THE HARDWOOD ECOSYSTEM EXPERIMENT: GOALS, DESIGN, AND IMPLEMENTATION

Rebecca A. Kalb and Cortney J. Mycroft[1]

Abstract.—The Hardwood Ecosystem Experiment (HEE) is a long-term, landscape-level field experiment initiated in 2006 by the Indiana Department of Natural Resources-Division of Forestry. The HEE is a multi-disciplinary, collaborative research project involving researchers from Purdue University, Indiana State University, Ball State University, Indiana University of Pennsylvania, and Drake University. It is designed to study the ecological and social impacts of forest management through a replicated series of study areas established across 730 hectares in two Indiana State Forests. Each of the nine study areas is approximately 80 ha in size. Over the next 100 years, the impacts of even-aged management, uneven-aged management, and no timber harvesting (control) will be assessed. Across these areas, long-term responses to forest management of various plant and animal taxa, including threatened and endangered species, will be monitored. Pre-treatment data collection began in 2006. Treatments were applied beginning in the summer of 2008.

INTRODUCTION

Disturbance patterns of fire, grazing, farming, and unregulated timber harvesting throughout the Central Hardwood Region has led to the ecological, economic, and social interdependencies found in the region's forests today (Carman, this publication). Both historically and currently, oak (*Quercus*) and hickory (*Carya*) are dominant throughout much of Indiana's forestland. As disturbance regimes have changed, however, oaks have become outnumbered in the seedling and sapling layers by more shade-tolerant species, principally maples (*Acer*) and American beech (*Fagus grandifolia*). This shift from oak-hickory to beech-maple poses a challenge for both the wildlife and people that depend on oak-dominated mid-successional species for their livelihoods (McShea et al. 2007, Shifley and Woodall 2007).

With the loss of American chestnut (*Castanea dentata*) in the early 1900s, oak acorns have become an even more important food source for many wildlife species throughout the Central Hardwood Region (Dalgleish and Swihart 2012). Acorns are readily available and rich in energy. With such a valuable food source, oak-dominated ecosystems support diverse wildlife communities (McShea et al. 2007, Rodewald and Abrams 2002). Beyond changes in overstory structure and composition, a reduction in mast-producing species may alter the representation of birds, small mammals, and other species (McShea et al. 2007).

Indiana's hardwoods are essential for sustaining forest-dependent wildlife, and they also provide an economic livelihood for citizens of the state. Indiana's forest products sector is the sixth largest industry in the state and directly employs more than 35,000 people

[1] Hardwood Ecosystem Experiment Project Coordinator (RAK), Purdue University, Department of Forestry and Natural Resources, 715 West State St., West Lafayette, IN 47907; Research Analyst (CJM), Southwick Associates, PO Box 207, New Market, IN 47965. RAK is corresponding author; to contact, call 765-494-3591 or email at rkalb@alumni.purdue.edu.

(Indiana Department of Natural Resources [IDNR] - Division of Forestry [DoF] 2011). Indiana has a rich history of high-quality hardwood production (Carman, this publication). There may be economic implications if the forests are allowed to shift to their climax state (Hoover, this publication).

Many people enjoy Indiana forests for recreation and aesthetic value. Bird watching is a particularly popular activity, with 1.4 million people observing birds around the state in 2001. More than 400,000 people visited Indiana's public woodlands in 2001 (U.S. Department of the Interior, Fish and Wildlife Service and U.S. Department of Commerce, Bureau of the Census 2003). Perception and acceptance of forest management differ considerably among individuals and can affect their enjoyment of these areas for recreation (Rogers et al., this publication; Witter et al., this publication).

Since the creation of Indiana's State Forests, their management has been primarily single-tree and small group selection (Carman, this publication; Parker and Ruffner 2004). The small canopy openings that result have been shown by previous researchers to favor the regeneration of shade-tolerant species (Johnson et al. 2002). Although even-aged silvicultural systems have been recommended for oak forests of the Central Hardwood Region (Johnson et al. 2002, McShea and Healy 2002), the public is often vehemently against the initial appearance these systems, especially clearcuts, leave on the landscape (Bliss 2000; Rogers et al., this publication). The social implications of creating larger openings to promote oak regeneration need to be weighed against the need for a diverse matrix of early- and late-successional stages in Indiana's remaining forestland.

The interface of ecological change and societal acceptance of forest management will present a growing challenge for land managers in the coming decades. Science-based management will be essential if the current oak-dominated landscape and its associated diversity are to be maintained. Moreover, educating the public about research findings and integrating the public's views into management objectives will enhance the likelihood of success (Hanley 1994). The questions surrounding oak regeneration are complex. The best hope of answering them is in the use of multi-disciplinary studies designed with long-term objectives. One such study currently underway in Indiana is the Hardwood Ecosystem Experiment (HEE). Although the HEE is in its initial stages, it is designed as a 100-year project. The HEE includes research on improving oak regeneration and seeks to create a better understanding of the relationships between the forest, its wildlife, and humans. The ultimate intent of the HEE is to provide information that will improve management prescriptions and thereby enhance sustainability of forest resources and improve the quality of life for Indiana residents.

THE HARDWOOD ECOSYSTEM EXPERIMENT

The HEE is a multi-disciplinary project initiated by the IDNR-DoF in collaboration with scientists from Purdue University, Indiana State University, Ball State University, Indiana University of Pennsylvania, and Drake University. The HEE is designed as a long-term, landscape-level field experiment to study forest management and its impacts. In collaboration with DoF, a replicated series of study areas was created at Morgan-Monroe and Yellowwood State Forests (MMYSF) in southern Indiana, on which alternative approaches to forest management will be implemented and monitored for 100 years. This framework of study sites will be used to quantify the long-term response of selected flora and fauna in both the treated areas and the surrounding forest. Assessing the attitudes of landowners and the general public toward active forest management is an equally important component.

Through the HEE, we seek to understand how harvest-induced disturbance affects individuals, populations, and communities of plants and animals. Some treatments are aimed at improving oak regeneration, whereas others likely will encourage conversion to beech-maple forests. Researchers will explore how different species use the landscape in response to the harvests. Research results will lead to a comprehensive guide for forest management with clear outcomes described for alternative forest management techniques.

Additionally, social scientists are studying the attitudes and values held by various stakeholders toward forest management. This research is aimed at understanding stakeholder attitudes toward forest management practices and policies, engaging stakeholders and decisionmakers in dialog, and designing outreach programs that address the attitudes and behavior of landowners, residents, and decisionmakers living adjacent to or near MMYSF. Stakeholders include landowners and non-landowners as well as recreational user groups.

HEE field work began in May 2006 with research efforts focused on collecting baseline data to determine the current state of forest resources in MMYSF. Silvicultural treatments were applied between 15 July 2008 and 6 January 2009. Baseline data collection was ongoing until the harvest period (Table 1); post-harvest data collection focused on the response of target species to the various harvest treatments.

STUDY OBJECTIVES

The goal of the HEE is to understand the ecological and social impacts of even-aged (EA), uneven-aged (UEA), and no harvest (NH) management on public and private lands in Indiana and the Central Hardwood Region, with the following primary research objectives:

1. Develop EA and UEA silvicultural systems that maintain oak-dominated forest communities and landscapes.
2. Determine the impacts of these systems on populations of herbaceous, avian, and terrestrial amphibian species groups.
3. Determine the social and economic ramifications of these systems for both the local and regional communities.
4. Provide demonstration sites and develop novel educational materials and techniques to engage the public concerning forest management.

The complete HEE objective tree is found in Appendix 1.

Table 1.—Complete listing of all active research projects during the pre-treatment period of the HEE. Also provided are the start dates, years of data collection, and field season for each.

Pre-treatment research projects:	Start date	Number of inventories	Primary field season
Breeding birds (Malloy and Dunning, this publ.)	2006	3	May-June
Oak mast production and removal (Kellner et al., this publ.)	2006	3	August-December
Wood-boring and longhorned beetles (Holland et al., this publ.)	2006	3	May-August
Bats: mist netting (Sheets, Whitaker, et al., this publ.)	2006	3	May-August
Bats: acoustic sampling (Sheets, Duchamp, et al., this publ.)	2007	2	May-August
Terrestrial salamanders (MacNeil and Williams, this publ.)	2007	2	February-May and August-November
Small mammals (Urban and Swihart, this publ.)	2007	2	June-August
Cerulean warblers (Islam et al. 2012)	2007	2	May-August
Timber rattlesnakes (MacGowan and Walker 2012)	2007	2	April-October
Eastern box turtles (Currylow et al., this publ.)	2007	2	May-October
Lepidoptera (Summerville et al., this publ.)	2007	1	May-August
Overstory/sapling/snag inventory (Saunders and Arseneault, this publ.)	2008	1	Year-round

STUDY AREA

MMYSF is located within the unglaciated Brown County Hills Section of Indiana's Highland Rim Natural Region (Homoya et al. 1985). The area was heavily forested before settlement by Europeans. Much of the land was burned, cleared, heavily grazed, and farmed by European settlers during the 1800s (Parker and Ruffner 2004). This degraded land was acquired by the State in the early- to mid-1900s and allowed to return to forest (Carman, this publication). The area is characterized by dry ridges with often steep ravines underlain by siltstone, shale, and sandstone bedrock. There are few natural water bodies other than steep ephemeral streams which drain to medium- to low-gradient creeks (Homoya et al. 1985). The silt-loam soils of the Wellston-Berks-Gillpin complex are found throughout this area (Jenkins, this publication).

The overstory is predominantly oak-hickory with black oak (*Q. velutina*), white oak (*Q. alba*), and shagbark hickory (*C. ovata*) dominating ridges and south-facing slopes. Almost pure stands of chestnut oak (*Q. prinus*) can be found on the driest, highest ridge tops. Northern red oak (*Q. rubra*), tulip poplar (*Liriodendron tulipifera*), American beech, sugar maple (*A. saccharum*), and hickories occur on the mesic north-facing slopes. The species composition of the understory is largely beech-maple; tulip poplar and sassafras (*Sassafras albidum*) are also common. Sedges (*Carex*) are prevalent on dry ridges, whereas ferns and other perennials occur on the mesic slopes and lowlands. One noteworthy species is the state-threatened yellowwood tree (*Cladrastis kentukea*), which occurs in Indiana only in Brown County. Yellowwood State Forest also has areas of pine (*Pinus*) plantations from the Civilian Conservation Corps era of the 1930s. Carman (this publication) and Jenkins (this publication) provide further history and description of the area.

Nine HEE management units were established in MMYSF in south-central Indiana (Fig. 1).[2] Morgan-Monroe State Forest contains >9,712 ha in Morgan and Monroe Counties, and was established in 1929. Yellowwood State Forest, created in 1947, encompasses >9,439 ha of Brown County. The HEE management units stretch across the landscape, covering 30 linear kilometers. The total area encompassed by the HEE is 3,603 ha, which is nearly 20 percent of the entire MMYSF complex.

Each management unit consists of a central research core area surrounded by a buffer area (Fig. 1) with the research core serving as the experimental unit. The management units were created using existing DoF management tracts with boundaries typically following ridges and valleys. Each research core comprises two to three DoF management tracts, totaling 78-110 ha (Table 2). Tracts immediately adjacent to these cores were designated as buffers to isolate research cores from state forest management activities not associated with the HEE. The sizes of the management units, including research cores and buffer areas (219-393 ha), range from 303 to 483 ha (Table 2). Each of the nine cores was randomly assigned a treatment: EA management using clearcut and three-stage shelterwood methods, UEA management using single-tree selection with patch cutting, and NH (experimental control), with three replicates of each. Most of the HEE inventory and monitoring systems are contained within the research cores.

The core areas of the nine HEE management units are to be managed on a 100-year rotation, regenerating 20 percent of each core area every 20 years. The management regime will remain constant, but the size and number of openings will be informed by the previous harvest results and current forest management practices within an adaptive framework (Walters and Holling 1990).

[2] All spatial information is recorded and presented in North American Datum 1983, Universal Transverse Mercator Zone 16N.

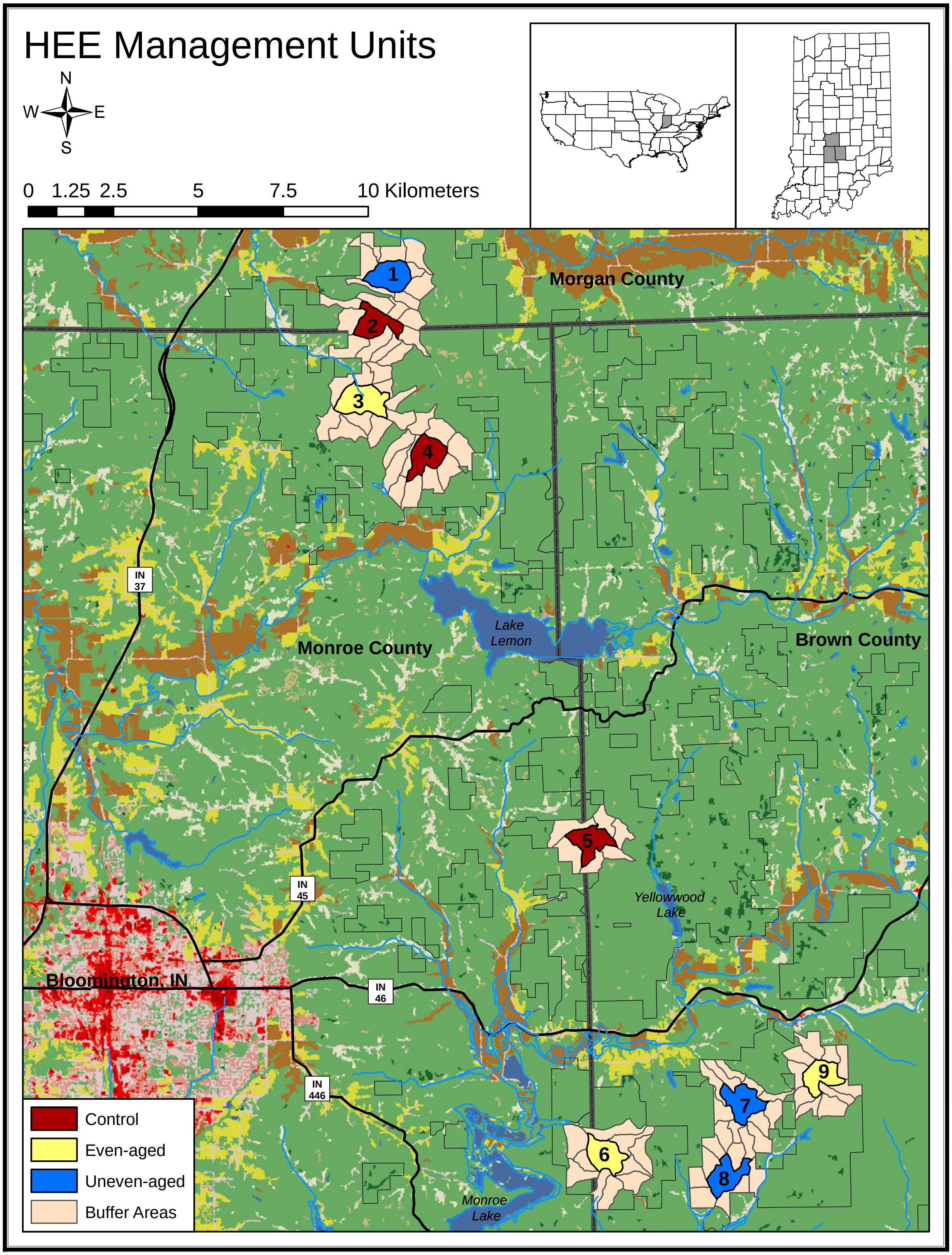

Figure 1.—Map of the entire HEE study area within Indiana. Management units are identified by management type and are shown with surrounding buffer areas. Straight lines are outlines of Morgan-Monroe and Yellowwood State Forest property boundaries. Green areas are deciduous forest as classified by the 2006 National Land Cover Dataset (see Multi-Resolution Land Characteristics Consortium 2011 for the complete land cover classification legend).

Table 2.—Area (in hectares) for each HEE Management Unit, including the research cores and buffer areas (see Fig. 1). All areas were calculated in ArcGIS version 9.3.1.

Unit #	Management type	Research core (ha)	Buffer area (ha)	Management unit (ha)
1	uneven-aged	91.46	253.90	345.37
2	control	83.52	350.83	434.34
3	even-aged	110.44	332.69	443.13
4	control	89.92	392.71	482.63
5	control	84.74	219.24	303.98
6	even-aged	87.15	383.34	470.48
7	uneven-aged	92.42	269.11	361.54
8	uneven-aged	84.59	296.61	381.20
9	even-aged	78.31	302.28	380.59

MANAGEMENT UNIT AND RESEARCH CORE AREAS

Even-Aged Management

To determine harvest locations in EA research cores, six points were randomly placed on the digital elevation map (DEM) using Hawth's Tools in ArcGIS (ESRI, Redlands, CA). The points were stratified by aspect with three on north or east aspects and three on south or west aspects. Two sites from each aspect were chosen by examining topographic maps for space availability and correct aspect. The topographic maps provided more accurate estimations than the DEM. Slopes with the smallest area were discarded. Other points were discarded based on composition or recent disturbance events using knowledge and data from MMYSF foresters. Harvest areas of 4.05 ha in size were drawn around these points to maximize the amount of upper and lower slope positions. Ridges and valleys were used as boundaries when possible. Of the four harvest areas in each unit, one northeast aspect and one southwest aspect were randomly assigned to shelterwood treatments. The remaining two harvest areas were assigned to clearcut treatments. The total area designated for harvest in the first year was 16 ha per core (a total of 48 ha for the three EA cores). EA management units are designated as Unit 3 (Fig. 2), Unit 6 (Fig. 3) and Unit 9 (Fig. 4).

Clearcut

All woody stems >30.48 cm diameter at breast height (d.b.h.) were harvested by a contracted logger. The completion of post-harvest cleanup resulted in a silvicultural clearcut with all woody stems removed. All remaining standing oak, hickory, ash (*Fraxinus*), tulip poplar, and black walnut (*Juglans nigra*) between 2.54 cm and 35.56 cm d.b.h. were coppiced to within 15.24 cm from the ground. All other tree species and larger stems were either felled and chemically treated (with glyphosate or glyphosate with picloram for maple) or girdled and chemically treated. All vines were cut with each end chemically treated. All tree of heaven (*Ailanthus altissima*) received a chemical basal bark treatment of triclopyr with imazypyr.

Shelterwood

The shelterwood treatment is a three-stage system (Smith et al. 1997). The 2008/2009 preparatory cut removed midstory and understory layers with a timber stand improvement (TSI) treatment, which removed most non-oak stems from the stand that were ≤25.4 cm d.b.h. A few small overstory culls were removed, neither lowering basal areas below 13.8 m^2/ha nor creating large canopy gaps. In 5-10 years an establishment cut will reduce stocking to a basal area of 13.8–16.1 m^2/ha. Removal will focus on poorly formed canopy and subcanopy trees, leaving an

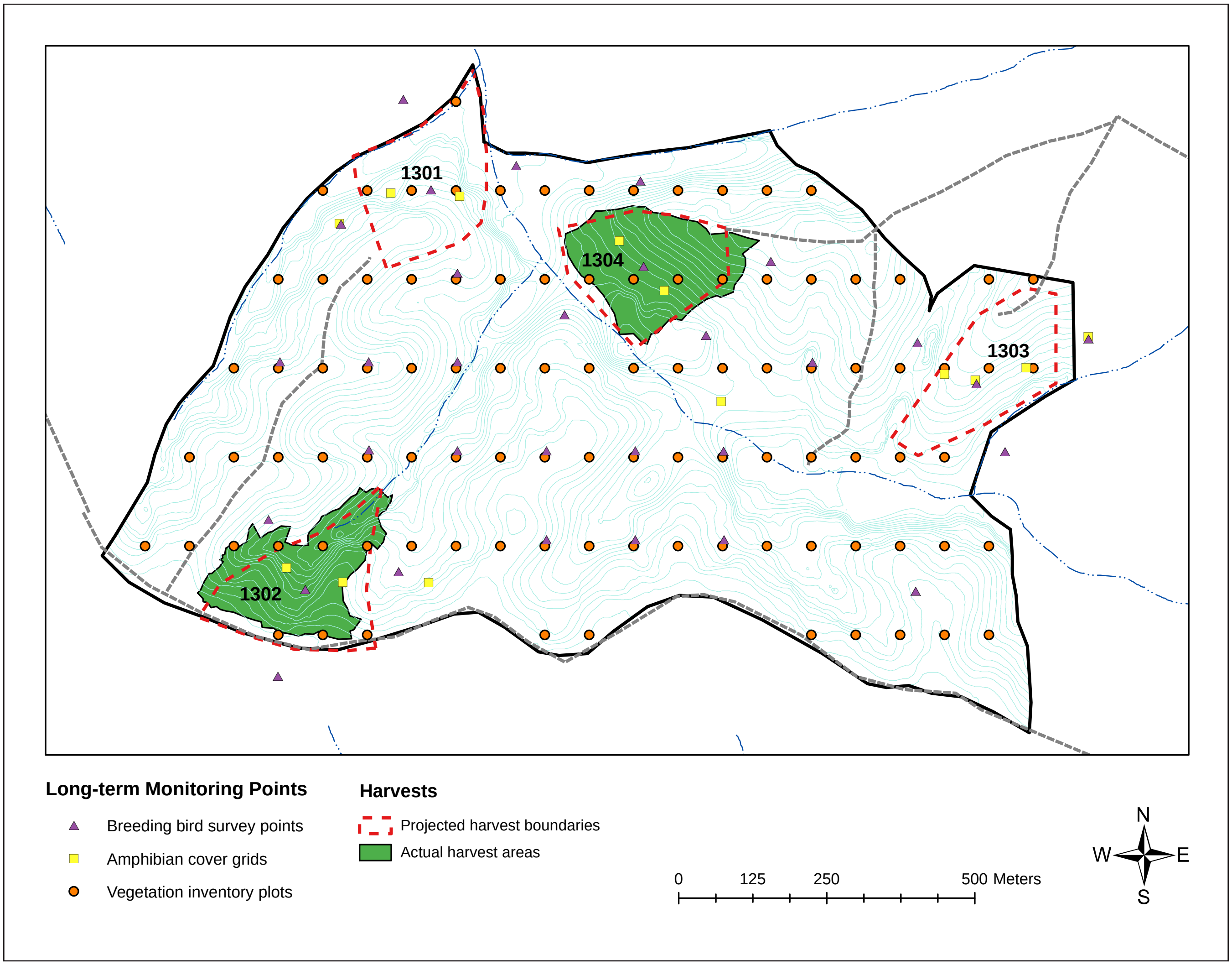

Figure 2.—Map of HEE Research Core 3 (even-aged management) shown with 3-m contour lines, access roads (gray dashed line), and streams (blue dot/dash line). Harvest types include clearcut and shelterwood. Projected harvest areas refer to the harvest areas that were digitally created in ArcGIS. Actual harvest areas were digitized following on-the-ground mapping of the harvest boundaries in 2009, post-harvest. The shelterwoods will be mapped following the mid-story removal stage, so actual harvest areas are not currently available. Long-term monitoring points for breeding birds, amphibians, and vegetation are also shown.

evenly dispersed overstory. Trees favored for retention should have vigorous crowns that will provide ample seed source. Species favored for retention will include oak and hickory. The final overstory removal cut will remove the remaining overstory trees 5-10 years after the establishment cut, or whenever ample oak regeneration reaches breast height (1.35 m), not to exceed 20 years from the initial preparatory cut.

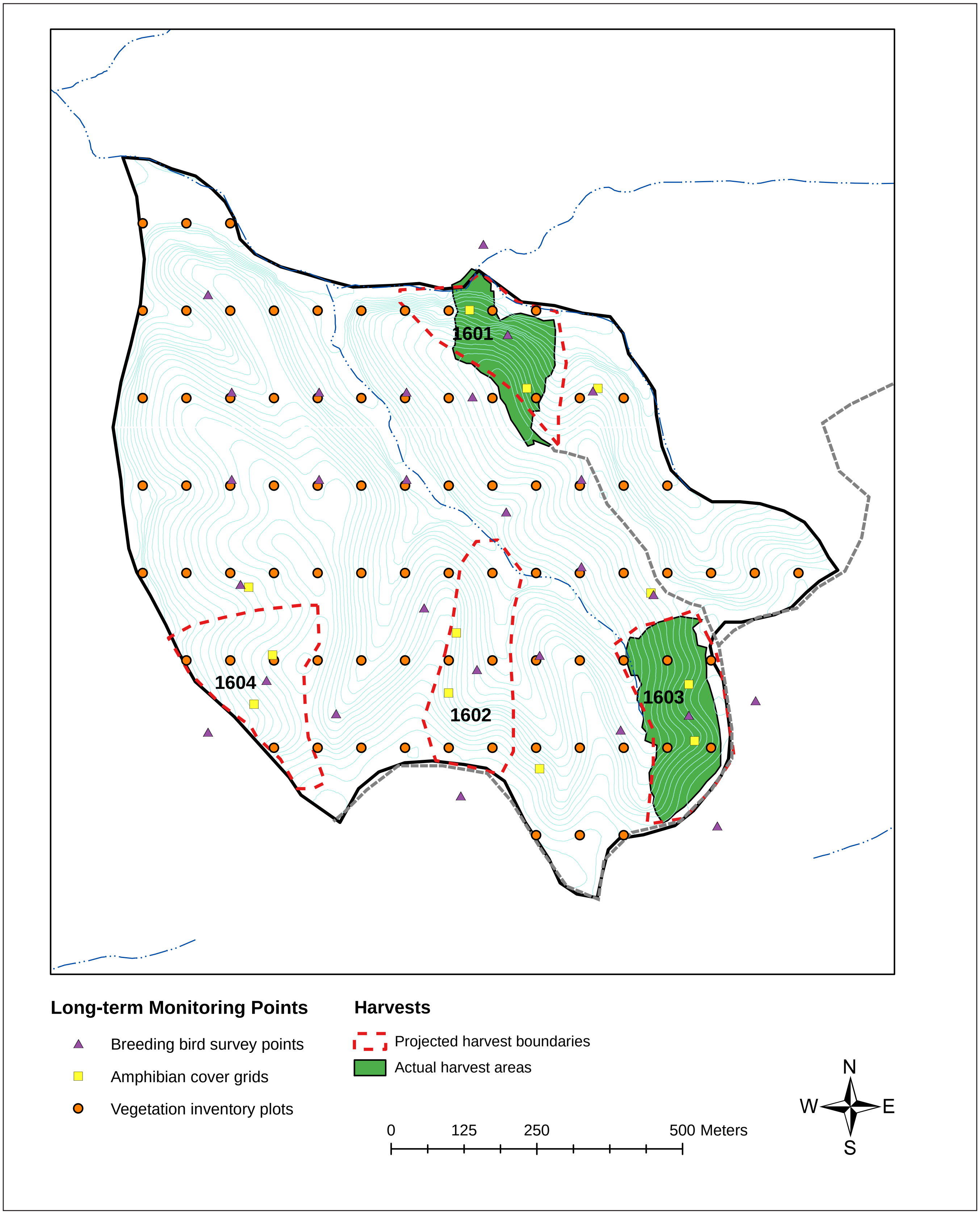

Figure 3.—Map of HEE Research Core 6 (even-aged management). Information is summarized as in Figure 2.

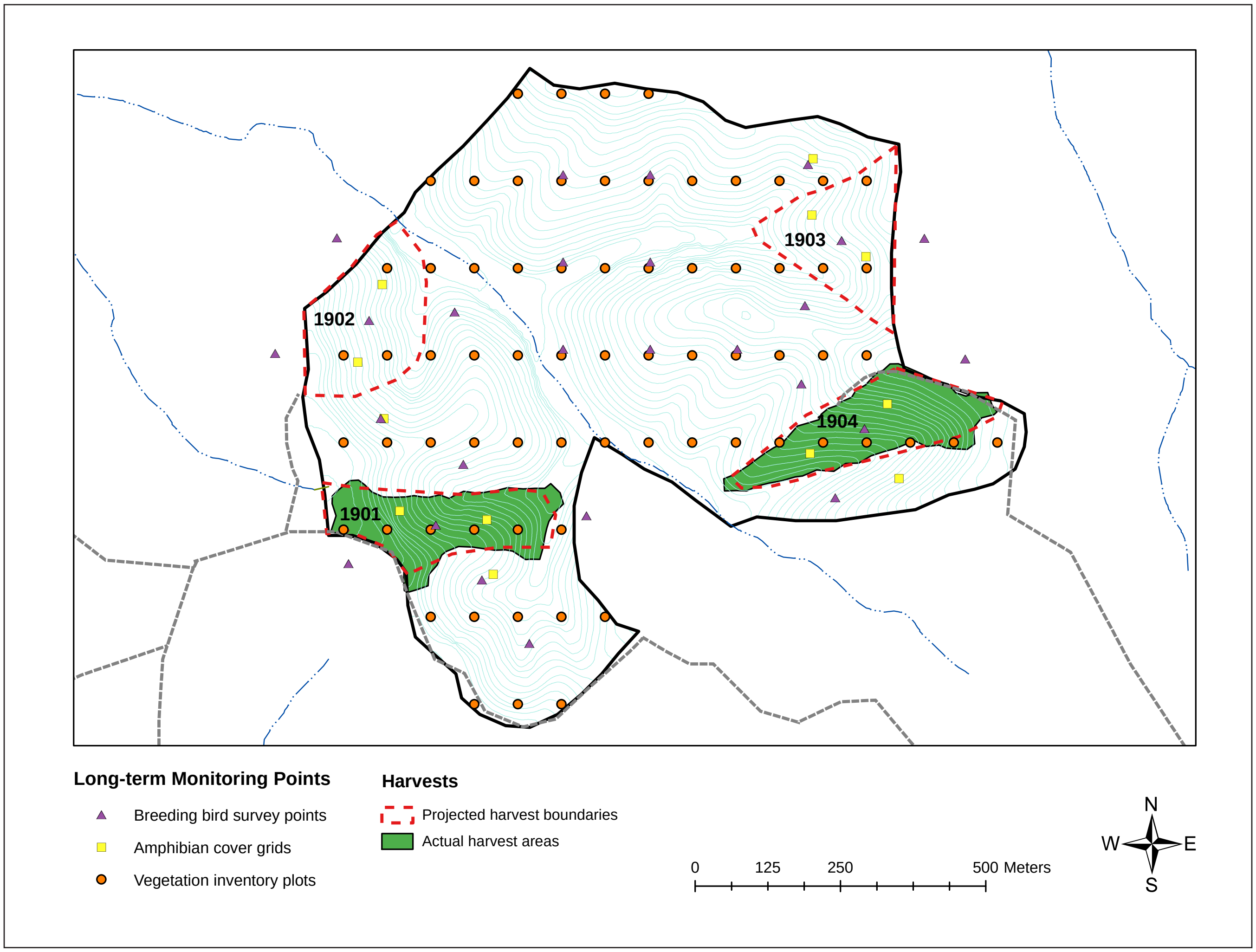

Figure 4.—Map of HEE Research Core 9 (even-aged management). Information is summarized as in Figure 2.

Uneven-Aged Management

The UEA management cores received patch cutting with single-tree selection. To determine patch locations in UEA research cores, eight randomly selected points (four northeast aspects and four southwest aspects) were established following the same method as in the EA cores. A harvest boundary was created around each point in three different patch sizes: two 2.02 ha, two 1.21 ha, and four 0.40 ha. Patch cuts were generally defined by four-sided polygons, centered on each point, with as much of the upper and lower slope positions captured as possible. Patch cuts may not be implemented with every 20-year entry. Single-tree selection was marked with a basal-area goal of 16.1-22.9 m^2/ha. Single-tree selection will recur every 20 years. Single trees will not be marked within 15.2 m of the patches to avoid expanding their size. UEA management units are designated as Unit 1 (Fig. 5), Unit 7 (Fig. 6), and Unit 8 (Fig. 7). This management type most closely resembles the current silvicultural practices used by DoF at MMYSF and throughout Indiana.

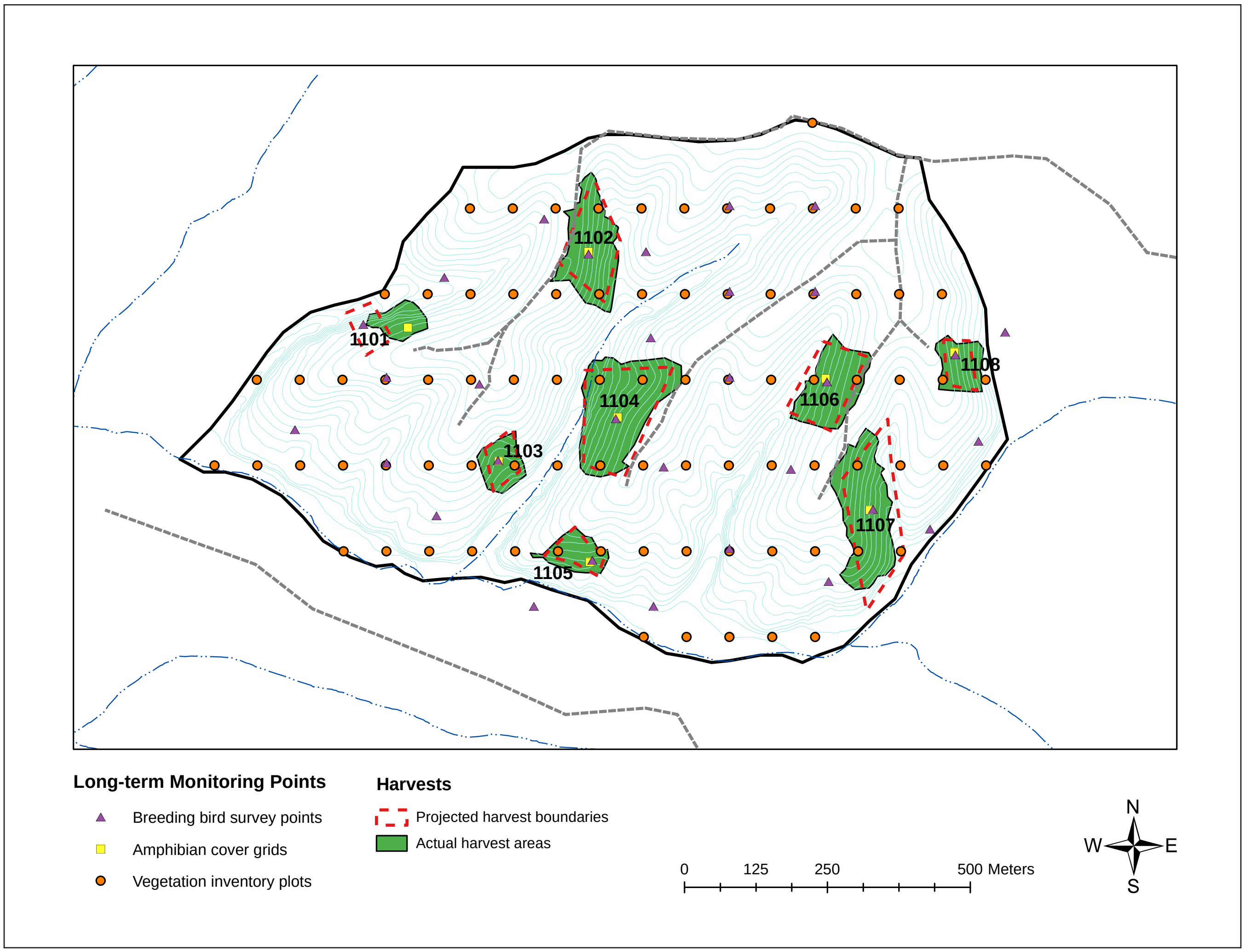

Figure 5.—Map of HEE Research Core 1 (uneven-aged management) shown with 3-m contour lines, access roads (gray dashed line), and streams (blue dot/dash line). All harvest types are patch cuts only. Single-tree selection harvests occur throughout the research core and are not depicted in this map. Projected harvest areas refer to the harvest areas that were digitally created in ArcGIS. Actual harvest areas were digitized following on-the-ground mapping of the harvest boundaries in 2009, post-harvest. Long-term monitoring points for breeding birds, amphibians, and vegetation are also shown.

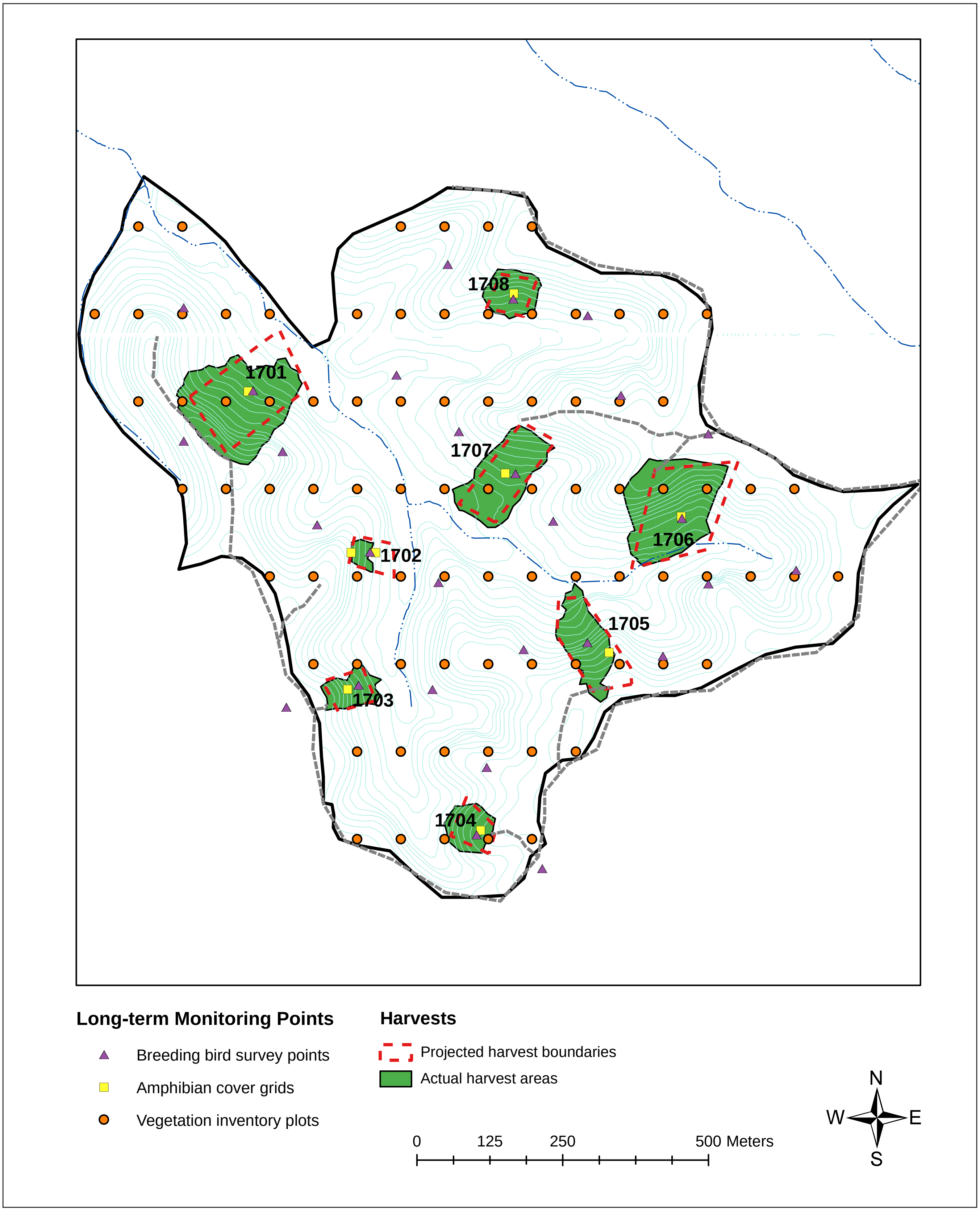

Figure 6.—Map of HEE Research Core 7 (uneven-aged management). Information is summarized as in Figure 5.

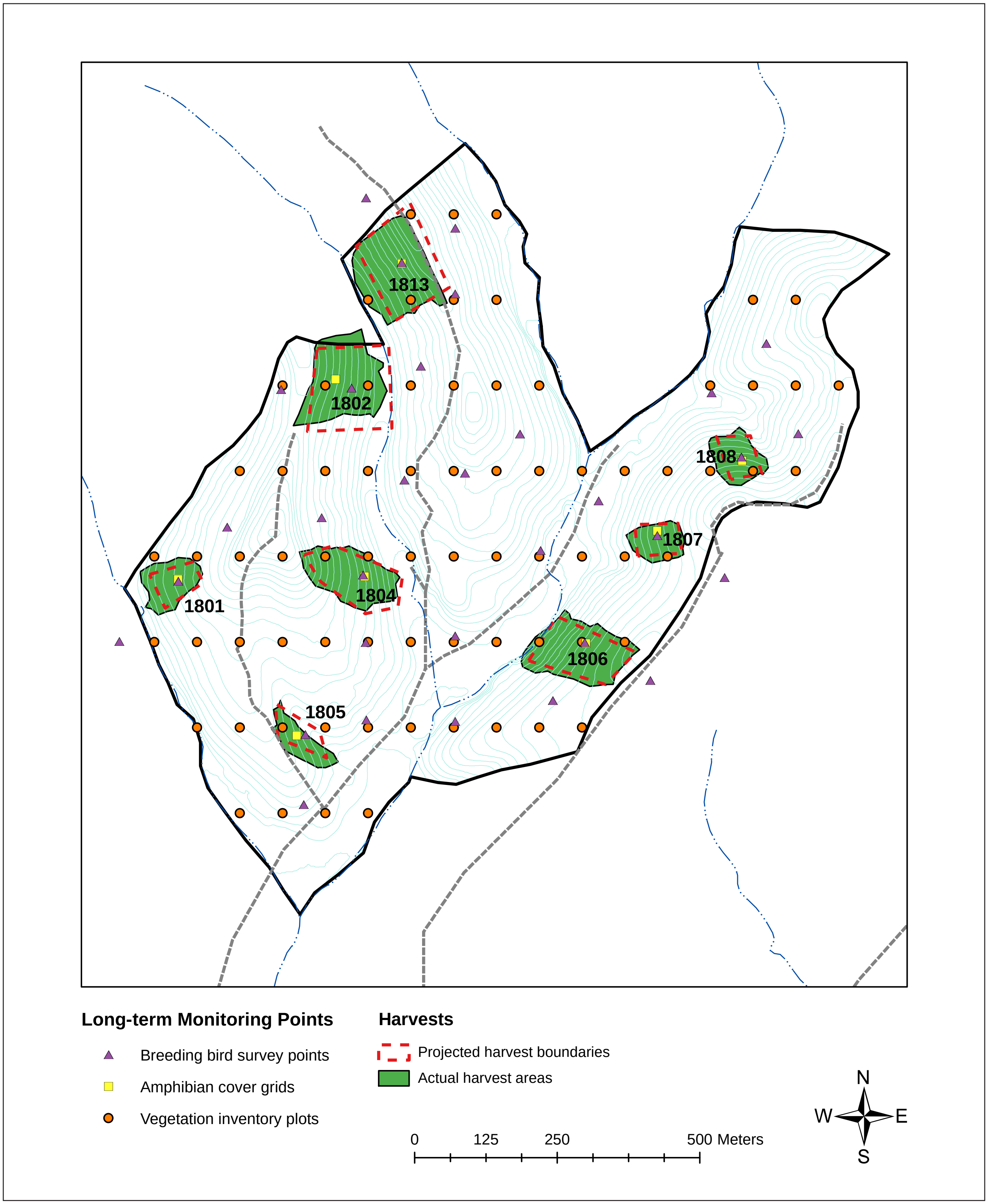

Figure 7.—Map of HEE Research Core 8 (uneven-aged management). Information is summarized as in Figure 5.

No Timber Harvesting

No harvests will be implemented on the control research cores. The three management units assigned to control are Unit 2 (Fig. 8), Unit 4 (Fig. 9), and Unit 5 (Fig. 10), which will receive no active harvesting in the research core for the duration of the study. The control units are used to monitor variation in plant and animal populations and communities in the absence of timber harvesting.

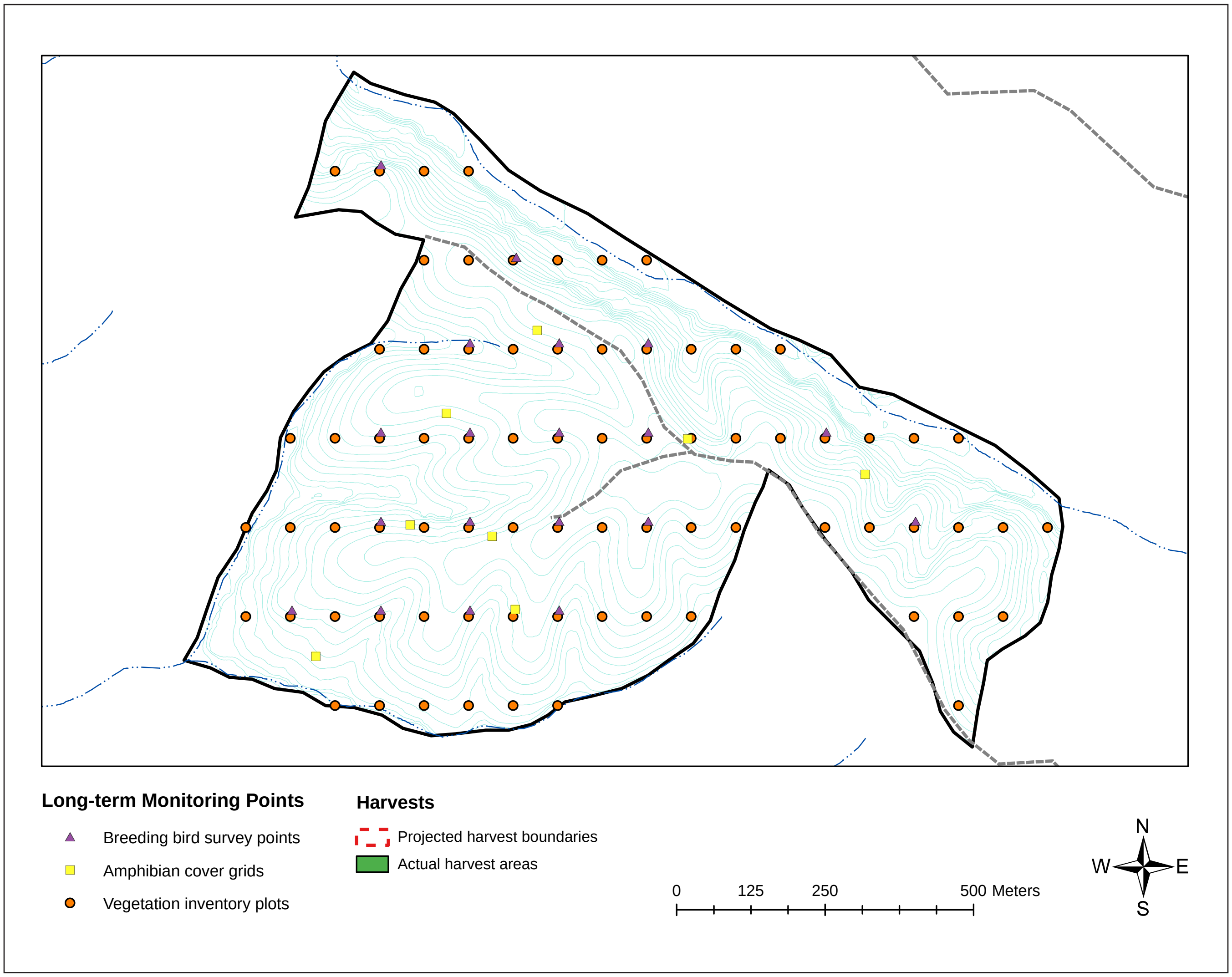

Figure 8.—Map of HEE Research Core 2 (control-no harvest) showing the locations of long-term monitoring points for breeding birds, amphibians, and vegetation with 3-m contour lines, access roads (gray dashed line), and streams (blue dot/dash line).

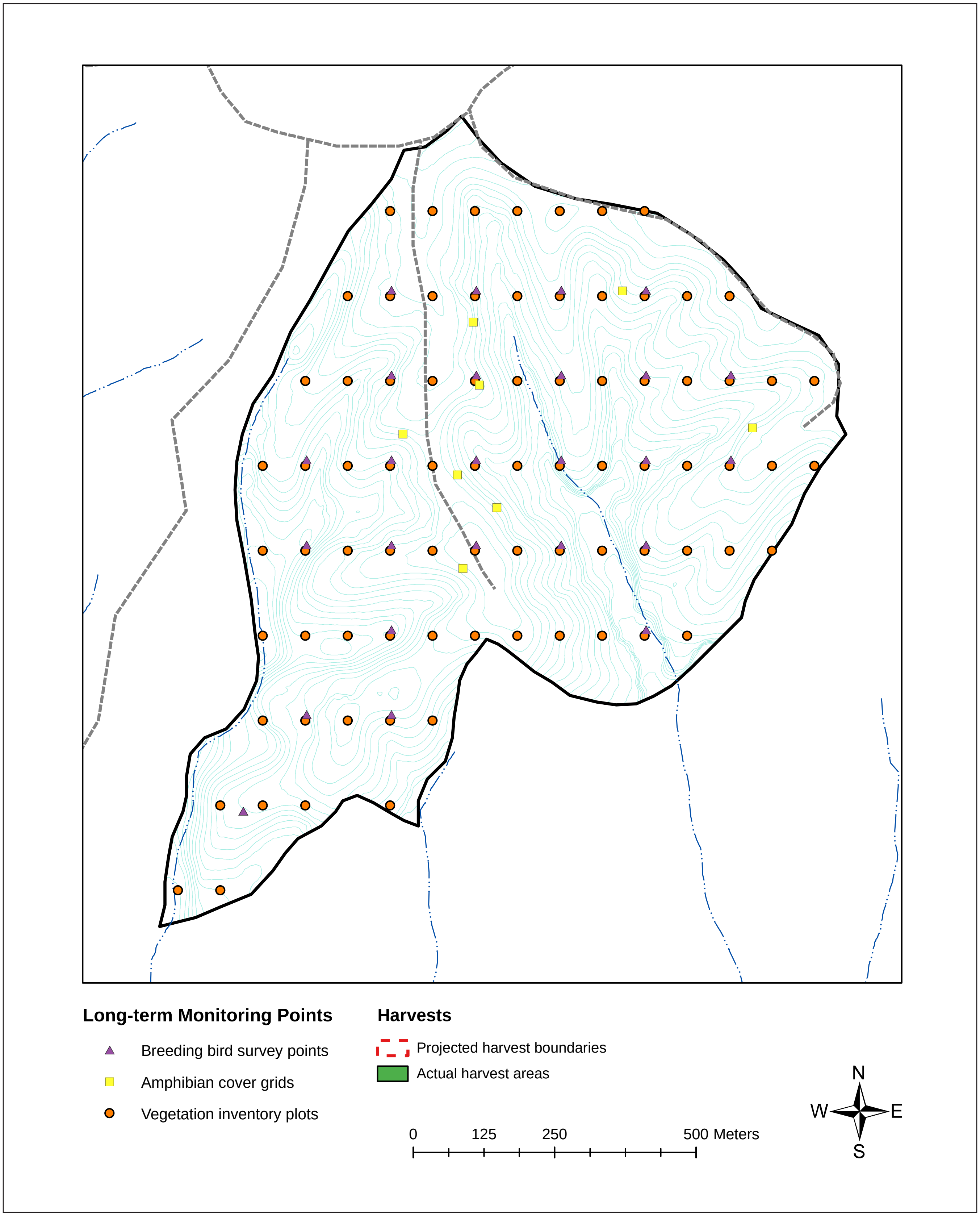

Figure 9.—Map of HEE Research Core 4 (control-no harvest). Information is summarized as in Figure 8.

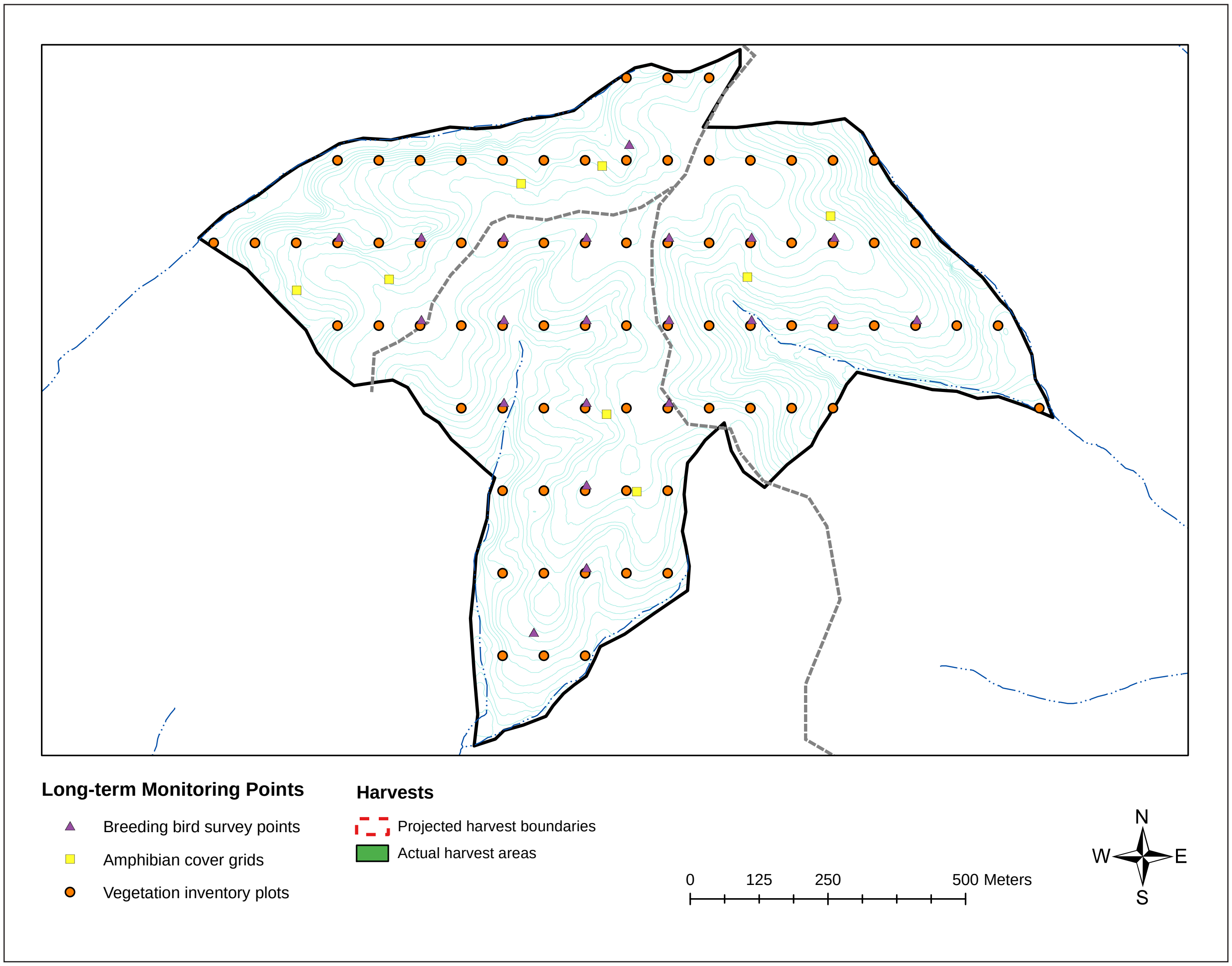

Figure 10.—Map of HEE Research Core 5 (control-no harvest). Information is summarized as in Figure 8.

Buffer Areas

The buffer areas around each of the nine research cores are managed by DoF according to its existing management practices. Management is standard among all buffers regardless of the management in the research core. Single-tree selection should bring stocking levels to between 70 and 75 percent. If it is deemed silviculturally appropriate for a group opening, an opening should be between 0.4 ha and 1.2 ha and the total area cut in group selections within a DoF management tract should not exceed 5 percent of the management tract area. Buffer area group openings may not be created within 100 m of any research core.

TIMBER HARVESTS

Timber was posted for closed bid on 17 April 2008 at Morgan-Monroe State Forest. To account for the differences in logging techniques, the units were divided into three blocks (Morgan-Monroe, Yellowwood East, Yellowwood West), each including a NH, UEA, and EA unit (Table 3). Timber was sold in blocks, and the buyer agreed to use the same crew on both the UEA and EA units within a block. UEA units were opened beginning 15 July 2008; buyers were asked to begin harvesting as soon as possible. UEA harvests had to be completed and closed before harvesting could begin in the block's EA unit. All harvesting was to be completed and closed by 28 February 2009. The six 4.05-ha shelterwood harvest areas were omitted from this sale because they received a preparatory cut that focused on understory trees and lacked sufficient merchantable timber to warrant harvesting.

All harvests followed Indiana best management practices for water quality, including water bar installation and proper skid trail and landing layouts (IDNR-DoF 2005). At all harvest sites, small-diameter slash and tree tops were left on site. Snags were not felled unless necessary for safety concerns. Post-harvest firewood cutting could not be regulated and was therefore prohibited at all sites.

Harvest sizes for the EA and UEA regeneration openings are listed in Tables 4 and 5, respectively. Areas of actual openings were calculated in ArcGIS v. 9.3.1 following on-the-ground mapping of the harvest boundaries in 2009. Single-tree removals were not mapped.

Table 3.—HEE management unit assignments and harvest dates for each timber sale block.

Block name	Total board feet marked for sale[a]	UEA unit	Start date	Close date	EA unit	Start date	Close date
Morgan-Monroe	742,149	1	15 July 2008	8 Sept. 2008	3	15 Nov. 2008	4 Dec. 2008
Yellowwood West	425,978	8	6 Oct. 2008	20 Nov. 2008	6	1 Dec. 2008	6 Jan. 2009
Yellowwood East	442,334	7	9 Sept. 2008	3 Oct. 2008	9	4 Oct. 2008	17 Oct. 2008

[a] The six 4.05-ha shelterwood areas were omitted from this sale because they lacked enough merchantable timber to warrant a logging company's entering the site.

Table 4.—Details for each harvest area in the three HEE even-aged management units. Types include clearcut and shelterwood harvests. Projected harvest size refers to the harvest areas that were digitally created in ArcGIS. Actual harvest size was calculated following on-the-ground mapping of the harvest boundaries in 2009, post-harvest (see Figs. 2 through 4). Shelterwood harvest areas will be mapped following the mid-story removal stage, so actual harvest sizes are not currently available. All areas were calculated in ArcGIS version 9.3.1.

Unit	Harvest #	Harvest type	Aspect	Projected harvest size (ha)	Actual harvest size (ha)
3	1301	shelterwood	NE	4.05	n/a
	1302	clearcut	NE	4.05	4.35
	1303	shelterwood	SW	4.05	n/a
	1304	clearcut	SW	4.05	4.43
6	1601	clearcut	NE	4.05	2.72
	1602	shelterwood	NE	4.05	n/a
	1603	clearcut	SW	4.05	3.70
	1604	shelterwood	SW	4.05	n/a
9	1901	clearcut	NE	4.05	4.05
	1902	shelterwood	NE	4.05	n/a
	1903	shelterwood	SW	4.05	n/a
	1904	clearcut	SW	4.05	4.25

Table 5.—Details for each harvest area in the three HEE uneven-aged management units. All harvest types are patch cuts only; single-tree selection harvests are not included in this table. Projected harvest size refers to the harvest areas that were digitally created in ArcGIS. Actual harvest size was calculated following on-the-ground mapping of the harvest boundaries in 2009, post-harvest (see Figures 5 through 7). All areas were calculated in ArcGIS version 9.3.1.

Unit	Harvest #	Aspect	Projected harvest size (ha)	Actual harvest size (ha)
1	1101	NE	0.40	0.46
	1102	NE	1.21	1.57
	1103	SW	0.40	0.59
	1104	SW	2.02	2.39
	1105	SW	0.40	0.58
	1106	SW	1.21	1.29
	1107	NE	2.02	1.97
	1108	NE	0.40	0.64
7	1701	NE	2.02	2.56
	1702	NE	0.40	0.15
	1703	NE	0.40	0.49
	1704	SW	0.40	0.54
	1705	NE	1.21	1.03
	1706	SW	2.02	2.28
	1707	SW	1.21	1.49
	1708	SW	0.40	0.62
8	1801	SW	0.40	0.70
	1802	NE	2.02	1.72
	1804	NE	1.21	1.25
	1805	NE	0.40	0.51
	1806	SW	1.21	1.60
	1807	SW	0.40	0.54
	1808	NE	0.40	0.65
	1813	SW	2.02	1.88

PHOTOGRAPHIC DOCUMENTATION

Photographic documentation points were first established in 2008 in Units 1, 2, and 3. The photographs are representative of each type of harvest method: clearcut (Fig. 11), shelterwood (Fig. 12), patch cutting (Fig. 13), single-tree selection (Fig. 14), and control (Fig. 15). Nearly all of the photographic points are associated with long-term vegetation plots that will quantitatively monitor the changes documented in the photographs over time. The points are permanently marked in the field, allowing a photographer to return to the exact location every year. Photographs are taken using a tripod with level indicators centered over the point marker. Using a compass, the photographer centers the initial image on north. Photographs then proceed clockwise (eastward) for six images, each with enough overlap to allow the images to be aligned. Points are generally located on level ground along the edge of the harvest areas looking downslope into the harvests. The first photographs were taken in May 2008, pre-harvest, by John Maxwell of the IDNR. Maxwell returned in November 2008 to take the immediate post-harvest pictures. This routine will be repeated each spring prior to full leaf-out. The individual photos are digitally stitched together to create a 360° panorama. These images can then be aligned to compare the changes within a forest opening over time. Due to the nature of this process, small areas of distortion within the images are possible. Although every effort is made to exactly replicate the conditions for taking each photograph, some deviation is possible; therefore images from year to year may not line up exactly.

Figure 11.—Panorama images from HEE Unit 3 (even-aged management), Harvest 1302 (4.35-ha clearcut). Top image is pre-harvest, May 2008. Bottom image is immediately post-harvest, November 2008. These images are panoramas of the harvest area only and do not include the uncut forest to the south. The true 360° panorama does not accurately reflect the large size of this particular harvest area. (Photo credit: John Maxwell, Indiana Department of Natural Resources)

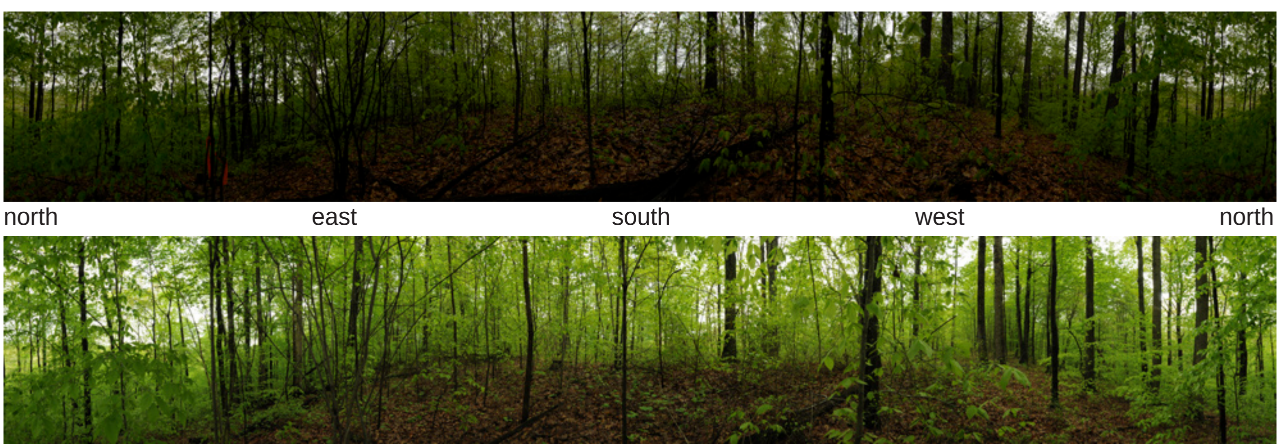

Figure 12.—360° panorama images from HEE Unit 3 (even-aged management), Harvest 1301 (shelterwood). Top image is May 2008, pre-harvest. Bottom image is immediately post-harvest, May 2009. (Photo credit: John Maxwell, Indiana Department of Natural Resources)

Figure 13.—360° panorama images from HEE Unit 1 (uneven-aged management), Harvest 1106 (1.29-ha patch cut). Top image is May 2008, pre-harvest. Bottom image is immediately post-harvest, November 2008. (Photo credit: John Maxwell, Indiana Department of Natural Resources)

Figure 14.—360° panorama images from HEE Unit 1 (uneven-aged management), single-tree selection. Top image is May 2008, pre-harvest. Bottom image is immediately post-harvest, November 2008. (Photo credit: John Maxwell, Indiana Department of Natural Resources)

Figure 15.—360° panorama images from HEE Unit 2 (control – no harvest). Top image is May 2008, pre-harvest. Bottom image is immediately post-harvest, November 2008. (Photo credit: John Maxwell, Indiana Department of Natural Resources)

RESEARCH PROJECTS

With the inception of the HEE in 2006, research projects designed for the long-term monitoring of several species and taxa were implemented. Other research projects were added in 2007, and more continue to be added every year. Baseline data collection began immediately with each project and continued until the implementation of the harvests. Post-harvest data collection began immediately after harvests. Table 1 provides a comprehensive listing of all field research projects associated with the pre-treatment period of the HEE.

Select forest vertebrates and invertebrates will continue to be monitored after silvicultural treatments to determine faunal responses at individual, population, and community levels. Survey techniques will be taxon-specific. Species selected for study include a range of taxa that represent both species of management concern and species indicative of microhabitat conditions and successional stages. Target species of management concern include Indiana bat (*Myotis sodalis*) (Sheets, Duchamp, et al., this publication; Sheets, Whitaker, et al., this publication), cerulean warbler (Islam et al., this publication), eastern box turtle (*Terrapene carolina carolina*) (Currylow et al., this publication), and timber rattlesnake (*Crotalus horridus*) (MacGowan and Walker, this publication). Important habitat indicators include wood thrush (*Hylocichla mustelina*), worm-eating warbler (*Helmitheros vermivorum*), hooded warbler (*Setophaga citrina*), red-backed salamander (*Plethodon cinereus*), shrews (*Sorex*, *Blarina brevicauda*), and native rodent species (MacNeil and Williams, this publication; Malloy and Dunning, this publication; Urban and Swihart, this publication). Survey plots for all taxa are distributed throughout the research cores to include the treatments, the adjacent forest edge, and the untreated forest.

Also essential to the HEE is long-term vegetation monitoring. To monitor the landscape-level changes in forest canopy structure and overstory recruitment by oak and other highly valued tree species in response to forest management over time, 683 vegetation inventory plots were installed across the 9 research cores using a 75m x 150m grid. Complete inventories of all plots are designed to follow a 4-year schedule (Saunders and Arseneault, this publication).

The second primary objective of the HEE is to determine the impacts of these systems on populations of herbaceous plants and avian and terrestrial amphibian species groups. Maps showing the locations of long-term monitoring points for these target groups are provided in Figures 2 through 10.

Through these many projects, the HEE provides educational and employment opportunities for students from across the United States and Canada. Nine graduate students from three universities were involved with the HEE during the pre-treatment period. Also during this time, the HEE employed 43 students to conduct summer field work; several students returned for multiple years. The HEE provides a unique opportunity for students to gain practical experience in a broad array of field-based research activities.

SUMMARY

The mission of the HEE is to examine the ecological, economic, and social ramifications of forest management systems that include EA, UEA, and NH. Compositional changes can be seen only over time. The long-term design of the HEE will allow for comparing these different treatments to address the role of forest management in the succession from oak-hickory to beech-maple forests while quantifying the responses of plants and animals to timber harvesting (Saunders and Swihart, this publication). It is equally important to understand the economic and social implications of these ecological changes. Our project will utilize outreach techniques to disseminate research findings to state agencies, non-profit groups, and the general public (MacGowan et al., this publication).

It is not one vector, but the combination of vectors—ecological, economic, and social—that will dictate the direction of forest management in the future (Haulton, this publication).

ACKNOWLEDGMENTS

This paper is a contribution of the Hardwood Ecosystem Experiment, a partnership of the Indiana Department of Natural Resources, Purdue University, Ball Sate University, Indiana State University, Drake University, Indiana University of Pennsylvania, and The Nature Conservancy. Funding for the project is provided by the Indiana Division of Forestry and Purdue University, Department of Forestry and Natural Resources. The authors thank past HEE project coordinator Ben Dolan for his dutiful record-keeping. R. Swihart, S. Haulton, R. Jensen, and an anonymous reviewer provided helpful comments for improving this manuscript. M. Saunders provided additional silvicultural advice. J. Arseneault assisted with map creation.

LITERATURE CITED

Bliss, J.C. 2000. **Public perceptions of clearcutting.** Journal of Forestry. 98(12): 4-9.

Dalgleish, H.J.; Swihart, R.K. 2012. **American chestnut past and future: implications for resource pulses and consumer populations of eastern U.S. forests.** Restoration Ecology. 20: 490-497.

Hanley, T.A. 1994. **Interaction of wildlife research and forest management: the need for maturation of science and policy.** The Forestry Chronicle. 70(5): 527-532.

Homoya, M.A.; Abrell, D.B.; Aldrich, J.R.; Post, T.W. 1985. **The natural regions of Indiana.** Proceedings of the Indiana Academy of Science. 94: 245-268.

Indiana Department of Natural Resources-Division of Forestry (IDNR-DoF). 2005. **Forestry best management practices.** Available: http://www.in.gov/dnr/forestry/2871.htm. (Accessed 5 October 2012).

Indiana Department of Natural Resources-Division of Forestry. 2011. **Indiana forests and forest industry quick facts.** Available: http://www.in.gov/dnr/forestry/files/fo-IN_forestry_facts.pdf. (Accessed 5 October 2012).

Johnson, P.S.; Shifley, S.R.; Rogers, R. 2002. **The ecology and silviculture of oaks.** New York: CABI Publishing. 503 p.

McShea, W.J.; Healy, W.M.; Devers, P.; Fearer, T.; Koch, F.H.; Stauffer, D.; Waldon, J. 2007. **Forestry matters: decline of oaks will impact wildlife in hardwood forests.** Journal of Wildlife Management. 71(5): 1717-1728.

Multi-Resolution Land Characteristics Consortium. 2011. **National land cover database 2006 (NLCD2006) product legend.** Available: http://www.mrlc.gov/nlcd06_leg.php. (Accessed 5 October 2012).

Parker, G.R.; Ruffner, C.M. 2004. **Current and historical forest conditions and disturbance regimes in the Hoosier-Shawnee ecological assessment area.** In: Thompson, F.R., III, ed. The Hoosier-Shawnee ecological assessment. Gen. Tech. Rep. NC-244. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 23-58.

Rodewald, A.D.; Abrams, M.D. 2002. **Floristics and avian community structure: implications for regional changes in eastern forest composition.** Forest Science. 48(2): 267-272.

Shifley, S.R.; Woodall, C.W. 2007. **The past, present, and future of Indiana's oak forests.** In: Buckley, D.S.; Clatterbuck, W.K., eds. Proceedings, 15th Central Hardwood Forest conference; 2006 February 27-March 1; Knoxville, TN. e-Gen. Tech. Rep. SRS-101. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 295-304.

Smith, D.M.; Larson, B.C.; Kelty, M.J.; Ashton, P.M.S. 1997. **The practice of silviculture.** 8th ed. New York: John Wiley and Sons, Inc. 537 p.

U.S. Department of the Interior, Fish and Wildlife Service; U.S. Department of Commerce, Bureau of the Census. 2003. **2001 National survey of fishing, hunting, and wildlife-associated recreation: Indiana.** FHW/01-IN-Rev. Washington, DC. 46 p.

Walters, C.J.; Holling, C.S. 1990. **Large-scale management experiments and learning by doing.** Ecology. 71(6): 2060-2068.

APPENDIX 1. HARDWOOD ECOSYSTEM EXPERIMENT OBJECTIVE TREE.

The objectives and hypotheses for the HEE are categorized as primary, secondary, and tertiary. Primary objectives are those that are considered fundamental to the study, the investigation of which will run the duration of the study and will be given top priority for funding. Secondary hypotheses or objectives are of long-term significance but are not necessarily funded as a permanent part of the project. Tertiary hypotheses or objectives are short-term in scope and are tested around the needs of the primary and secondary hypotheses or objectives. Secondary and tertiary hypotheses or objectives can be nested within or unrelated to a primary objective.

Primary Objectives:

1. Develop even-aged and uneven-aged silvicultural systems that maintain oak-dominated forest communities and landscapes.

   Related Secondary/Tertiary Hypotheses or Objectives:

   1.1. The spatial distribution of advanced oak regeneration is related to the spatial distribution and abundance of overstory species and edaphic factors.

   1.2. Silvicultural systems that promote development of advanced oak regeneration will lead to higher oak stocking in the successive stand than those systems relying on seedlings established after canopy removal.

   1.3. Acorn production will increase for trees with canopies adjacent to harvest areas due to increased access to resources caused by competitive release.

   1.4. Small mammal dispersal of acorns from harvest edges into openings will decline with distance from the harvest edge but increase with age of the opening. Dispersal will be more likely for black oak (*Quercus velutina*) than white oak (*Quercus alba*) due to differences in germination schedules.

   1.5. Wood-boring beetles will respond to timber harvest and have direct influences on tree mortality and stand succession.

   1.6. Seed and seedling predators (e.g., deer and small mammals) will have a significant impact on the abundance, growth, and spatial distribution of oak in the successive stand.

      1.6.1. Small mammals will have a greater impact on oak regeneration in larger canopy openings than in small openings or the intact matrix.

      1.6.2. Deer herbivory will lead to lower stocking of oak in the post-treatment stand, dependent on local deer density.

      1.6.3. Interiors of large clearcuts will suffer less damage from deer than areas along edges or small openings.

2. Determine both the positive and negative impacts of these systems on populations of herbaceous, avian, and terrestrial amphibian species groups.

   Related Secondary/Tertiary Hypotheses or Objectives:

   2.1. Relative abundance and species richness of terrestrial salamanders will remain the same or decrease in post- compared to pre-harvest sampling periods in treatment areas, and will be lower in clearcut and group selection openings compared to treatments with canopy remaining.

2.2. Abundance and species richness of terrestrial salamanders will remain the same or decrease along a gradient from the forest interior to a recent clearcut interior.

2.3. Cerulean warbler (*Setophaga cerulea*) populations will be less affected by group selection cuts than by even-aged treatments.

2.4. One objective is to locate successful breeding habitat of the cerulean warbler in relation to canopy openings created by even-aged or uneven-aged management techniques.

2.5. Shrews (*Blarina brevicauda* and *Sorex* spp.) will be less affected by group selection cuts than by even-aged treatments.

2.6. Lepidopteran community resistance to disassembly will be proportional to level of timber harvest; community resilience will be related to speed of oak and hickory regeneration.

2.6.1. Alpha diversity will recover within harvest sites faster than beta-diversity; shifts in the rank order of the most abundant taxa will generate heterogeneity in species dominance compared to pre-harvest.

2.7. Changes in lepidopteran species assemblages will generate broader shifts in trophic structure within even-aged management units. Bottom-up trophic control of bird guild structure and bat foraging activity will be proportional to magnitude of reduction in moth species diversity.

2.8. Ecological assembly rules for butterfly and moth metacommunity structure will be more significantly related to niche parameters (e.g., shifts in host plant availability post-harvest) than dispersal parameters.

2.9. Wood-boring beetle assemblages will change with disturbance, and the dominance of species attacking living trees or recently dead trees will increase post-management. Thereafter, assemblages will shift over time and approach controls.

2.10. Bat species specialized for interior forest will be negatively affected by the even-aged treatments, but other bat species will be positively affected by the openings created by the even-aged treatments. All bat communities will be less affected by group selection cuts than even-aged treatments.

2.10.1. Bat diets will not be affected by either type of treatment despite the effect on the communities because bats choose from specific prey species and do not simply choose whatever is available.

3. Determine the social and economic ramifications of these systems in both the local and regional communities.

Related Secondary/Tertiary Hypotheses or Objectives:

3.1. Public acceptance of uneven-aged management will be greater than that of even-aged management.

3.2. Economic benefits of ecosystem services (e.g., carbon sequestration) will more fully inform forest management policy and improve how harvest concessions are allocated across the state of Indiana and in the Midwest.

3.3. Attitudes regarding silviculture will vary with informational intervention and duration of exposure to treatments.

4. Provide demonstration sites and develop novel educational materials and techniques to engage the public concerning forest management.