-oriented synthesis, outreach training for scientists, focused exchanges with decision makers, and innovative programs to facilitate interactions between scientists and the media. The primary work of the consortium will be undertaken by interdisciplinary, inter-site teams of 8 – 12 LTER scientists and 4 – 6 decision makers who will address focused, societally relevant questions related to LTER research in 1 – 2 year projects. These will be included in HFR scientific synthesis efforts (**§II.B**). The first three projects will be: (1) developing additional future scenarios of LULCC and climate change in New England (see also **§II.A.1**); (2) informing management responses to new and evolving insects and pathogens (see also **§II.A.3**); and (3) clarifying the land-water connection with its changes in water quantity and quality (see also **§II.A.6**). The consortium will be directed by HFR co-I Lambert (HFR) in collaboration with HBR's David Sleeper. The NSPC also will include formative and summative evaluations to inform best practices for effective boundary spanning activities and communication and outreach programs.

III.B.2. Engaging Media Professionals

Expanding Media Coverage. The Harvard Forest Communications Manager (HFR co-I Hart) improves media coverage of HFR research and illuminates the value of long-term ecological research through direct engagement with media professionals. Improved media coverage of HFR research since 2010 demonstrates that a focused communication strategy strongly increases media impact. For example, press releases sent to multiple communications professionals at NSF, LTER, relevant universities, NGOs, and HFR media contacts has more than doubled HFR media coverage over the past 2 years[87]. During LTER V, we will expand these efforts and integrate them with the LTER Network's Communication Strategy[73],[207].

Journalist Training. In LTER V, we will continue to host site visits from communications faculty and students at Emerson College (mentored by HFR co-I Oswald), mid-career journalism fellows from programs such as the Niemann Fellowship at Harvard, and New England-based reporters to expand ecological knowledge in all phases of journalistic training and to create new opportunities for long-term research to be featured in the media. As part of the NSPC (**§III.B.1**), we will partner with the Logan Science Journalism Program at MBL/Ecosystems Center (directed by PIE co-I Neill) to coordinate and host longer-term "immersions" for journalists who are attuned to the questions and issues addressed in the problem-oriented syntheses by cross-site teams (**§II.B, §III.B.1)**.

New tools. We will expand our toolkit for science-media communications, and avail ourselves of rapidly evolving approaches to new media, through a partnership with the Newhouse School of Communications at Syracuse University (in collaboration with HBR co-I Driscoll), which will focus on media production and roll-out for the projects associated with the NSPC.

Scientist training. The HFR Communications Manager periodically offers trainings to research staff, graduate students, undergraduates, and sLTER teachers in communications strategies that promote research visibility, including writing op-eds, interacting with reporters and other media professionals, and devising an "elevator speech." Future workshops will include LTER themes such as expression of data uncertainty and communication about long-term processes. The Communications Manager also provides media support for research staff, including the creation of media packets for new publications.

III.B.3. Engaging the General Public

The Harvard Forest Communications Manager coordinates several projects to engage the general public and increase public understanding of the value of long-term ecological research, through: (1) LTEaRts; (2) museum programs; and (3) video projects.

LTEaRts. HFR (together with AND, BNZ, NTL) is a founding member of LTEaRts, a pilot science-arts program funded by NSF to advance new outreach mechanisms for ecological research. At Harvard Forest, artists are given access to long-term research sites and engage with research staff to produce interpretive works that are made widely available to new audiences. Works by HFR LTEaRtists are exhibited through the Fisher Museum at Harvard Forest and, along with others from the LTEaRts program, will be exhibited in spring 2012 at NSF headquarters; in August 2012 at the ESA annual meeting; and in September 2012 at the LTER All-Scientists Meeting. During LTER V, we will continue to support artists whose work broadens the visibility and increases public understanding of long-term research, and to develop new regional and national opportunities to publish and display their work.

Museums. During LTER V, we will develop new educational tools and materials to deepen public and student engagement with HFR research. The main venues for engagement will be the Fisher Museum, our interpretive trails, and the public seminar series at the Harvard Forest; the Harvard Museum of Natural History (HMNH) in Cambridge; and the HFR web site. Enhanced tools will include:

- Real-time streaming of, and distance participation in, weekly HFR research seminars;
- HFR web-site and Fisher Museum displays of (near-) real-time sensor data and visualizations from meteorological and hydrological sensors, eddy-flux towers, and phenology web-cams;
- Updates to interpretive trail signs at Harvard Forest research sites, in collaboration with NEON;
- An on-line Flora [217]and a new on-line Field Guide to the Harvard Forest Laboratory and Classroom to encourage student and public explorations of ecologically and cultural unique sites at the Forest;
- Development of materials based on the new, permanent exhibit on New England Forests at HMNH, which features HFR LTER research, has already placed a substantial amount of educational material online, and reaches tens of thousands of urban visitors each year;
- Programming for Harvard alumni including tours, panel discussions, and online resources.

Video. In summer 2011, HFR collaborated with Emerson College videographer Roberto Mighty to document several long-term experiments. Five web-based videos aimed at university audiences, media professionals, K-12 teachers, and the general public will be available online beginning in summer 2012. An ongoing collaboration with Jeremy Monroe (Freshwaters Illustrated), supported by a 3-year NSF EAGER grant, will result in short videos and still images for use by HFR and the LTER network, and will focus on LTER's relevance to societal needs. Other research-focused film projects completed by students and visiting filmmakers have been developed and made available online. The short film "Secrets of the Mud," produced by an HFRREU student in 2010, was screened at a public event at the Museum of Science in Boston[218].

IV. Mid-term Evaluation: Issues and Response

Mid-term evaluations have been used constructively by HFR for obtaining external perspectives and advice. Working closely with NSF Program Officers, the HFR Science Team structures site visits to include a comprehensive overview, specific topics for feedback, and far-reaching discussions on the future of science, LTER, and new opportunities for HFR. Strategic discussion topics always include: (1) science, education, site management, and information management goals and status; (2) transitions in personnel, experiments, and measurements; (3) infrastructure; (4) integration of HFR with other HF activities (*e.g.*, DOE/TCP, NEON, ULTRA, SIGEO); (5) balancing among site, regional, and national efforts. Strong leadership from NSF (T. Callahan, S. Collins, H. Gholz, T. Crowl) and Review Team chairs (B. Hayden, R. Waring, N. Christensen, J. Zimmermann) has made all reviews highly productive.

The 2009 review identified strengths, areas for continuity, and recommendations. Overall, HFR research, personnel, publications, and data products were deemed outstanding and characterized as repeatedly transforming the way scientists think about ecological systems. Major *strengths* included:

- Regional and synthesis activity, LTER network participation, and leveraging of LTER funds;
- Integration of experiments, measurements, and studies on land use, hurricanes, legacies, C, N;
- Site policies that encourage outside use, involvement of new HFR scientists, and a lack of distinction between LTER and non-LTER researchers and HF-based and external researchers;
- Strong and diverse education programs: sLTER, REU, RET, and graduate students;

The review team recommended the following major activities for *continuity and strengthening*; each of these recommendations has been actively embraced and expanded on in the LTER V proposal:

- *Northeastern regional integration*: expanding remote sensing (albedo), modeling, field measurements, and collaboration with other LTER sites, ULTRA's urban-rural program, and NEON;
- *Scenarios research*: addressing questions of societal relevance, forging comparison among MA, NH, and VT, and linking the study of social drivers, regional land-use change and climate change;
- *Find balance* among long-term measurements, experiments, and modeling, and between non-LTER and LTER activities and scientists;
- *Continue / expand* warming, foundation species, and moose studies, while terminating high N plots
- *Ethic* of inclusive (HF-wide) data management and leadership in LTER-wide information initiatives.

The Site Review team's r*ecommendations* for addressing gaps were discussed at length among HFR scientists and management and embraced, leading to shifts in priorities and resources and the inclusion of new scientists, facilities, research capacities and strategic activities:

- *Increase the understanding of physical factors and their coupling with ecological processes*. New Co-Is Finzi, Richardson, Hutyra, and Williams will advance coupled atmosphere, biosphere, geosphere studies using NEON and ULTRA infrastructure, modeling and stable isotope use. This group, E. Boose, W. Munger, W. Sobczak and others, are working with hydrologists (P. Barten, J. Saiers), meteorologists (R. Hellstrom), aquatic biogeochemists (P. Raymond), and geomorphologists (Sara Gran Mitchell) to improve the understanding of subsurface flows, ground and surface water exchange, and linkages between headwater processes, regional flows and societal needs;
- *Organize a multidisciplinary effort on N cycling* including 1) inorganic drivers, processes, and components and 2) microbial processes and populations. We have: constructed a new laboratory for microbial studies, included two new microbiologists PIs (Blanchard, DeAngelis), and begun new synthesis activities with Finzi, Davidson, Melillo, Frey and a LTER post-doc[13],[17],[162];
- *Integrate individual species research, ecosystem monitoring, and modeling efforts*. This focal area for LTER V research includes studies on foundation species (hemlock and oak), exotic insects (ALB, HWA, EHS, EAB), and ungulates (moose and deer populations), improved remote sensing through expanded hyperspectral capabilities (NASA and NEON collaborations), and modeling (LANDIS) with improved species attributes, and new co-Is, J. Thompson, S. DeStefano.
- *Strengthen the graduate program*. Cohesion within this group has been strongly advanced through annual workshop gatherings of northeastern LTER graduate students, while overall numbers are increasing with new co-Is from Boston University, Clark, and University of Massachusetts.
- *Enhance web page capacities*. The newly released web-site offers enhanced graphical data presentation, spatially-based data queries and time-stamped data.
- *Future leadership*. This is a central thrust of LTER V strategic activities.

V. Literature Cited

For more information about the HFR LTERIV 10 most significant publications, including links to the full articles, go to: http://harvardforest.fas.harvard.edu/notable-hfr-publications-lter-4.

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VIII. Supplementary documentation

VIII.A. Site management

Administration and Oversight. The HFR LTER program is unusual in the LTER Network as it is administered at the research site, which is home to: the PI, many co-Is, and students; the major experiments and research facilities; data management; and administrative and financial offices. The Harvard Forest is a department in the Faculty of Arts and Sciences of Harvard University; administers the Masters in Forest Science, Charles Bullard Fellowship, the Summer Undergraduate Research Program in Ecology, and Field Course in Archaeology and Paleoecology; offers undergraduate and graduate-level courses on-site and in Cambridge; and mentors the Ph.D. degree through various on-campus departments. Many senior scientists hold adjunct faculty appointments and advise graduate students at the University of Massachusetts at Amherst. Partial funding for HFR is derived from university endowments; most research activity is supported with grants. Science, education, and policy activities are also supported by various foundations.

As PI and Director of the Harvard Forest, David Foster is responsible for project administration, coordination of science meetings and the HFR research group, and site representation in the LTER Science Council. Other Harvard Forest-based senior scientists and co-Is include Emery Boose, Elizabeth Crone, Aaron Ellison, Clarisse Hart, Kathy Lambert, David Orwig, and Kristina Stinson. The local LTER team meets monthly with LTER Field Coordinator Audrey Barker Plotkin, and Director of Administration Edythe Ellin, and meets regularly with the rest of the LTER Science Team (co-Is Adrien Finzi, Serita Frey, David Kittredge, Jerry Melillo, Bill Munger, Scott Ollinger, Andrew Richardson, and Steve Wofsy). LTER co-Is focus much of their research on HFR-based projects and the Science Team is responsible for policy decisions, developing research directions, inter-site collaborations, data management policies, and representing HFR in the scientific community. All proposals for new research are submitted through an on-line system, reviewed by the Science Team for compatibility with existing and prospective research and approved and conducted under the long-term HF Land Use Master Plan (http://harvardforest.fas.harvard.edu/sites/harvardforest.fas.harvard.edu/files/HF-masterplan-exec-summary.pdf). Since its installation in 2005 more than 325 applications have been received, including ~100 new scientists. Information management and technology activities are overseen by Emery Boose (Information Manager) and Julie Pallant (System and Web Administrator) with assistance from Liza Nicoll (Data Analyst), Mark Van Scoy (Field Technician), Manisha Patel (Laboratory Manager), Brian Hall (GIS Research Assistant), and Elaine Doughty (Archivist and Librarian Assistant). Clarisse Hart (Communications Manager) oversees public relations, informal education via the Fisher Museum and, with Schoolyard LTER Coordinator Pam Snow, K-12 education. Edythe Ellin, oversees facilities and financial staff and coordinates the summer undergraduate research program with Aaron Ellison (REU PI) and Manisha Patel. The skilled Facilities staff assists with research implementation and is equipped for experimental manipulations, forestry operations, and construction and maintenance of research projects.

Enhancing Collaborations. The growth of integrated research and education programs at HFR has been accompanied by an exploding user-group of national and international scholars, educators, students, agencies, and organizations: >100 outside scientists representing >40 institutions; more than three dozen state and federal agencies and NGOS; and >3,000 K-12 students in >50 schools. The Summer Undergraduate Research Program annually draws an extremely diverse student body from >600 applicants. The 185 students hired since 2005 come from 150 small liberal arts colleges and research universities nationally; one-third of the students are from groups traditionally underrepresented in science. The Summer Program also serves as a key opportunity for recruiting new researchers as we prioritize intern funding for new investigators and projects. We engage students in team projects that link multiple students and multiple mentors in a single, broad project; these teams themselves expand collaborations between new and long-term projects. We actively seek to enhance collaboration and research by non-LTER scientists, educators, artists, and practitioners by widely advertising all opportunities – including Bullard Fellowships, the Summer Research Program, our Annual Ecology Symposium, weekly seminars, special events, and facilities – and the availability of long-term measurements and experiments through our web page, social media, e-mailings, and print venues.

The Annual HFR Ecology Symposium (third week in March) is paired with other workshops or focused discussions to provide a forum for synthesis, exchange, and development of new research directions and collaborations. The symposium engages all researchers working at the Harvard Forest (>100 individuals), is widely advertised, open to all scientists, students, and professionals in the northeastern US, and is a major venue for forging new collaborations. The symposium is well attended by agency representatives, policy makers, and educators, and abstracts are published on-line (http://harvardforest.fas.harvard.edu/symposia). The schedule emphasizes synthesis, critical review of program development, and opportunities for interdisciplinary interactions (*e.g.,* historical ecologists, atmospheric scientists, and population biologists).

Strategic Assessment, Planning, and Investment. HFR has exhibited remarkable stability over 25 years: one lead institution, whose director has served as PI; a small group of lead collaborating institutions (Ecosystems Center at MBL, University of New Hampshire, University of Massachusetts, and three departments at Harvard University); one Information Manager (co-I Boose), and a core set of experiments and measurements. The existing management framework has also worked effectively with major personnel transitions – LTER PI from John Torrey to David Foster (1994); collaborator leaderships from John Aber to Serita Frey and Scott Ollinger (2006); Steve Wofsy to Bill Munger (2006); and Fakhri Bazzaz to numerous Harvard PIs (2006) – and has integrated many new institutions, research directions, senior personnel and students, with a strong focus on diversifying the age, gender, and backgrounds of participants. During LTER V, we will use this strong stable platform to initiate a program of strategic assessment, planning, decision-making, and investment that will engage the entire HFR community and many outsiders in charting future directions and leadership of HFR. A number of factors make this exercise especially timely: the need to prepare for future senior personnel changes in science, information management, and administration; new collaborations with major national partners – Smithsonian Institution, NEON, USFS, USGS, including the 2011 SIGEO plot and 2012 launch of NEON construction; the development of Northeast Science & Policy Consortium (NSPC); and the growing group of collaborating institutions and PIs. It is critical that HFR address new opportunities along with transition, growth and diversification proactively in order to advance the LTER program to its fullest potential.

Stage I – New Investment in Individuals and Infrastructure. The first stages of this strategic process were initiated in LTER IV and include:

- Allocating all new funds and some base funding to diversifying PI and institutional participation: A. Finzi (Boston University; >8 BU faculty work at HFR), J. Thompson (Smithsonian), C. Williams (Clark University), S. DeStefano (USGS Fish & Wildlife), and K. Lambert (Director of the NSPC), A. Richardson (co-I), E. Crone (co-I), and C. Hart (Communications) (all at Harvard);
- Developing an integrated team model for the Summer Research Program and broadening REU partners to include NEON, NASA and Lincoln University, a historically black liberal arts college;
- Renovating the Torrey laboratory (with NSF FSML and Harvard funds) to be ADA compliant and to accommodate major needs of LTER, NEON and SIGEO researchers, including microbiology;
- Funding a new laboratory manager position and expanding a highly successful model of program-wide staffing for laboratory analyses and quality control, data management and analyses, field technology and equipment, field sampling and measurement, and GIS;

- Leveraging Harvard University's institutional investments in infrastructure (biomass heating plant, forest harvesting, measurements) to evaluate real-world carbon dynamics, and pro-active land protection (>500 acres in LTER III-IV) to secure the integrity of field sites;
- Developing a new web platform to advance data sharing, accessibility to research and education, and outreach and communication;
- Submitting an FSML proposal (in February 2012) to develop walk-up and radio towers to complement NEON, SIGEO, LTER studies and increase education and outreach (http://harvardforest.fas.harvard.edu/harvard-forest-media);
- Collaborating with NEON and Harvard University to extend, improve, and safeguard electrical capacity to accommodate new science, and to improve security, safety, and reliability.

Stage II – Strategic Planning Teams and White Papers. To develop strategies to best integrate and leverage new research platforms and collaborations for HFR, we will assemble small groups of co-Is and collaborators to: (1) identify opportunities for HFR and, where applicable (e.g., NEON, SIGEO) LTER nationally; (2) develop 3 – 5-page white papers exploring relevant opportunities and making specific recommendations; (3) generate reviews of these documents through focused discussions at HFR Symposia and external review; and (4) distribute the white papers from the HFR web page to other LTER sites, the LTER Network Office, and the LTER Executive Board. A parallel and analogous process will be followed for consideration of senior transitions in management, science, and information management. The preliminary charge and composition of these groups includes:

- **LTER – NEON – SIGEO** (Crone, Stuart Davies, Foster, Frey, Hart, Melillo, Moorcroft, Munger, Ollinger, Orwig, Thompson). How do we best integrate aquatic, terrestrial, and atmospheric measurements, aerial observations, experiments, and historical and social science capacity of these programs? What future experiments, measurements, and modeling activities will complement these? What new capabilities are needed to advance this combined research and education?
- **LTER – Federal Agency, including USDA/USFS, APHIS, USGS Fish & Wildlife** (Brett Butler, DeStefano, Faison, Kittredge, Lambert). How can the LTER program best take advantage of, and complement, federal programs such as the National Woodland Owners program; funding for biomass energy and urban forestry; programs to combat and control infestations of HWA, ALB, EAB; or the northeastern ungulate program? How do we best advance science and policy integration across these joint efforts?
- **LTER – ULTRA** (Hutyra, Kittredge, Munger, Ryan, Short, Stinson, Thompson, Warren). Two Boston-based ULTRA-Ex projects collaborate actively with HFR, using an urban (Boston)-to-rural (HFR) gradient to organize measurements and analyses. How can we best integrate these efforts? And, in the event of a termination of ULTRA funding, how can LTER assist with relevant research transitions and data archiving? There are strong connections to NEON and USFS (50% of ULTRA-Ex funding) and so there will be strong interactions with those groups.
- **HFR Leadership and Information Management** (Boose, Driscoll, Ducklow, Ellin, Foster, Frey, Melillo, Porter [FAS Dean], Wofsy). With the continued tenure of senior personnel (Foster and Boose each have been at Harvard for > 30 years) and the central role of the Harvard Forest in HFR, future transitions cut across institutional, scientific, and educational realms. Planning for transitions in HFR and the Harvard Forest will require strong involvement of LTER Science Team, outside science advisors, and University Deans.

VIII.B. Information Management and Technology

The Harvard Forest Information Management System (IMS) is designed to store and deliver digital information from all scientific research at the Forest. The online Data Archive (http://harvardforest.fas.harvard.edu/data/archive.html) includes most data collected over the last 25 years and selected data from earlier studies recorded in the Document Archives. As a general rule, datasets are included if they support a publication or are deemed to have long-term scientific value, regardless of the funding source. The Harvard Forest endorses the LTER Network data access policy and (with rare, documented exceptions) data are made freely available online within two years of collection.

Construed more broadly, the IMS also encompasses the Publication List, Document Archive catalog, Sample Archive catalog, and Library catalog. This section will focus on the Data Archive with occasional reference to the other components.

Personnel

The following full-time personnel at Harvard Forest have duties related to information management or information technology:

- Dr. Emery Boose (Information Manager). Duties include scientific information management, networking and telecommunications, database programming, meteorological and hydrological measurements, informatics research, and LTER Network IM activities.
- Julie Pallant (System & Web Administrator). Duties include system administration, website management, library and archive management, administrative database management, and user support.
- Liza Nicoll (Data Analyst). Duties include data analysis and preparation of data and metadata files for long-term archiving.
- Brian Hall (GIS Specialist). Duties include GIS support for research projects and GIS data management.
- Elaine Doughty (Archivist and Librarian Assistant). Duties include management of Archives and Library collections with assistance from professional librarians at Harvard.

HFR IM personnel are actively engaged in LTER Network-wide IM activities. Boose currently serves on the Information Managers Committee, Information Managers Executive Committee, and LTER Executive Board (as IM representative), and participates regularly in LTER technical working groups and workshops.

Cyberinfrastructure

The location of HFR administration and core researchers on the field site (120 km west of the Harvard main campus in Cambridge) provides many advantages, but also presents challenges for developing the cyberinfrastructure (CI) required for an LTER site. After many years of effort and resources from NSF and the university, the Forest now has CI capabilities comparable to those on campus (Table 1). Notable CI milestones (Table 2) reached during LTER IV included: upgrade of our network connection to the university from a T-1 line (1.5 Mbps) to optical fiber (100 Mbps), putting us virtually on campus; migration of our local servers to virtual servers on campus (relieving HF IT staff of server maintenance); and design and commissioning of a new field wireless network that offers exceptional speed (3-6 Mbps) and flexibility for a field installation (see below). Major upgrades to the IMS included: migration of offsite datasets to the local system, completion of EML files to level 5 and standardization to current best practices (EML version, units, controlled vocabulary; see below), and deployment of a native XML database (eXist) to support on-line queries of the cross-indexed HF Data Archive and Publications (see below).

Table 1. Cyberinfrastructure Development at Harvard Forest

Year	LTER Cycle	Internet Access (bps)	Wired Network (buildings)	Wireless Network (buildings)	Field Network (sites)	Computers	Servers	Datasets Online	EML (level)
1988	I	none	0	0	0	6	0	0	none
1991	I.5	9.6K	0	0	0	10	0	0	none
1994	II	14.4K	0	0	0	30	0	0	none
1997	II.5	56K	3	0	0	45	0	30	none
2000	III	1.5M	3	0	1	60	0	47	none
2003	III.5	1.5M	6	0	1	100	4	66	3
2006	IV	1.5M	6	4	1	100	4	95	3
2009	IV.5	100M	7	6	1	100	6	146	5
2012	V	100M	7	6	7	100	Virtual	193	5

Table 2. Cyberinfrastructure Milestones in LTER IV

2006. Research Project Application (RPA) system created
2007. Historical documents from HF Archive digitized in LDI project
2008. Field Technician & Data Analyst hired
2008. Internet access upgraded from T1 to optical fiber (100 Mbps)
2009. Telephone system upgraded from analog to digital PRI
2009. Offsite datasets migrated to HF server
2009. EML completed to level 5 with Morpho
2009. eXist deployed for EML and HF publications
2010. Field wireless network commissioned
2010. HF servers migrated to virtual servers on campus
2010. EML units standardized to LTER unit registry
2011. EML files updated to version 2.1.0
2011. Video-teleconferencing center established
2011. EML keywords standardized to LTER controlled vocabulary
2012. HF website redesigned and converted to Linux / Drupal

Information Management System

System architecture. Metadata are encoded in EML version 2.1.0 and stored in eXist. Data files are stored in a structured file system on the web server. The online Data Archive includes direct links to data files and numerous options for searching (by investigator, keyword, taxon, dates, and general search) and browsing (by ID number, title, investigator, keyword, taxon, location name, research topic, study type, LTER core area, and project status) through XQuery forms. Web pages for individual datasets are generated directly from the EML using an XSL style sheet stored in eXist. All submitted materials (data and metadata) and an exact copy of the materials posted on the web server are stored on a separate server. Servers are backed up daily at the university. A copy of the entire Data Archive is backed up to DVD annually and stored offsite.

Research project applications. All scientists conducting research at the Forest are required to submit or update an online research project application (RPA) annually for each of their projects. The RPA includes a data section where the applicant must indicate acceptance of the HF data access policy (*i.e.,* data will be submitted for publishing online within two years of collection unless the project is a student thesis project; other exceptions must be approved by the Director). RPAs are not approved if the applicant has not met his or her past data obligations.

Project design. The Information Manager is regularly consulted for large projects and proposals and is available for consultation on any project. Scientists submitting proposals for research at the Forest are strongly encouraged to include a line item for information management in the proposal budget.

Metadata. Researchers are required to download and submit a copy of the HF Metadata Form for each project. The IM staff use this information, a template file, and an XML editor (XMLSpy) to create an initial EML file. Entity-level information is then added to the EML file using Morpho and the associated data files. Once the EML file is completed and checked, it is loaded into eXist. EML encoding is regularly updated to conform to LTER best practice recommendations. During LTER IV, EML files were updated to version 2.1.0; units were standardized to current LTER best practices and custom units submitted to the LTER Unit Registry; and keywords were standardized to the current LTER controlled vocabulary with a short list (14) of HFR-specific keywords. Custom elements under `<additionalMetadata>` are currently used for HFR-specific applications, including links to related HFR datasets, project status (completed or ongoing), major research category (12 categories used throughout the HF webpage), study type (5 categories), and LTER core area (5 categories). This additional information is displayed on the web page for each dataset.

Data. Researchers are required to submit data files for each project. Though primary responsibility for data quality rests with the original investigator, each data file is checked and reformatted (as necessary) by IM staff. Any questions or problems are referred back to the original investigator. Tabular data are archived as comma-delimited text files. Spatial data are generally archived as ArcGIS or Idrisi files. Large files may be compressed to zip format.

User tracking. External users are required to identify themselves (name, institution, and e-mail address) before downloading datasets. This process is required only once if cookies are enabled on the user's system. Downloads are tracked by user ID, IP number, dataset ID, and file name.

Documentation. Detailed documentation of system architecture, information management protocols, passwords, *etc.* is recorded on paper and in a safe location (offline). Instructions for individuals seeking to use the Data Archive or to submit data and metadata are posted on the website.

NIS contributions. EML files are harvested weekly into the LNO Metacat. Meteorological and hydrological data are submitted monthly to ClimDB-HydroDB.

Related Projects

HF website. The Harvard Forest recently worked with a consulting company and Harvard Unix systems support to migrate the HF website from a Windows/html platform to a Linux/Drupal platform. The new system provides many advantages: *e.g.,* other (non-technical) staff are able to provide and update content directly; the system integrates well with our custom Administrative database, which also utilizes Apache-MySQL-PHP (see below); and content is tagged (*e.g.,* to major research category) to support comprehensive browsing across the website. In addition to a new visual design, the new website incorporates new and expanded content, including outreach (news events, featured projects, photo gallery), policy and conservation highlights, reservation information for our research facilities and conference center, real-time data display, researcher and lab profiles, and LTEaRts highlights.

Field wireless network. The Harvard Forest Field Wireless Network (HFFW) provides high-speed Internet access to field sites across the Prospect Hill Tract (http://news.lternet.edu/Article2247.html). After many years of planning and testing, the final design was achieved through a partnership among Harvard Forest, Harvard Network Operations, and Silvian Technology Services. The physical layout takes advantage of existing towers (plus a new 40-m relay tower) for line-of-sight transmissions between towers above the canopy as well as transmissions down through the canopy to surrounding experimental sites on the ground. Radios in two unlicensed frequency bands are used: 5.8 GHz for tower to tower (faster) and 900 MHz for tower to ground transmission (better canopy penetration). Joining the Harvard University network required radios with VLAN support, which makes it possible to have separate virtual networks (*e.g.*, data, voice, network management) over the same physical network. At each major research site, radios are connected via Ethernet to a network switch and Wi-Fi access point. Since all of this equipment requires line power, we decided to limit the HFFW itself to sites with power, though sensor networks and other extensions of the HFFW might be powered in other ways. As part of the Harvard network, the HFFW takes advantage of core network functions for registration, management, and security. Remote access is enabled through a dedicated VPN (virtual private network). All major nodes (radios, switches, and access points) are continuously monitored and e-mail alerts are sent whenever a node goes down. In its present form, the HFFW supports more than 60 semi-permanent devices (computers, data-loggers, cameras, and other measurement equipment), plus Wi-Fi access for laptops and smart phones, at seven major field sites. The network design is scalable to accommodate significant expansion in the future.

Video-teleconferencing center. A new video-teleconferencing center for up to 30 people was established in the Shaler Hall Seminar Room with funding from Harvard University. The new center includes a 65-inch LCD color display, remote-controlled video camera, portable wireless microphones, overhead speakers, and a dedicated PC that supports a wide range of videoconferencing software. The center is used for video and telephone conferencing as well as local audio-visual presentations.

Schoolyard website. K-12 teachers who participate in the HF Schoolyard LTER program receive instruction in information management and data analysis through a series of workshops offered each year at the Forest. At the end of the fall and spring semesters, teachers and students prepare and submit Excel spreadsheets containing the data they have collected in the field. The data are then checked and posted on the Harvard Forest website (since 2005).

Administrative databases. The Harvard Forest has an extensive online database system for applications (research projects, REU students, Bullard fellows, *etc.*) and reservations (housing, lab space, field sites, vehicles, research equipment, *etc.*). The system utilizes Apache-MySQL with Perl and (more recently) PHP programming. Originally designed by outside consultants, the system is managed by Pallant with database programming by Pallant (Perl) and Boose (PHP).

Future Projects

EML congruency checker. The Forest has received initial reports from the EML congruency checker and will address any data-metadata issues identified in those and future reports. Boose is a member of the EML metrics working group that is developing criteria for the checker.

Spatial maps. Working with the Center for Geographic Analysis at Harvard, Pallant and Hall developed a series of queryable online maps of the Harvard Forest and surrounding areas that includes bounding rectangles (extracted from the EML) for each online dataset. The maps support direct links to datasets and other digitized historical data from their spatial location. Over the past year, Nicoll created a set of simplified polygonal coordinates for each dataset that will provide a more informative map. Early in 2012 these coordinates will be entered into the respective EML files and a link will be added to the map from each dataset web page.

Migration to MySQL. Over the coming year, we plan to migrate our Schoolyard data management system from individual submission and processing of Excel files to an online data entry and query system based on Apache-MySQL-PHP, the same technology used in our Administrative database. We expect that this change will save time for participating teachers and their students, as well as our IM staff, and may serve as a model for Schoolyard programs at other LTER sites. We plan to use the same technology to support online queries of some of our larger scientific datasets (*e.g.,* meteorology, hydrology, eddy flux). It has been our experience that posting data files for download in their entirety has worked well for nearly all users and datasets. However, as some of our automated sensor data files grow in size, it would be helpful to provide users with an option to query subsets of the data.

Integration with other catalogs. Metadata for the Data Archive and Publication List are currently cross-indexed, encoded in EML or XML, and available for on-line queries using eXist. The catalog of research files in the Document Archive is currently available on-line through the university. An electronic catalog of the Sample Archives exists but is not yet available on-line. We plan to further integrate these catalogs so that users will be able to locate all publications, research files, and samples for a given dataset (at present only the publications link is enabled). HF Library holdings are cataloged and available online through the Harvard University Library.

New data types. Ecological datasets are no longer limited to simple tables. We routinely archive historical narratives, programming scripts, webcam images, and GIS data in our IMS. In LTER V we plan to expand on these efforts by: (1) Incorporation of more GIS data into our IMS as methods and best practices for documenting GIS data with EML become available. (2) Development of strategies for handling very large datasets. Some datasets (e.g. genomic data) may exceed our local infrastructure and require hosting in a dedicated community database such as GenBank.

Data versioning and persistent identifiers. A significant challenge for data providers is how to store (or recreate) previously published versions of a dataset that other scientists may have used in their analyses. This problem is particularly acute for datasets that are updated frequently or in real time. A related challenge (also significant) is how to assign persistent identifiers so that datasets may be properly cited by users and their use may be accurately tracked by providers. On our website we currently provide citation information for each dataset and the most recent revision date for datasets that have been updated. However we would like to implement better solutions as they become available in the LTER Network and the ecological community.

Other IMS enhancements. Other improvements planned for the information management system include: (1) Incorporating statistical summaries and plots for each dataset, as suggested by the mid-term review, using the statistical language R. (2) Developing effective real-time graphs of sensor data collected via the field wireless network to be displayed on the new website.

VIII.C. List of Datasets Available Online

Datasets currently available on the Harvard Forest website are listed below along with the year in which each dataset was first published online and the number of times it was downloaded during the five-year period 2007-2011. The number of downloads does not include downloads from the Harvard Forest subnet (HFR scientists) or the LTER Network Office subnet (EML Congruency Checker) or downloads by HFR IM staff. Additional search and browse options are provided on the Harvard Forest Data Archive (http://harvardforest.fas.harvard.edu/data-archive).

Dataset	Published	Downloads	Title
HF003	2000	1503	Phenology of Woody Species
HF001	2001	1256	Fisher Meteorological Station
HF008	1999	584	Chronic Nitrogen Amendment Experiment
HF004	1999	518	EMS – Canopy-Atmosphere Exchange of Carbon, Water & Energy
HF014	2003	508	Massachusetts Historical Land Cover and Census Data
HF069	1999	438	EMS – Biomass Inventories
HF070	2007	334	Prospect Hill Hydrological Stations
HF006	1999	295	EMS – Soil Respiration, Temperature, and Moisture
HF005	1999	271	Soil Warming Experiment - Prospect Hill
HF000	1999	257	Shaler Meteorological Station
HF013	2003	240	Forest Change and Human Populations in New England
HF015	2003	237	Land Use and Forest Dynamics at Harvard Forest
HF007	1999	184	DIRT Litter Manipulation Experiment
HF113	2009	182	Warm Ants Experiment - Microclimate
HF127	2009	182	Western Massachusetts Timber Harvesting Field Study
HF110	2005	181	Harvard Forest GIS
HF103	2003	171	Hemlock Tower - Net Carbon Exchange of an Old-Growth Hemlock Forest
HF017	2003	171	Vegetation Patterns of a New England Sand Plain (Montague, MA)
HF080	2009	157	Massachusetts Timber Harvesting Study
HF011	2003	155	Landscape and Regional Impacts of Hurricanes in New England
HF012	2006	146	Landscape and Regional Impacts of Hurricanes in Puerto Rico
HF024	1999	141	EXPOS: Modeling Topographic Exposure to Wind
HF116	2009	137	Harvard Forest Flora Database
HF018	2003	129	Soil Warming Experiment - Barre Woods
HF147	2009	126	The Ants of New England
HF082	2006	124	Ecosystem and Vegetation Response to Hemlock Logging
HF102	1999	122	EMS – Radiation Measurements
HF133	2009	118	CRUI Land Use Project - Litterfall, Biomass, and Productivity
HF041	2000	116	Pisgah Forest Permanent Plots
HF075	2006	115	Salamander Abundance at Harvard Forest
HF068	2007	113	EMS – Soil Respiration Along a Hydrological Gradient
HF085	2006	104	Avian Response to Hemlock Woolly Adelgid in Southern New England
HF037	2000	101	1986 Vegetation Inventory (3000 acres)
HF087	2003	93	Southern New England and Long Island Witness Tree Data
HF021	1999	93	Stand and Community Response to Hemlock Woolly Adelgid in Southern NE

HF066	1999	89	EMS - Concentrations and Surface Exchange of Air Pollutants
HF122	2009	86	1830 Map of Massachusetts
HF025	1999	82	HURRECON: Modeling Hurricane Wind Speed, Direction, and Damage
HF055	1999	82	Prospect Hill Tract GIS
HF071	2006	81	Ecological Impacts of Hurricanes Across the Yucatan Peninsula
HF081	2003	80	Landscape Response to Hemlock Woolly Adelgid in Southern New England
HF032	1999	79	Lyford Mapped Tree Plot
HF027	2000	78	Long-term Dynamics of Vegetation and Environment in Central Massachusetts
HF088	2003	78	Massachusetts Growing Degree Day and Precipitation Maps
HF030	2000	76	Effects of Acorn Production on White-Footed Mouse Populations
HF058	2003	74	Breeding Bird Species at Harvard Forest
HF023	1999	72	INTERPNT: Mapping Trees Using Distance Measurements
HF036	1999	72	Overstory Mapped Tree Plots
HF056	2003	72	Vascular Plant Species at Harvard Forest
HF106	2005	71	Hemlock Removal Experiment - Understory Vegetation
HF108	2005	70	Hemlock Removal Experiment - Air and Soil Temperature
HF079	2006	69	Invasive Species Mapping at Harvard Forest
HF016	2003	66	Dynamics of Old-Growth Forests on Wachusett Mountain (Princeton, MA)
HF150	2009	65	HEM and LPH Towers – Leaf Area Index
HF072	2005	65	LPH Tower – Net Carbon Exchange of a Young Upper-Slope Deciduous Forest
HF002	1999	65	Simulated Hurricane Experiment - Vegetation Response
HF045	2009	64	Soil Warming Plus Nitrogen Addition Experiment
HF033	1999	62	Soil Warming Experiment - Phenology and Growth of Vegetation
HF043	2009	59	Carbon Biogeochemistry of Forested Headwater Streams
HF039	2003	58	1937 Vegetation Inventory (3000 acres)
HF115	2009	56	Moose foraging in the temperate forests of Massachusetts
HF031	1999	55	Hemlock Mapped Tree Plot
HF143	2009	53	CRUI Land Use Project – Soil Properties
HF160	2010	51	Hemlock Removal Experiment - Ants and Ecosystem Function
HF073	2003	51	Long-term Dynamics of Oak & Chestnut in Central Massachusetts
HF097	2007	50	Inventory of Ants at the Black Rock Forest (Cornwall, NY)
HF128	2009	48	Impacts of Hemlock Harvesting in Central Massachusetts
HF057	2003	47	Bryophyte Species at Harvard Forest
HF076	2003	47	Long-term Vegetation Dynamics on the Massachusetts Coast
HF065	2006	45	Structure of Ant Communities in Declining Hemlock Stands
HF155	2009	44	Harvard Forest Snow Pillow
HF137	2009	43	CRUI Land Use Project – Mapped Trees
HF084	2006	41	Impact of Hemlock Woolly Adelgid on Canopy Throughfall
HF050	2006	41	Long-Term Decomposition Plots
HF026	2003	41	Vegetation Patterns Over Recent Centuries in Northeastern North America
HF126	2005	40	Hemlock Removal Experiment - Overstory Vegetation
HF153	2009	39	HEM and LPH Towers – Soil Water Content
HF040	2000	39	Hurricane Recovery Plots
HF044	2006	39	Land Use on the Southern New England and New York Coast

HF046	2006	39	North Quabbin MA Timber Harvesting Study
HF010	1999	39	Reconstruction of 1938 Hurricane (New England) and Hurricane Hugo (Puerto Rico)
HF144	2009	38	CRUI Land Use Project – Soil Respiration
HF148	2009	38	HEM and LPH Towers – Soil Respiration
HF134	2009	37	CRUI Land Use Project – Tree Canopy Leaf Area Index
HF059	1999	36	Canopy Photosynthesis Study
HF159	2010	35	Moths, Ants, and Pitcher Plants (MAPP)
HF149	2009	34	HEM and LPH Towers – Tree Growth and Above-Ground Biomass
HF142	2009	33	CRUI Land Use Project – Herbaceous Community Composition
HF061	2009	33	Impacts of Hemlock Woolly Adelgid at the Arnold Arboretum
HF090	2009	33	Source-Sink Dynamics of Garlic Mustard Invasion
HF054	2009	32	Hemlock Removal Experiment – Community and Ecosystem Impacts
HF028	2003	32	Paleolimnology of Lakes in Central New England
HF048	1999	31	Hemlock Understory Vegetation Plots
HF077	2003	31	Long-term Vegetation Dynamics in Southwestern New Hampshire
HF114	2009	31	*Sarracenia purpurea* prey capture
HF053	2006	30	Hemlock History Plots
HF109	2005	29	Effects of Prey Availability on Sarracenia Physiology
HF118	2009	29	Hemlock Removal Experiment – Ant Assemblages
HF038	2006	29	Hemlock Removal Experiment – Salamander Response
HF034	2006	29	Longitudinal Streamflow in Headwater Streams on Prospect Hill Tract
HF111	2008	29	Prey capture by carnivorous plants 1923-2007
HF049	1999	28	Gap Partitioning Among Maples (*Acer*) in Central New England
HF104	2006	27	Hemlock Woolly Adelgid Adult Population Survey (Massachusetts)
HF078	2006	27	Influence of Little Ice Age on New England Vegetation
HF130	2009	26	Hemlock Removal Experiment – Soil Respiration
HF120	2009	26	Hemlock Removal Experiment – Tree Seed Dispersal
HF083	2006	24	Ecosystem Response to Hemlock Woolly Adelgid in Southern New England
HF158	2008	24	Harvard Forest PhenoCam Images
HF086	2007	24	Hemlock Removal Experiment – Dendrochronological Record
HF029	2003	24	Long-term Stand Dynamics in Central Massachusetts
HF062	1999	23	Canopy Chemistry Study
HF138	2009	23	CRUI Land Use Project – Microclimate
HF009	1999	23	Forest Damage Patterns in the 1938 Hurricane
HF100	2003	21	Holocene Development of a Forested Wetland in Central Massachusetts
HF047	2000	21	Regeneration Following Clear-cutting Study
HF060	1999	20	EMS – Methane Data
HF095	2006	20	Headwater Habitat Streams in Central Massachusetts
HF162	2010	20	Plantation Biodiversity Plots
HF112	2008	18	Construction costs of carnivorous plants and non-carnivorous plants
HF139	2009	18	CRUI Land Use Project – Photosynthetic Light Response Curves
HF063	2003	18	Hemlock Tower - Physiological Model of CO_2 Exchange by Hemlock Forests
HF051	2003	17	Fern Understory as an Ecological Filter
HF154	2009	17	HEM and LPH Towers – Tree Growth in Hemlock and Deciduous Forests

HF119	2009	15	Hemlock Removal Experiment – Ant Diversity and Vegetation Composition
HF131	2009	14	Eastern Redback Salamander Abundance in North Central Massachusetts
HF165	2010	13	Barn Tower Meteorological Station
HF067	1999	13	EMS – Measurements of CFCs and Radiatively Important Trace Species
HF151	2009	13	HEM and LPH Towers – Litterfall
HF125	2009	13	Hemlock Removal Experiment – Coarse Woody Debris
HF105	2005	13	Hemlock Removal Experiment – Seed Bank
HF096	2007	13	Nitrogen Cycling Dynamics in Sarracenia Purpurea
HF121	2009	13	Stream Macroinvertebrates in Hemlock and Deciduous Watersheds
HF166	2011	12	Chronic Nitrogen Amendment Experiment – 20-Year Root Mass
HF141	2009	12	CRUI Land Use Project – Tree Seedlings
HF107	2005	12	Hemlock Removal Experiment – Light Environment
HF064	2009	12	Stream Subsurface Flowpaths and Macroinvertebrate Communities
HF074	2003	11	Development and Expansion of Peatlands in Central New England
HF020	1999	11	Landscape-Scale Forest Dynamics in the Luquillo Experimental Forest (PR)
HF135	2009	10	CRUI Land Use Project – Canopy Sky Factors
HF136	2009	10	CRUI Land Use Project – Herbaceous Species
HF093	2006	10	Ecology and Biogeography of a Northern Caddisfly (Cape Cod MA)
HF089	2006	10	Environment and History in a Rich Mesic Forest in Western Massachusetts
HF052	2000	10	Simulated Hurricane Experiment – Trace Gas Fluxes & Soil N Dynamics
HF123	2009	9	Hemlock Removal Experiment – Canopy LiDAR Measurements
HF132	2009	8	Eastern Redback Salamander Abundance at the Arnold Arboretum
HF124	2009	8	Hemlock Removal Experiment – Deer and Moose Browsing
HF042	2009	8	North Quabbin MA Conservation Study
HF145	2009	7	EMS – Hydrocarbon Concentrations
HF035	2000	7	Linking Community Dynamics and Ecosystem Function
HF094	2006	7	Physiological Ecology of Euryhaline Chironomid Midges (Cape Cod MA)
HF019	2000	6	Demography and Morphology of Ericaceous Species on Montague Sand Plain
HF152	2009	6	Detection Histories for Hemlock Woolly Adelgid Infestations at Cadwell Forest
HF101	1999	6	Simulated Hurricane Experiment – Litterfall
HF099	2009	6	Stream Periphyton Response to Hemlock Mortality
HF092	2006	5	Hydraulic Pathways in Leaves of Temperate Trees
HF098	2008	5	Transformation and Fate of Allochthonous Nutrients in the *Sarracenia* Microecosystem
HF157	2009	4	HEM and LPH Towers – Leaf Litter Moisture Content
HF129	2009	4	Linking Xylem Diameter Variations with Sap Flow Measurements
HF175	2011	4	Tree Growth and Coarse Woody Debris in Regenerating New England Forests
HF161	2010	3	Hemlock Removal Experiment – Litterfall
HF170	2011	3	LTER Thresholds Working Group - Synthesis Data
HF167	2011	2	DIRT Litter Manipulation Experiment - 2008 Autumnal Litter Input
HF168	2011	2	Ecophysiology of carnivorous plants
HF146	2009	2	Organic and Inorganic Nitrogen Uptake by Sarracenia Purpurea
HF163	2010	2	Short-Term Effects of Soil Warming and Nitrogen Addition on Vegetation

HF174	2011	2	The Role of Moose and Deer Browsing in Harvested Forests of Southern New England
HF192	2011	1	Annual Maps of Mean Winter Temperature for Eastern North America
HF140	2009	1	CRUI Land Use Project – Herbaceous Stratum Sun-fleck Regimes
HF156	2009	1	HEM Tower – Sapwood Temperatures in Hemlock Trees
HF171	2011	1	Soil Warming Experiments – Root and Mycorrhizal Respiration
HF172	2011	0	Allelopathy of *Frangula Alnus* to Native New England Wetland Vegetation
HF182	2011	0	Bayesian Analysis of Tree Distributions Across Space and Time
HF183	2011	0	Canopy Phenology, Remote Sensing, and Microclimate
HF169	2011	0	Decomposition Dynamics in the Sarracenia Purpurea Microecosystem
HF117	2009	0	Harvard Forest Herbarium Database
HF179	2011	0	Hemlock Removal Experiment – Inorganic Nitrogen Pools and Tree Composition
HF177	2011	0	Hemlock Removal Experiment – Soil Arthropods
HF173	2011	0	How Personal Connections Shape Decisions About Private Forest Use
HF184	2011	0	Lake Sediment Pollen from Berry Pond (North Andover MA)
HF185	2011	0	Lake Sediment Pollen from Blood Pond (Dudley MA)
HF187	2011	0	Lake Sediment Pollen from Knob Hill Pond (Marshfield VT)
HF188	2011	0	Lake Sediment Pollen from Little Pond (Bolton MA)
HF186	2011	0	Lake Sediment Pollen from Little Pond (Royalston MA)
HF189	2011	0	Lake Sediment Pollen from Wildwood Lake (Long Island NY)
HF180	2011	0	Limits to Proteolytic Enzyme Activity in Temperate Forest Soils
HF190	2011	0	Modeling Range Expansion of the Hemlock Woolly Adelgid
HF176	2011	0	Nonstructural carbohydrates in forest trees
HF181	2011	0	Regional and Historical Variation in Garlic Mustard Distribution
HF191	2011	0	Regional Distribution and Abundance of Eastern Hemlock
HF178	2011	0	Suspended Sediment and Particulate Organic Matter in Bigelow Brook
HF091	2006	0	The Analytic Web: Process Metadata for Ecological Analysis and Synthesis
HF022	1999	0	The PnET Models: Modeling Carbon, Water, and Nitrogen Dynamics
HF164	2010	0	*Umbilicaria mammulata* and nitrogen deposition

VIII.E. Postdoctoral mentoring plan

Postdoctoral Research Fellows supported by HFR are mentored directly by senior research personnel and have access to outstanding training opportunities at Harvard and collaborating universities, and throughout the network of HFR collaborators. For example, post-doc strategic professional development resources are offered by Harvard's Office for Postdoctoral Affairs, including: monthly talks; panels; discussions on *curriculum vitae* and resume writing, interviewing, mentoring, writing grant proposals, formal speaking, and presentation development; an informational series on starting and managing a lab; individual, one-on-one career counseling; grants to attend training courses (*e.g.*, GIS methods); and a course on professional and ethical practices in research to meet NSF and NIH requirements. HFR post-docs will be provided with office space, lab space, computer, and internet access at the Harvard Forest, Boston University, and University of New Hampshire where they can regularly interact and meet with their direct supervisors to discuss research progress, data analysis, manuscript development, and long term career opportunities. Post-docs typically attend at least one national conference per year, attend weekly seminars by outside speakers, and are able to participate either in person or electronically, in weekly Harvard Forest lab meetings, where research staff regularly share ideas, datasets, and manuscripts for feedback, and have opportunities to practice presentation skills in a collegial, supportive academic environment. They are also invited to participate in the annual graduate student and post-doc gathering described in section III.A. Finally, post-docs from all institutions can mentor undergraduates in the Harvard Forest Summer Research (REU) program and often lecture or teach courses in nearby colleges and universities.

X. Facilities, Equipment, and Other Resources at the Harvard Forest

A standalone department in Harvard University's Faculty of Arts and Sciences with a full-time staff of approximately forty, the Harvard Forest in the central Massachusetts town of Petersham has operated as Harvard University's 1400-ha field laboratory and classroom for ecological research and education since 1907. With intensively documented and diverse forests, wetlands, streams, water bodies, and pastures complemented by expansive research, educational, and residential facilities, the Harvard Forest provides a complete base for research in forest, ecosystem, and historical ecology and biosphere-atmosphere interactions.

Since 1988, when the Forest became an NSF LTER site, the Forest has witnessed phenomenal growth in scientists, educators, students, collaborators, research, and education programs, and associated laboratory, computing, archival, teaching, and housing facilities. The Harvard Forest is the core site for the Northeast domain of the National Ecological Observatory Network (NEON), which has begun field measurements and will commence construction of major research installations in 2012. The Forest also recently completed the installation of a 35-hectare permanent gridded plot as part of the Smithsonian Institute Global Earth Observatory (SIGEO plot).

Shaler Hall, the 2,800 m^2 central building for research, administration, and education, contains 30 offices, a seminar room, a 10,000-volume library, dining facilities for 50, laboratories for paleoecological, morphological, computational, and GIS studies, and a complete herbarium of the local flora. Digital projectors are available in the Fisher Museum auditorium (seating for 125) and Common Room (seating for 100). The new audio-visual facility in the Seminar Room supports video-teleconferencing for up to 30 people. The **Fisher Museum** houses the Harvard Forest Models, twenty-three dioramas portraying the history, ecology, and management of central New England forests, and video displays for visitors on the first floor. A large space for poster sessions and permanent exhibits related to forest ecology, including root biology, soil science, plant/pathogen interactions, the effects of disturbance on vegetation, and the local history of land-use in Petersham, is located on the second floor.

Laboratories. The paleoecology laboratory includes several compound and dissecting microscopes, a pollen and spore reference collection, drying and combustion ovens, and a fume-hood and centrifuge for preparation of pollen, charcoal, macrofossil, and ^{14}C samples. The dendrochronology lab contains a Velmex tree-ring measuring system and International tree ring data base (ITDRDB) software. The newly-renovated (NSF FSML awards in 2003 and 2009), ADA-compliant 370 m^2 John G. Torrey Laboratory is a multi-investigator, multi-institutional facility adapted for diverse research interests and educational activities. It includes two fully-automated research greenhouses, offices, and wet-labs for ecophysiology, biogeochemistry, microbial/molecular ecology, and microsocopy. Facilities include chemical storage and fume hoods, two biosafety (laminar-flow) hoods, Lachat 8500 autoanalyzer, Elementar CHN analyzer, distilled and RO water system, ultra-clean dishwashers, autoclave, -80° C freezer, microplate reader, spectrophotometer, precision balances, dissecting microscopes, muffle furnace, and drying ovens.

The **Harvard Forest Archives,** the physical part of the Information Management system, includes a soil/plant tissue archive facility that can provide storage and electronic cataloging for over 32,000 samples, a cold storage facility, and an extensive document archive of the Harvard Forest, comprised of maps, photos, data sheets and related materials representing >100 years of research activity. The archives also includes the Harvard Forest Herbarium, which contains >3,000 specimens of >700 species collected locally over the last 100 years.

Field Facilities. The four major tracts of the Harvard Forest are managed under a long-term plan that includes three land-use zones: wildland reserves (no active management or destructive research); experimental forests (active manipulation allowed for scientific, educational and demonstration purposes); and woodlands (harvesting and scientific manipulation allowed). The Environmental

Measurement Station (EMS), the oldest continuously operated eddy-flux and micrometeorological tower in North America (*est*. 1989), is located approximately 1.7 km from Shaler Hall, in the middle of the 400-ha Prospect Hill Tract. Two additional flux towers provide parallel measurements in an old hemlock forest in the early stages of infestation by the hemlock woolly adelgid and a rapidly re-growing clearcut. A recent FSML proposal (submitted January 2012) seeks to expand on the two walk-up towers that provide access for canopy measurements, additional instrumentation and education. A mobile canopy access vehicle with a 22-m reach (funded by a NSF MEU grant in 2001) and three-person platform adds great flexibility for diverse studies. Collaboration with NEON is expanding this field infrastructure: existing buried primary electrical cable to the EMS and other experiments will be replaced and extended throughout the core area of Prospect Hill; an Aquatic Instrumental Array will complement existing stream gages and biogeochemical measurements and a Fundamental Instrument Unit (FIU) tower will eventually replace the EMS tower after several years of parallel operation. An automated weather station (*est*. 2001) complying with LTER Climate Committee guidelines replaces the earlier manual station (*est*. 1964) while a new snow pillow (*est*. 2009) measures the water content of snow pack.

Large experiments. These core LTER facilities accommodate many outside collaborators and include: Soil Warming (*est*. 1990 and 2004), Nitrogen Saturation (*est*. 1988), Hurricane Manipulation (*est*. 1990), air warming study of seedling and ant responses (*est*. 2009), four large clear-cuts with deer/moose exclosures (*est*. 2008-12), and Hemlock Removal Experiment (*est*. 2003). Forest harvesting for timber and cordwood to fuel a planned central biomass facility is conducted under a long-term management plan to support studies of ecosystem dynamics and a comprehensive analysis of carbon dynamics with small-scale biomass heat production.

Permanent plots address the diverse needs of HFR and collaborating scientists, and include: >100 400m^2 plots across all forest types on Prospect Hill (*est*. 1937); control plots associated with each experiment (*est*. 1988-2012); Lyford Grid (*est*. 1967), a 4.5-ha oak forest measuring all stems, downed wood and disturbances; and a 0.7-ha Hemlock grid (*est*. 1985) for measuring tree structure and function. The 35-ha SIGEO forest dynamics plot (*est*. 2011-2012) encompasses hemlock, oak and wetland communities, two eddy-flux towers, and aquatic infrastructure. All stems (>1cm) are measured and mapped and extensive non-destructive complementary measurements are taken on ecosystem process, plants, and animals.

Information Technology. An optical fiber circuit (100 Mbps) connects Harvard Forest to Harvard University's main campus and to the Internet. Wired and wireless network access is available in all offices and labs and in some residences. A new field wireless network (funded by NSF and jointly managed by the Harvard Forest and Harvard Network Operations) provides high-speed Internet access to major experimental sites across the Prospect Hill Tract. Scientific data from all projects (regardless of funding) are documented and posted in the HFR data archive within two years of collection. Virtual servers for the HFR website and associated databases (as well as shared disk space for HF staff) are provided by the university on the main campus in Cambridge MA.

The **five-person facilities staff** is skilled in experimental manipulations, forestry operations, construction, and maintenance. Large equipment includes a back-hoe, tractor, skidder, dump truck, flat-bed truck, three pick-up trucks, and a 12-passenger van. The staff operates a wood-working shop and small technology shop that serves as the center for equipment design and building maintenance. A sawmill is operated as needed.

University-owned **housing** includes Raup and Fisher Houses located adjacent to Shaler Hall that accommodate visiting groups and summer students (capacity of 40), and an additional 15 residences occupied by visiting faculty, graduate students, and post-doctoral fellows and their families.