Sustaining Long-term Research Through Changing Times at the Harvard Forest

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> "Given the unique nature of permanent plots, the involved effort, and results, permanent plots are more than a method of science; they may be viewed as a cultural phenomenon. Permanent plots deserve to be treasured as living national monuments" (B. Zeide 2001).

Introduction

Walk along the nature trails at the Harvard Forest in Petersham, Massachusetts, and you will see a forest that is fairly typical for southern New England. Airy stands of oaks and maples are interspersed with the deep shade of hemlock groves. Stone walls and old farm roads run throughout the woods. Look more closely and you will see wood, metal and PVC stakes marking permanent plots and an array of devices that measure forest metabolism and change, from dendrometer bands on individual trees to towers that quantify the exchange of carbon, water and energy between the forest and the atmosphere. In a hemlock stand in the middle of the forest, the trees bear numbered tags in a large plot originally installed to document the gradual changes following 19th century land use but now poised to capture the dramatic demise of the hemlocks as the exotic hemlock woolly adelgid invades the forest. What makes this typical forest remarkable is the decades of documentation and interpretation of this landscape and its place within the region. This painstakingly documented history provides a unique basis for tracking of how these forests are changing over time.

Forest ecosystems are shaped by processes that unfold over the life spans of trees and their development is often directed by infrequent disturbances. As a consequence, the Harvard Forest integrates a long-term perspective into its overall research program. We develop paleoecological reconstructions that provide a millennial perspective on vegetation dynamics, utilize historical records of land use, develop stand reconstruction techniques (Henry and Swan 1974, Oliver and Stephens 1977), maintain a broad series of permanent plots (Foster and Aber 2004), initiate large experimental manipulations (with controls) that we evaluate for decades (Cooper-Ellis et al. 1999, Melillo et al. 2002, Aber 2004), and measure forest metabolism at instantaneous to multi-year time scales (Barford et al. 2001).

Permanent plots are a key component of a long-term ecological research program. They provide direct insights into forest development, which complement reconstructive and space-for-time techniques. Whereas chronosequence studies may confound site differences and temporal changes, in long-term plots forest processes are captured in real time on the same site. Continuous monitoring of permanent plots allows forest stand-level studies of vegetation change through time in which individual tree development, growth, mortality and decomposition can be followed. Sites in which the trees are mapped provide detail into the mechanisms of forest change and spatial patterns of forest dynamics.

Results from permanent forest plots are crucial to the development and validation of forest process models. Predictions about how forests change over time and respond to climate change, invasions of exotic organisms, wind and fire disturbance, and forest management all need to be grounded in long-term observation. In designing experiments to test the effects of change to the forest, permanent plots can provide useful comparisons in addition to experimental controls.

In this paper, we catalog ongoing permanent plot studies at Harvard Forest (Table 1), and highlight results that would have eluded shorter term studies. We don't cover a suite of large experimental manipulations that examine the effects of soil warming, nitrogen additions, hurricane disturbance and exotic insect infestation (Cooper-Ellis et al. 1999, Melillo et al. 2002, Aber 2004), despite the fact that they underscore the value of long-term studies. We do briefly discuss our field and data management strategies for maintaining continuity for these long-term studies, and comment on how the Harvard Forest has thrived for nearly a century.

Extensive Plots

Since 1909, quantitative forest inventories of the Harvard Forest have been undertaken every 10-30 years. One of these inventories was completed in 1937, fortuitously providing a detailed set of baseline data to compare to the post-1938 hurricane forest (Foster 1992, Motzkin et al. 1999). In 1992 permanent plots in the approximate locations of the 1937 inventory plots were re-established (Figure 1). An augmented sampling of all vascular species and soil chemical and physical properties allowed an analysis of the relative importance of site factors, 19th century land-use (clearing for till agriculture and pasture), and 20th century disturbance (1938 hurricane, logging) in determining vegetation patterns and composition. This study helped to elucidate persistent effects of past land-use and disturbance on current forest structure and function (Motzkin et al. 1999, Compton and Boone 2000). To our surprise, the signal of the intensely damaging 1938 hurricane was fairly weak. In contrast, vegetation patterning by historic land use actually became more distinct between the 1937 and 1992 inventories, in part due to the increasing prominence of hemlock over time in former woodlots.

A similar study was established in a pitch pine-scrub oak system at the Montague Sand Plain in the Connecticut Valley to examine the effects of land-use on modern vegetation and soils in a setting with little environmental variation (Motzkin et al. 1996, Compton et al. 1998). Soil analyses confirmed the homogeneity of site conditions. Modern vegetation patterns in this sand plain are strongly patterned by land-use. Pitch pine was found on formerly plowed sites, whereas scrub oak occurred mainly on sites that had never been plowed. Several other species showed striking patterns by land-use history (Motzkin et al. 2004). Slow-growing, clonal plants have not recolonized formerly plowed sites, even after 50-100 years (Donohue et al. 2000). The permanent sampling points established for that effort have been used subsequently for diverse studies ranging from assessing the impacts of wildfires to monitoring the success of sandplain restoration efforts. The serendipitous use of permanent plots for unanticipated natural or human experiments is one of their great values.

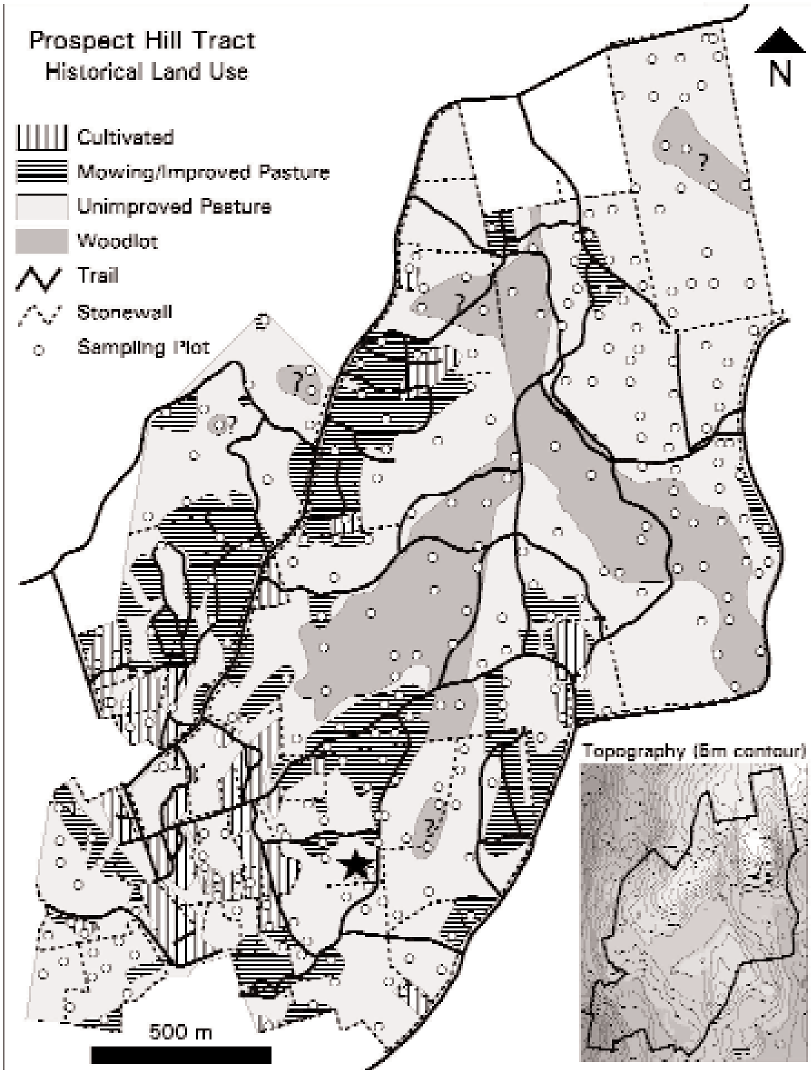

Figure 1. Historical land use on the Prospect Hill tract, as reconstructed from historic records and soil sampling. Only 16% of the tract remained wooded through the historical period. Former cultivated areas and improved pastures/hay fields have soils that show evidence of past plowing, whereas in areas formerly in unimproved pasture the forest vegetation was cleared but soils were not significantly altered. Dots indicate the location of vegetation sampling points. The star indicates the location of the Lyford Grid. Modified from Motzkin et al. 1999.

Another focus of our long-term studies is the effect of selective removal of an overstory species by a pest or pathogen outbreak. A series of permanent plots was established in 1995 in hemlock forests in southern Connecticut along a gradient of infestation by the lethal hemlock woolly adelgid (*Adelges tsugae*). These permanent plots give us the opportunity to examine the stand and ecosystem consequences of losing hemlock. Ten years of monitoring these plots has revealed that hemlock decline can take years to decades, and documents the major changes in species composition, microenvironment and nutrient cycling that occur with loss of hemlock (Orwig and Foster 1998, Orwig 2002).

Mapped Forest Sites

Our studies of the ecosystem consequences of current hemlock decline are nicely complemented by mapped hemlock forest plots at the Harvard Forest. The Hemlock Woodlot is a 0.7 ha site, and there are four additional 0.1 ha hemlock plots at other locations in the Forest. These plots have been subject to intensive paleoecological reconstructions (Foster et al. 1992, Foster and Zebryk 1993, McLachlan et al. 2000) from small basins and humus monoliths, allowing the reconstruction of stand-scale history of vegetation. All sites have been dynamic as a consequence of climate change, natural disturbance, European settlement, and the abrupt decline of hemlock 4500 years BP. We also have individual tree measurements for the sites from 1990 and 1999 (*Hemlock Woodlot*) or 1995 and 2002 (0.1 ha plots). In 2002, we rated crown vigor of all hemlocks in these sites to begin forest health assessment before the hemlock woolly adelgid invades the area. Studies of soil N flux, understory vegetation, and a sapling census were added in 2002. These local plots provide valuable baseline information and complement the extensive plots in Connecticut as this "natural experiment" unfolds.

Another study initiated in 1990 was designed to be a manipulative study looking at selective tree death. Although the treatments were not implemented as we turned our attention to the unfolding hemlock decline in our region, these four 0.25-ha plots are valuable reference stands representing typical red oak-red maple forest for this region. These plots have been used as a base for studies of the competitive effect of ferns on tree regeneration (the 'understory filter' effect) (George and Bazzaz 1999a, 1999b), tree crown morphological plasticity (Muth and Bazzaz 2003), novel tree mapping techniques (Boose et al. 1998, Kay 2005) and tree canopy light modeling (Anderson 2004). In Fall 2003, stem diameters were remeasured and new stems that had grown above 5cm dbh were tagged and mapped. A treefall gap occurred in one plot during the interval, but no noticeable canopy disturbance or major stand changes were otherwise noted. We will continue to census these plots every 10-15 years.

A particularly detailed 3-hectare study was established in a typical mixed hardwood site with variation in soils and damage from the 1938 Hurricane. Walter Lyford, a soil scientist at Harvard Forest for many years, made large-scale (1" = 5') maps of the site showing trees, windthrows, stumps, soils, even boulders (Figure 2). Living and dead trees have been remeasured four times from 1969 – 2001. This rich spatial data set can be examined in many ways; one recent analysis showed persistent effects on forest stand development and tree species composition of the 1938 Hurricane (Wilson 2002). This is in contrast to the weak hurricane signal seen in the Prospect Hill-wide analysis described above, perhaps because of the smaller, more intensive scale of study on a site with relatively uniform land-use history.

(More) Legacies of the 1938 Hurricane

Two other permanent plot studies provide further insight into the legacies from the 1938 Hurricane. Research at the Harvard Tract of the Pisgah Forest, an 8-hectare area of old-growth hemlock-white pine forest in southwestern New Hampshire, has been ongoing since the 1920s (Branch et al. 1930). The current set of permanent forest plots (fourteen 20x20m plots) was established in 1984 (Foster 1988) and trees are censused every five years. This stand was severely damaged by the 1938 hurricane. The hurricane eliminated white pine from the stand, while beech, red maple and black birch became important species (Figure 3). Tree density is approaching pre-disturbance levels now, but basal area may not recover to the very high pre-hurricane levels after loss of the emergent white pine. The ongoing monitoring of the forest complements and extends the intensive reconstruction of one plot by Henry and Swan (1974), which documented how past wind and fire disturbances shaped the forest at Pisgah, and the long-term historical reconstructions conducted through paleoecological analyses of small hollows and wetlands (Schoonmaker 1991).

At Harvard Forest, fourteen small permanent plots (0.025-0.1 ha) were established in 1940 to document vegetation recovery after the 1938 hurricane. All but one of the plots was dominated by white pine before the hurricane; fifty-three years later, red oak and red maple share importance with white pine. These plots add to our understanding of successional trends in both trees and understory vegetation (Spurr 1956, Hibbs 1983, Mabry and Korsgren 1998).

Field and Data Management Issues

Maintaining field sites and records for long-term plots is a major commitment, especially when results do not easily lend themselves to publication at each remeasurement cycle. Harvard Forest has a full-time research assistant, an archivist and a data manager engaged in this activity, and employs crews of undergraduate research assistants each summer. Even with this commitment, it is a challenge to keep up with plot remeasurements and data management, especially as new studies are developed. However, insights from the long-term plots are irreplaceable and this continuing legacy is central to the value of Harvard Forest as a research and educational institute.

We maintain maps of ongoing field studies on Harvard Forest land, and have detailed stand maps of all historic operations, including forest management and research activities. We have recently brought compartment-level records together into a GIS database. On the ground, we try to ensure that permanent plots are marked with lasting monuments (e.g. metal corner posts), and that markings on temporary research plots are removed after a study is completed.

Harvard Forest has a stand-alone archive to store maps, historical documents, and research study data. The building is climate controlled and records stored there are noncirculating. The archive helps make studies more accessible than if record-keeping was dispersed among the file cabinets of the researchers who initiated the studies, especially since there are many researchers who are based at other institutions. Records are cataloged and indexed by topic, author and date. Stand records from 1907 and other key documents are backed up on microfilm, which at this time is a less expensive option than digital scanning.

Electronic storage of study data is constantly evolving with advances in technology, with the goal of an accessible, well-documented, searchable database of studies. Harvard Forest has a searchable, web-based data catalog (http://harvardforest.fas.harvard.edu/data.html) linked to the Long-Term Ecological Research Network (http://lternet.lternet.edu/). Data sets are accompanied by metadata that describe the contents of each data column, and detailed study descriptions.

Information management is an entire field, and there is always more work to be done to develop effective, lasting systems for storing and sharing data. However, simply the act of bringing research files to the paper or electronic archive forces a higher level of organization from busy researchers than if a study remained in a more idiosyncratic format.

Sustaining Long-term Research

Harvard Forest will celebrate its centennial in 2007. The first 100 years of research make a strong case that understanding the history of the forest is a key to interpreting the present and predicting the future. A brief look at the history of Harvard Forest may help inform how this institution has been able to sustain its efforts over the past century.

The Harvard Forest has been a part of the professional lives of many foresters and ecologists. Students from Harvard University and many other institutions have contributed to the long-term research here; many have built their studies with the well-documented history of the land as the foundation. The combined research and education mission of Harvard Forest has allowed the value of this place to spread around the world through the many students, managers and researchers who have spent time here.

There have been junctures in Harvard Forest's history that might have proved fatal to the institution had not creative thinking and strong leadership intervened. For example, the great New England hurricane of 1938 felled any hope of the Harvard Forest becoming the example of sustained-yield forestry that was originally intended. However, the researchers and students had already broadened their view to examine the roles of land-use history and disturbance in shaping the forest and in turn, how the land would respond to management. Thus, Harvard Forest was poised to delve into a wide range of ecological studies that complemented and extended the earlier forestry work. At another juncture, funding from a critical foundation expired, leaving the future of Harvard Forest uncertain. Again, the carefully documented forest records, broad ecological thinking and leadership from within and beyond the university positioned the Harvard Forest to be selected by the National Science Foundation as a Long-Term Ecological Research site. Historical insight and a lengthy record of measurement on permanent plots are invaluable and will serve well other sites that have or are developing a legacy of long-term studies.

Conclusions

Well-documented permanent plots form a living legacy of research that continues to grow and change, and provide an excellent base to answer new questions (Zeide 2002). Permanent plots vividly illustrate the concept of forest change over time.

To Summarize...

> Permanent plots can be used to answer questions unanticipated when the study began. For example, the hemlock study plots at Harvard Forest form a valuable basis for understanding hemlock forest dynamics before the invasion of the hemlock woolly adelgid, and will help us interpret future change with the expected invasion of the insect and decline of the hemlock.
>
> Permanent plot studies can prompt shifts in scientific thinking. For example, forested plots at Harvard Forest have been an important part of ongoing research that illustrates the long-term legacies of human land-use on forest ecosystem structure and function. These insights are leading ecologists to explicitly consider land-use history in their study designs, and are promoting a shift in thinking about the role of humans as an actor in all ecosystems. For example, the history of the forest surrounding the carbon flux towers at Harvard Forest is explicitly included in explanations of long-term trends in carbon storage (Wofsy 2004).
>
> Permanent plots contribute to our understanding that forests are dynamic and constantly responding to a suite of disturbances and stresses. This understanding helps inform forest conservation and management. For example, the Harvard Forest has published a recent report that recommends setting aside large forest reserves. In contrast to restoration projects that aim to bring a small area to a pre-defined state, large reserves would allow for change and for natural processes to operate (Foster et al. 2005). Equipped with an extensive series of permanent plots, such reserves will provide an invaluable reference and resource for future generations.

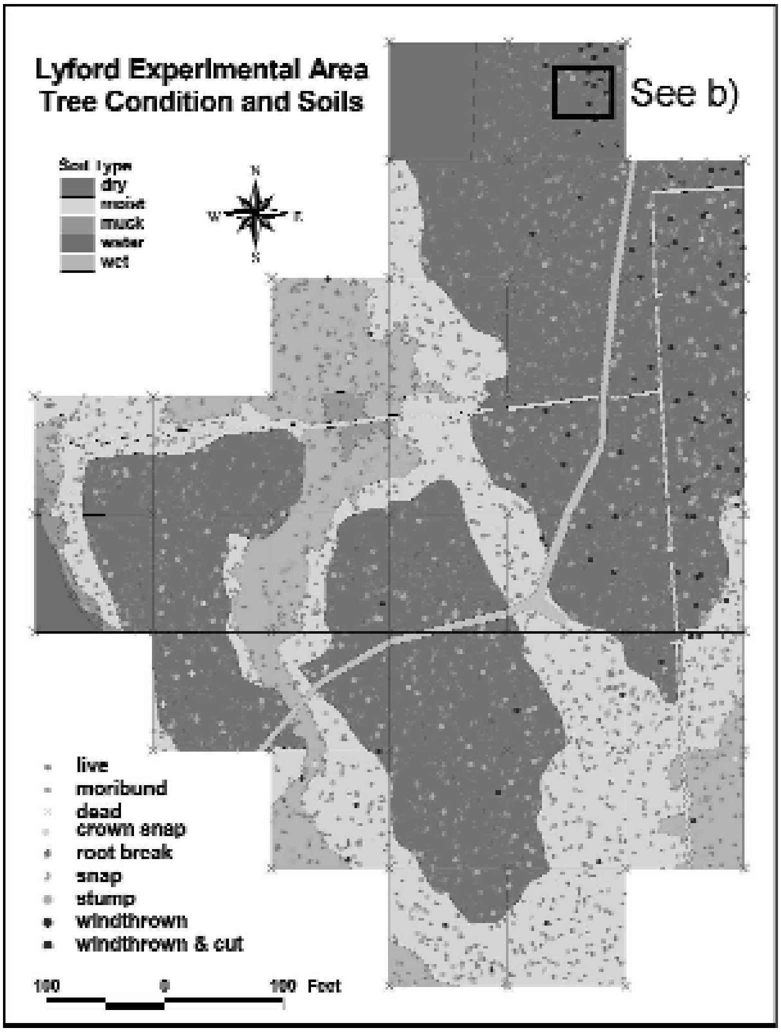

Figure 2a. The Lyford Grid details the structure and dynamics of a typical central New England hardwood forest. (see Figure 1 for location within the Prospect Hill Tract). Individual living and dead trees have been remeasured four times since 1969, and overlaid on mapped site and disturbance features.

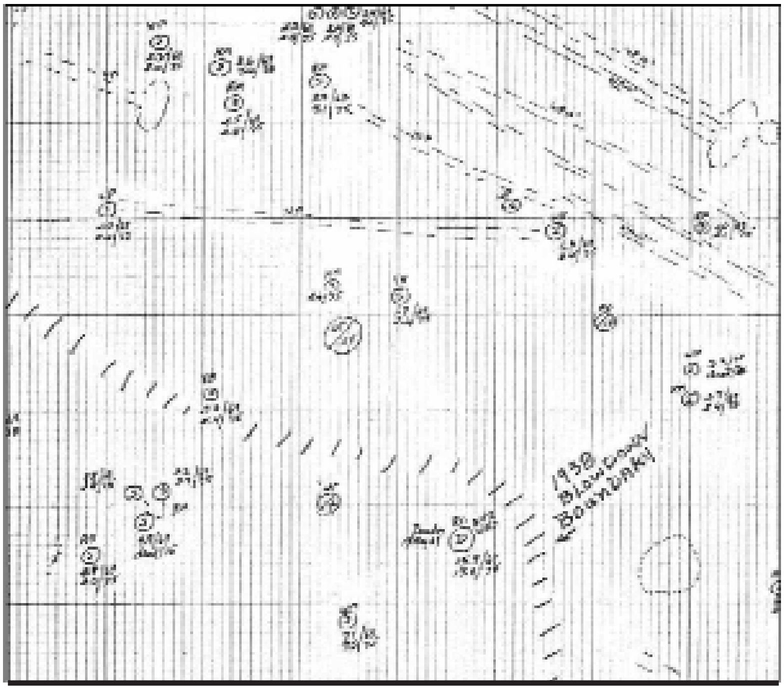

Figure 2b. The scale of the original, hand-drawn maps is 1 inch = 5 feet on the ground.

Table 1. Major permanent plot studies at the Harvard Forest, Petersham, Massachusetts (42.5°N, 72°W).

A. Extensive Plots

Study	Year established	Location, size and number of plots	Core Measurements	References
Hurricane Recovery Plots	1940	Fourteen 0.025-0.1 ha plots across the Harvard Forest ownership in Petersham	Tree density by species (1940, 1941, 1942, 1944, 1948, 1978, 1991); Understory vascular vegetation species presence/absence (1940, 1948, 1978, 1991)	14, 16, 27
Prospect Hill Vegetation Survey[a]	1937	In 1992, 161 plots from the 1937 inventory were re-established, plus 108 more plots that were open land or plantations in 1937. Plot size: 22.5 x 22.5 m, located across the 375 ha Prospect Hill Tract of Harvard Forest	Trees by size and species (1937, 1992); Advance regeneration, vascular understory plants, bryophytes (presence/absence in 1937, cover in 1992); Soil physical and chemical analysis, including evidence of plowing (1992)	5, 19, 21
Montague Sand Plain studies	1993	121 20x20m plots across the ~775 ha sand plain in the town of Montague, MA	Tree size, species, sprouts, age on a subset of 11 plots (1993, partial resurvey 1997); Saplings, vascular understory plants cover (1993); Soil physical and chemical analysis, including evidence of plowing (1993)	6, 7, 19, 20
Hemlock Woolly Adelgid Plots	1995	46 plots across 8 hemlock-dominated stands with differing initial adelgid infestation, 20m x 20m plot size, south-central CT	Tree size, species, hemlock vigor rating (1995-1997, 1999, 2001, 2005) and stand age structure; Vascular species cover, seedling density and height (1995-1997, 1999, 2001, 2005); Soil moisture, temperature, pH and nitrogen mineralization, nitrification and availability (1998-ongoing)	24, 25
EMS Biometry Plots	1993	40 plots surrounding carbon-exchange tower on Prospect Hill Tract of Harvard Forest Plot size: 10m radius	Tree species and growth by weekly growing-season dendrometer measurements (1998-2004, initial diameter measurements in 1993); Litterfall (1993, 1998-2004); Soil respiration and moisture; Coarse woody debris (1999-2004)	3

[a]First survey one year before 75% standing timber blown down by 1938 hurricane. In 1937, the center tree of each plot was tagged to mark the plot, but none of these tags were found in 1992. However, plot locations were carefully noted on 1"=200' maps, so locations could be matched closely.

B. Intensive Mapped Plots

Study	Year established	Location, size and number of plots	Core Measurement types and dates	References
Mapped Overstory	1990	4 plots, 50x50m, Tom Swamp Tract of Harvard Forest	Tree size, location, species, canopy class (1990, 2003)	4, 12, 13
Hemlock Woodlot	1990	One 120x60m plot, Prospect Hill Tract of Harvard Forest	Tree size, location, species, canopy class (1995, 2002); Sapling density and species (2002); Vascular understory vegetation cover, tree seedling density (2002); Soil nitrogen cycling (2002, 2003, 2004)	10, 11
Hemlock History Plots	1995	4 plots, 30x30m, Prospect Hill and Slab City Tracts of Harvard Forest	Tree size, location, species, canopy class (1995, 2002); Sapling density and species (2002); Vascular understory vegetation cover, tree seedling density (2002)	17
Lyford Grid	1969	32 contiguous 100x100 ft. plots, Prospect Hill Tract of Harvard Forest	Tree size, location, species, canopy class, condition after death, including length and orientation of fallen stems (1969, 1975, 1987-1992, 2001); Soil type/drainage, boulders, stone walls and trails mapped	28
Pisgah Tract	1984	14 20x20m plots, Pisgah Tract, Winchester, NH	Tree size, species, age, canopy position (1984, 1990, 1995, 2000, 2005); Downed stem decay and orientation (1984) Understory vascular plant cover, tree seedling/sapling density (1984)	8, 26
Pisgah Tract	1990	30x30m permanent grid established over 8 ha Pisgah Tract, 115 plots, Winchester, NH	Tree size, species (1990); Plot aspect and microsite (1990) Sapling density and understory vascular plant cover (1990)	8
Montague Sand Plain	1998	4.5 ha area completely mapped for trees and understory, Montague, MA	Trees by location, species and size (1998); 14 species of clonal understory vascular plants mapped (1998)	20

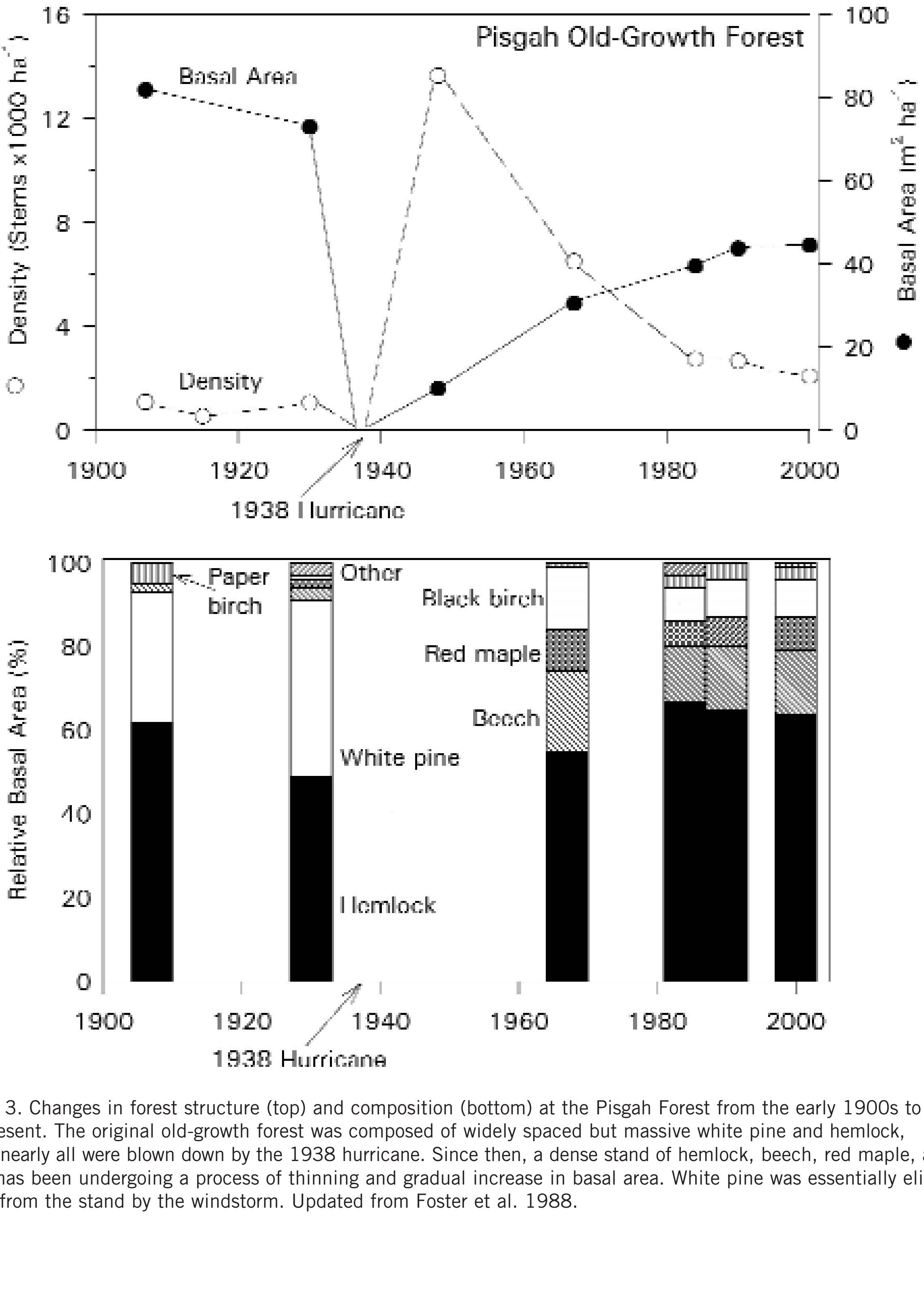

Figure 3. Changes in forest structure (top) and composition (bottom) at the Pisgah Forest from the early 1900s to the present. The original old-growth forest was composed of widely spaced but massive white pine and hemlock, which nearly all were blown down by the 1938 hurricane. Since then, a dense stand of hemlock, beech, red maple, and birch has been undergoing a process of thinning and gradual increase in basal area. White pine was essentially eliminated from the stand by the windstorm. Updated from Foster et al. 1988.

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