SCIENCE IN THE HARDWOOD ECOSYSTEM EXPERIMENT: ACCOMPLISHMENTS AND THE ROAD AHEAD

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Abstract.—Over the next century, the Hardwood Ecosystem Experiment (HEE) in Indiana will provide numerous opportunities for collaborative research on how forest management affects the ecological, economic, and social resources of southern Indiana. Here, we highlight the pre-treatment research conducted at the HEE sites from 2006 through 2008 and discuss the role that pre-treatment differences among experimental units and/or treatments may have on future research activities. We then formulate hypotheses about the effects of the various silvicultural regimes on communities monitored for the duration of the study (i.e., woody plants, terrestrial salamanders, birds), focal communities and species (i.e., box turtles, timber rattlesnakes, cerulean warblers, moths, and wood-boring beetles), and public attitudes toward forest management. HEE researchers will face a number of key challenges, ranging from overcoming constraints in experimental design to maintaining scientific, managerial, and social relevance. However, each of these challenges provides opportunities for high-impact research and outreach that can improve the management of our Central Hardwood Forests for decades to come.

INTRODUCTION

The Hardwood Ecosystem Experiment (HEE) is a multi-faceted, 100-year project in south-central Indiana involving multiple universities, state natural resource agencies, and non-governmental organizations. The overarching goal of the HEE is to improve the sustainability of forest resources and quality of life of Indiana residents by understanding ecosystem and human responses to forest management (Kalb and Mycroft, this publication). Fundamental to the HEE are ecological and social studies designed to address three key research objectives: (1) development of silvicultural systems for regenerating oak-dominated forests, (2) quantification of the responses of plants and animals to these systems, and (3) determination of the social and economic implications of these systems. This paper summarizes research findings from studies conducted during 2006-08 to establish baseline conditions during the pre-harvest period, considers predictions related to responses following the initial harvests in 2008-09, and identifies opportunities and challenges awaiting future HEE research.

STUDY AREA AND DESIGN

The location and design of the HEE are covered in detail by Kalb and Mycroft (this publication). Briefly, the HEE is located on Morgan-Monroe (9,710 ha) and Yellowwood (9,440 ha) State Forests (hereafter MMYSF) in south-central Indiana. Nine research core areas ($\bar{x}$ ± s.d. = 89 ± 9 ha) serve as the sites to which one of three silvicultural treatments (uneven-aged, even-aged, or no harvest) was assigned randomly, subject to the constraint that each treatment was assigned to an equal number of (n=3) cores. Each research core was surrounded by a buffer area

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(311 ± 59 ha) to isolate the core areas from effects of ongoing management in other portions of the state forest. Each core and associated buffer constituted a management unit (400 ± 60 ha).

Initial harvests associated with silvicultural prescriptions commenced in July 2008 and concluded in February 2009. The uneven-aged (UEA) cores received patch cutting with single-tree selection; harvesting created four small (0.5 ± 0.1 ha), two medium (1.4 ± 0.2), and two large (2.1 ± 0.3) patches in each UEA core (Kalb and Mycroft, this publication). Even-aged (EA) cores each received two clearcuts (3.9 ± 0.6 ha) and two three-stage shelterwoods. The midstory-removal stage of the shelterwood cuts was completed in the initial entry; the projected size of the shelterwood cuts is equal to the clearcuts.

In general, two types of ecological studies were implemented prior to harvest. Long-term monitoring began for woody plants (Saunders and Arseneault, this publication), breeding birds (Malloy and Dunning, this publication), and terrestrial salamanders (MacNeil and Williams, this publication). These communities were selected for monitoring because they either define the habitat (woody plants) or respond to the habitat at landscape (birds) or local (salamanders) scales.

The second group of ecological studies characterized responses of either focal species or focal communities. During the pre-harvest period, sampling was conducted for populations of cerulean warblers (*Setophaga cerulea*) (Islam et al., this publication), timber rattlesnakes (*Crotalus horridus*) (MacGowan and Walker, this publication), eastern box turtles (*Terrapene carolina Carolina*) (Currylow et al., this publication), and oak acorns (*Quercus alba* and *Q. velutina*) (Kellner et al., this publication) using designs specific to each taxon. Similarly, pre-harvest sampling occurred for assemblages of wood-boring beetles (Holland et al., this publication), moths (Summerville et al., this publication), small mammals (Urban and Swihart, this publication), and bats (Sheets, Duchamp, et al., this publication; Sheets, Whitaker, et al., this publication). These particular species and communities were selected for study based either on their conservation status and suspected sensitivity to one or more of the silvicultural treatments planned for the HEE (eastern box turtles, timber rattlesnakes, cerulean warblers, and bats) or for their anticipated rapid community-level response to changing resources (acorns) or habitat (small mammals, wood-boring beetles, and moths).

Lastly, sociological research was begun before or soon after initial harvests at the HEE. Social surveys of MMYSF recreationists and local residents were conducted during the pre-harvest period (Rogers et al., this publication), and a statewide survey to assess attitudes regarding forest management was completed shortly thereafter (Witter et al., this publication). In addition, a comprehensive assessment of values associated with forest-related activities on MMYSF was undertaken (Hoover, this publication).

This paper summarizes key findings from the ecological and sociological studies mentioned above, offers predictions for post-treatment responses, and concludes with a consideration of challenges and opportunities for HEE research in the future.

RESEARCH HIGHLIGHTS - ECOLOGICAL

Communities for Long-Term Monitoring

Plant communities form the basis for most wildlife habitat and are the most visible representations of forest ecosystem responses to management. Saunders and Arseneault (this publication) assessed the composition and structure of trees and large shrubs at two spatial scales. First, they tested for differences among the nine research cores using data from 683 sampling plots arranged systematically in a 75m × 150m set of arrays. Encouragingly, they found no significant differences among sites slated for different silvicultural treatments. Comparisons among research cores without regard to assigned treatments revealed that tree diameter and basal area were similar among cores, although Core 7 exhibited fewer trees in the 30- to 50-cm diameter at breast height (d.b.h.) class. Core 7 also had lower stem density than most other cores. Basal area was dominated (44-75 percent of total basal area) by oak and hickory (*Carya*) and was concentrated in a relatively few large overstory trees. Although nearly absent from the overstory class, red maple (*Acer rubrum*) and sugar maple (*A. saccharum*) made up the majority of small stems. Once again, Core 7 differed in composition, with greater dominance of shade-tolerant species, lower basal area of oak and hickory, and lower species diversity than other cores. When importance values were considered from a multivariate perspective at the core level, treatment centroids exhibited little separation relative to the separation demonstrated across all nine cores.

Saunders and Arseneault (this publication) also found considerable variability in composition of woody vegetation within each of the research cores. Core 8 was notable for a large block of plots with a high proportion of white pine (*Pinus strobus*) and Virginia pine (*P. virginiana*) associated with plantings dating to the 1930s. Cores 1-4 in the northern portions of the HEE have larger components of intolerant tree species, likely reflecting the greater levels of natural disturbance experienced by these areas over the past two decades.

How will wildlife assemblages respond to changes in forest environments induced by silvicultural treatments? Terrestrial salamanders can serve as reliable indicators of forest ecosystem health at local scales, as they are sensitive to environmental change (Welsh and Droege 2001). MacNeil and Williams (this publication) sampled 5,092 salamanders of 5 species with 66 cover-object grids during the pre-treatment phase of the HEE. An additional 464 salamanders of 4 species were detected with quadrat surveys. Eastern red-backed (*Plethodon cinereus*) and northern zigzag (*P. dorsalis*) salamanders were ubiquitous and dominant members of the salamander community, constituting 65.2 percent and 28.8 percent of all encounters, respectively. Mean encounter rates based on cover objects showed little variation for units classified by proposed silvicultural treatment. However, salamanders were more likely to be encountered under cover objects on northeast-facing slopes in fall and on southwest-facing slopes in spring, which suggests an interaction of temperature and humidity on abundance, activity, or both. Interestingly, quadrat surveys, which were done only in spring, did not support the pattern seen with cover objects.

Wildlife responses to silvicultural treatments also can occur at landscape scales. Because of their greater mobility and concerns over declining trends in abundance, Neotropical migrant birds were chosen for monitoring as part of the HEE. Malloy and Dunning (this publication) analyzed pre-treatment data on 17,806 detections of 74 bird species collected at 240 survey points distributed systematically across the 9 management units. For a set of 12 indicator species, neither individual management units nor proposed silvicultural treatments explained meaningful levels of variation in detection probability. Moreover, abundance of the 12 species did not differ among the proposed silvicultural treatments. Comparison of results with avian surveys conducted in the Hoosier National Forest (HNF) in southern Indiana demonstrated that the HEE bird community closely resembled the HNF community in composition.

Focal Species and Communities

The eastern box turtle is one of the longest-lived vertebrates in eastern deciduous forests (Stickel 1978). Some evidence suggests that box turtles are sensitive to disturbances that alter local features of the environment, and the species has experienced substantial declines in abundance over the past several decades (Currylow 2011, Hall et al. 1999). Radio-tracking was undertaken in the HEE for 23 of 236 eastern box turtles captured and revealed that home ranges before harvest were nearly double the largest estimates reported previously for the species (Currylow 2011; Currylow et al., this publication). Home ranges in 2007 (2.6 ha) were on average only 56 percent as large as in 2008 (4.6 ha), suggesting that the hot, dry conditions of 2007 may have depressed movements (Currylow et al., this publication). Size of home ranges did not differ notably between sexes, and only two individuals exhibited seemingly nomadic behavior (Currylow et al., this publication). Annual survival was estimated as 0.964, which provides an important baseline for future studies examining effects of timber harvest or other human disturbance on eastern box turtles (Currylow et al. 2011).

Timber rattlesnakes are endangered in Indiana and exhibit behavioral and demographic traits that could make them vulnerable to timber harvesting. Behaviorally, rattlesnakes, especially gravid females, exhibit philopatry to hibernacula sites (Brown 1991, Brown et al. 1982) and thus create clumped spatial patterns that could be affected negatively by harvesting of timber near den sites. Demographically, females exhibit long inter-birth intervals (3-5 years) and a lengthy developmental period before onset of reproduction (7-11 years, Brown 1991). Radio-tracking was used by MacGowan and Walker (this publication) to study movements of timber rattlesnakes in the HEE. Of 55 rattlesnakes captured, 23 were tracked during the pre-harvest period. Predictably, home ranges of these predators were substantially larger than observed for the omnivorous box turtles. Male rattlesnake home ranges (65.7 ha) also were substantially larger on average than those of females (20.6 ha) (MacGowan and Walker, this publication). Home-range sizes of rattlesnakes varied considerably within sexes (MacGowan and Walker, this publication). A portion of this variation appeared due to variation in body size, with correlations of $r = 0.65$ for 9 non-gravid females and $r = 0.60$ for 10 males ($P < 0.05$ for both one-tailed tests). Interestingly, the 23 rattlesnakes used 13 different den sites, and most of these were within research core areas (MacGowan and Walker, this publication).

Like eastern box turtles, cerulean warblers have experienced notable declines in abundance over the past several decades. Indeed, an annual rate of decline of 2.6 percent over the past 43 years has been estimated, which is a more rapid decline than all but two other woodland bird species covered in the North American Breeding Bird Survey (Sauer et al. 2011). Cerulean warblers are endangered in Indiana. Some evidence indicates that large-scale disturbance of habitat, including timber harvesting, can affect the species negatively (Jones et al. 2001, Wood et al. 2006). Point count surveys by Islam et al. (this publication) in the HEE detected cerulean warblers in all nine management units during the pre-harvest period. Abundance averaged 6.2 males km^{-2}, which is greater than densities found at other sites in southern Indiana (Islam et al., this publication). Mapping of 120 territories during the same period indicated an average territory size of 0.28 ha, within the range of territory sizes reported for other areas in southern Indiana. Most territories in the HEE units were spatially clustered, a pattern observed previously in cerulean warblers (Roth and Islam 2007).

Oaks are experiencing regeneration failure in the Central Hardwood Region, apparently due to suppression of disturbances that favor this shade-intolerant group (Abrams 2003, Aldrich et al. 2005, Larsen and Johnson 1998). Because of oaks' importance to wildlife and local economies (Johnson et al. 2002, McShea et al. 2007), loss of oak from MMYSF would create substantial shifts in natural and human communities. Kellner et al. (this publication) studied mast production by 112 individual black oak (*Quercus velutina*) and white oak (*Q. alba*) trees located in the HEE research cores during the pre-treatment period. They also estimated rates of *Curculio* weevil infestation and removal of acorns by wildlife. Not surprisingly, mast production covaried with tree size and was variable across years.

With the exception of a mast failure for black oaks in 2008, black oaks tended to produce more acorns than white oaks. Black oak acorns also suffered from greater probability of weevil infestation than white oak acorns, with highest rates of infestation observed during 2008, a year of mast scarcity. Overall, there were no differences in removal rates of black and white oak acorns by wildlife. Vertebrates removed 39 percent of acorns from exclosures and were less likely to remove infested acorns, or those that were damaged or germinating. When white-tailed deer (*Odocoileus virginianus*) and wild turkey (*Meleagris gallopavo*) were denied access to acorns in exclosures, rates of acorn removal did not decline, indicating that these large vertebrates were not important predators of acorns in the HEE during the period of study. In contrast, when squirrels (*Sciurus*) were denied access to acorns, rates of removal appeared to decline somewhat (Kellner et al., this publication).

The Lepidoptera function as key agents of herbivory and pollination in forest systems, in addition to serving as an important prey resource. Summerville et al. (this publication) collected 277 species of macrolepidoptera in 1 year of pre-harvest sampling. Over one-third of these species were oak feeders. Analysis revealed significant correlations between the moth assemblage found within a forest stand and the importance of oaks, tree density, and percent basal area of shrubs and saplings. However, less than 25 percent of the moth community structure could be explained with the environmental variables measured. Moreover, moth communities across 20 forest stands exhibited weak or no spatial autocorrelation. Although niche-assembly processes appear to play a role in structuring forest moth communities, stochastic or other factors may be even more important, at least in the absence of disturbance or successional events that alter overstory composition (Summerville et al., this publication).

Wood-boring beetles (Buprestidae and Cerambycidae) rely on living or recently killed trees for portions of their life cycles. They serve as decomposers, ecosystem engineers, pollinators, and food resources within forest ecosystems (Gutowski 1987; Holland 2009; Linsley 1961, cited in Holland et al., this publication). Regrettably, some species in these groups also damage valuable hardwood species and thus function as pests. Holland et al. (this publication) captured 102 species of wood-boring beetles during the pre-treatment phase of the HEE, including several new state and county records. Fortunately, no exotic invasives were collected in the sample. Analysis revealed no differences in measures of species diversity among sites scheduled for future treatments. However, differences were noted between assemblages of proposed harvest sites and sites within the units that were not slated for the initial harvest. These differences may have been due to sampling of harvest and non-harvest sites in separate years, coupled with differences in weather in the 2 years. Roughly half of the species responsible for the difference appear to have generation times >1 year, which could cause annual variation in abundance that would have been reflected in the harvest versus non-harvest site comparisons.

Many species of temperate bats depend on forests for roosting and foraging habitat, and silvicultural practices have the capacity to alter the quality of these habitats. Concern also exists regarding the conservation status of bats, especially so for the federally endangered Indiana bat (*Myotis sodalis*). Sheets, Duchamp, et al. (this publication) and Sheets, Whitaker, et al. (this publication) assessed bat communities across the nine HEE management units. Mist netting yielded 342 bats of 8 species from 18 locations over 3 years (Sheets, Whitaker, et al., this publication), and acoustic sampling with bat detectors produced 3,759 min of recordings with bat calls of 7 species from 157 locations over 2 years (Sheets, Duchamp, et al., this publication). A single silver-haired bat (*Lasionycteris noctivagans*) was captured via mist netting in 2008 and likely was a migrant (Mumford and Whitaker 1982).

Based on acoustic sampling, bat activity was similar among sites designated for the three silvicultural treatments. Bat diversity was slightly higher at sites designated for EA management. Sites designated for UEA treatment exhibited greater probability of high levels of bat activity than other sites. Levels of activity in four habitats were interior forest < corridors < forest edge ≤ pre-harvest openings, corresponding to reductions in structural density of vegetation. Among species, northern long-eared bats (*Myotis septentrionalis*) were more likely than other bats to exhibit high levels of activity within interior forest sites. Tri-colored bats (*Perimyotis subflavus*) also used interior forest locations at relatively high levels. Northern long-eared and Indiana bats used forest openings less than other species did.

Small mammals form an important prey base for forest predators, serve as important predators of insects and seeds, and promote dispersal of seeds and mycorrhizal fungi in some circumstances (Maser et al. 1978, Moore et al. 2007, Whitaker and Hamilton 1998). Urban and Swihart (this publication) captured 3,422 small mammals of 7 species from 32 trapping grids during the pre-treatment phase of the HEE. Site occupancy probability did not differ as a function of proposed silvicultural treatment for any of the small mammal species. Relative abundance of eastern chipmunks (*Tamias striatus*) was lower on sites proposed for EA treatment but did not differ among proposed treatments for white-footed mice (*Peromyscus leucopus*), pine voles (*Microtus pinetorum*), or short-tailed shrews (*Blarina brevicauda*). Survival of local pine vole populations was greater at sites with northeastern aspects, as was relative abundance of white-footed mice and short-tailed shrews. Amount of herbaceous cover was positively associated with relative abundance of pine voles and short-tailed shrews, and pine voles also were more abundant at trap sites with greater amounts of coarse woody debris.

Baseline Comparisons

Despite the wide array of taxa surveyed, few differences were reported in the pre-treatment data (Table 1). Differences fell into three broad categories. For those studies where inventories were taken over successive years, temporal differences were often reported either for the community as a whole, or for individual species within that community. Malloy and Dunning (this publication), for example, reported an increase in relative abundance of several focal bird species over the 3 years of pre-treatment data. Likewise, MacNeil and Williams (this publication) reported an increase in salamander encounters from 2007 to 2008. The exact causes of many of these increases are unknown, but they may be attributed to temporal variation induced by weather either on the HEE sites or, in the case of birds, on wintering grounds.

The second group of differences was related to local neighborhood habitat features (Table 1). Although Saunders and Arseneault (this publication; Figs. 7 to 15) did not statistically test for intra-core differences, they used spatially explicit maps to display the large variability in the woody plant community across each research core. They effectively demonstrated that habitat differed widely within cores, often varying by slope position and aspect. Corresponding to this variation in habitat, differences were noted for terrestrial salamander (MacNeil and Williams, this publication) and small mammal (Urban and Swihart, this publication) communities on northeast versus southwest aspects.

Other researchers alluded to intra-core differences within their communities but did not formally test for them, often because experimental design was not appropriate (Table 1). For example, Holland et al. (this publication) observed significantly different beetle assemblages between areas designated for future harvest and matrix sites (i.e., the remaining areas within each research core). However, as sampling of these two areas was conducted in different years, intra-core variability and temporal variability were confounded. Holland et al. (this publication) postulated that the synchronized emergence of several species with generations spanning multiple years would naturally lead to different community assemblages across years, and hence, pre-treatment spatial variability may not be that important for the wood-boring beetle community.

Table 1.—Summary of pre-treatment data results from ecological studies in the Hardwood Ecosystem Experiment. Significant temporal (i.e., across years) or spatial (i.e., within or across cores or treatments) comparisons tested by the authors of the source are denoted by capital letters; differences mentioned but not significantly tested are in lowercase. Comparisons not tested or mentioned are denoted by a question mark. In several cases, the comparisons were not applicable (denoted by n/a), usually because the sampling design did not allow temporal comparisons or spatial comparisons at that scale.

			Differences tested or mentioned				
Group	Units	Number of inventories	Temporal	Intra-core	Inter-core	Inter-treatment	Source†
Monitoring communities							
Woody vegetation	1-9	1	n/a	y	Y	N	8
Breeding birds	1-9	3	Y	n/a			7
Salamanders							
Cover objects	1-9	2	Y	Y	?	N	6
Quadrat surveys	1-9	1	n/a	Y	?	Y	6
Focal groups							
Eastern box turtles	4-9	2	N	n/a	Y	N	1
Timber rattlesnakes	2,5,6,9	2	n	?	y	?	5
Cerulean warblers	1-9	2	N	n/a	N	N	3
Oak mast	1-9	3	Y	?	?	N	4
Bats							
Mist netting	1-9	3	N	?	y	?	10
Acoustic	1-9	2	Y	y	?	Y	9
Small mammals	1-9	2	N	Y	?	Y	12
Moths	1,2,3	1	n/a	y	Y	n/a	11
Wood-boring beetles	1-9	3	Y	y	?	N	2

† In alphabetical order, sources (all in this publication) are: 1) Currylow et al., 2) Holland et al., 3) Islam et al., 4) Kellner et al., 5) MacGowan and Walker, 6) MacNeil and Williams, 7) Malloy and Dunning, 8) Saunders and Arseneault, 9) Sheets, Duchamp, et al., 10) Sheets, Whitaker, et al., 11) Summerville et al., and 12) Urban and Swihart.

The last group of differences occurred at the broader landscape scale, either between units or between treatments (Table 1). There was no consistent pattern in reported differences at this scale; EA cores were highlighted as different for chipmunk abundance by Urban and Swihart (this publication), whereas UEA cores had lower terrestrial salamander encounter rates in quadrat surveys (MacNeil and Williams, this publication) and higher-level bat use (Sheets, Whitaker, et al., this publication). These differences may be due to landscape-level environmental gradients and/or differences in land use history. Jenkins (this publication) noted that the northernmost units (i.e., cores 1-3) lie within the pre-Wisconsin glacial limit; therefore, they have less topographic relief than the more southern units. Likewise, Carman (this publication) noted that Yellowwood State Forest was created in 1947, some 18 years after Morgan-Monroe. This difference in ownership history contributes to the legacy of the Great Depression-era planting of conifers throughout the Yellowwood State Forest by the Civilian Conservation Corps; two of these plantations exist in research core 8 (Saunders and Arseneault, this publication).

Given the variability in pre-treatment habitats (Saunders and Arseneault, this publication) and the inherent environmental gradients of such a large-scale study, even minor, nonsignificant, pre-treatment community differences could partially mask treatment effects (Monserud 2002). This outcome may be particularly troublesome for those species or communities that have inherently high inter-annual variability in abundance and/or composition. Our hope is that the treatments are severe enough perturbations to the study species and communities to overcome these limitations of the HEE design. Nevertheless, mean responses may not convey the true treatment effect, and researchers should specifically look for non-uniformity in response by research unit within a given treatment, relating those differences back to unit-specific, pre-treatment data and known environmental variables whenever possible. Therefore, researchers should consider using mixed-modeling approaches for analysis, treating individual treatment units as random effects and tying the random effects to longitudinally measured, environmental covariables whenever possible.

Lastly, potential inter-unit differences may limit the ability to generalize results from studies using a subsample of units for comparison. Summerville et al. (this publication), for example, used only research cores 1-3 for their sampling and observed slight differences in moth communities across these cores (Table 1). Given their use of these data in broader, regional studies (e.g., Summerville et al. 2009), this experimental approach is an appropriate one. However, it would be improper to infer that the observed harvest treatment effects on these most northerly of the units would be representative of the response on the Yellowwood units, given the known differences in overstory communities (Saunders and Arseneault, this publication).

RESEARCH HIGHLIGHTS – SOCIOLOGICAL

As public property, state forests serve a wide array of stakeholders. Thus, it is useful to consider attitudes regarding forest management at multiple scales. Witter et al. (this publication) surveyed 1,402 Indiana residents from across the state to assess their opinions about forest management. Ninety percent of respondents professed to be somewhat or very interested in the state's fish, forests, and wildlife and the out-of-doors. Nearly 80 percent of respondents indicated that they had visited a state forest, although most did not distinguish among properties managed by the Department of Natural Resources-Division of Forestry as opposed to other state agencies. In keeping with this generic sense of state forests as any publicly owned land, 58 percent of respondents confessed to not being familiar with the Indiana Division of Forestry. Although 85 percent of Indiana forestlands actually are held in private ownership, 73 percent of respondents indicated they believed that government ownership accounted for half or more of Indiana's forestlands. When informed that state forests make up only 3 percent of Indiana's forests, 55 percent of respondents felt that this percentage was not enough.

Concern over the long-term health of Indiana's forests was greater for residents who were woodland landowners, had recently purchased lumber/wood products for home improvement, lived in southern Indiana, were >44 years of age, or professed liberal-leaning political views. When asked about harvesting of timber as a forest management tool, the approval rate was 95 percent if the goal was to protect woodlands from disease or wildfire, 85 percent if harvesting was overseen by professional foresters, 82 percent to improve wildlife habitat, and 61 percent to make lumber or other wood products. The vast majority (88 percent) of respondents agreed that Indiana forests should be managed for multiple uses. Lifestyles, early life experiences, and influences from resource professionals were important in shaping 48 percent of respondents' values about forest land.

To gain a clearer understanding of attitudes held by individuals directly affected by forest management on Morgan-Monroe State Forest, Rogers et al. (this publication) conducted an on-site survey of 165 recreational users and a mail survey of 1,239 neighboring landowners. The surveys contained an informational intervention designed to assess the degree to which enhanced knowledge about forest management would change attitudes. Hiking was the most common form of recreation mentioned. Of landowners, 78 percent indicated they felt uninformed about forest management activities occurring on Morgan-Monroe State Forest.

Respondents compared images of mature unharvested stands as well as single-tree selection, shelterwood, and clearcut harvests. Forest stand density was correlated positively with the acceptability of management practices, desirability of forest scenes, and likelihood of visiting managed forests. In general, order of preference was intact stands > single-tree selection > shelterwood > clearcut. Recreationists varied in their support for harvesting timber from forests to derive ecological benefits. Not surprisingly, opponents of harvesting were 13 times more likely to find images of shelterwood cuts unacceptable. Providing information on the benefits of forest management increased acceptability scores for all treatments except the no-harvest treatment. Acceptability of the no-harvest option tended to decline following information intervention, which is consistent with a greater appreciation of the value of forest management. Providing information to respondents who initially held neutral or undecided attitudes about forest management for human benefits resulted in levels of acceptability for all practices except clearcutting that were comparable to attitudes held toward no harvest.

The multiple uses of MMYSF complicate attempts at valuation, as many of the benefits derived from these properties cannot be monetized readily, if at all. Hoover (this publication) considered intrinsic, cultural, and aesthetic values as they relate to human ties to forests generally and specifically to the role of forest management in creating a mix of successional stages. No monetary values were assigned for these attributes, or for the values of ecosystem services or research. Hoover (this publication) estimated monetary values associated with forest recreation, wildlife, and timber sales. Estimates for the first two categories were derived indirectly from secondary data. Using data for the HNF, day trips to MMYSF were estimated to make up >60 percent of the total visits. Expenditures for day trips likely ranged from $30 to $40 per party per trip (2003 dollars). With regard to fish and wildlife on MMYSF, annual hunting value was estimated at about $148,000, fishing value was estimated at roughly $246,500, and viewing value was estimated at $2,164,000.

Direct comparison of these values to impacts estimated from timber harvesting is not appropriate, because multipliers for determining total economic impact of wildlife are not available. The gross annual economic impact of timber sales from MMYSF for 1993-2010 averaged $94.9 million, assuming a gross economic multiplier of $51 per board foot (Hoover and Settle 2010). With regard to the various silvicultural treatments considered in the HEE, application of EA silviculture was estimated to reduce the value of forest land by approximately $2,500-$7,000 per ha. This reduction is due to the long waiting period for intermediate and final harvests with EA management.

PREDICTING POST-HARVEST RESPONSES

The studies summarized above provide a baseline from which to examine how populations of plants, wildlife, and humans respond to the silvicultural treatments. Theory and prior studies can guide predictions and form the basis for the material presented in this section. The focus here is on predicting short-term responses, as the uncertainty associated with responses increases at least proportionately with time since disturbance. Of course the timespan encompassed by short-term responses will differ according to the taxa considered. For instance, the length of time over which a short-term response is operative for overstory tree communities is likely an order of magnitude longer than the time frame of response for insects.

In the absence of overstory disturbances resulting from a widespread windstorm or from timber harvesting, the woody plant community of the HEE can be expected to continue its compositional shift from oak-hickory dominance to maple dominance that began decades ago. This shift is well documented in the literature (Abrams and Nowacki 1992, Fei et al. 2011, Johnson et al. 2003, Nowacki et al. 1990, Rentch et al. 2003). For example, Aldrich et al. (2005) reported that oaks had largely failed to recruit into the overstory of an Indiana old-growth stand for over 75 years in absence of grazing, fire, or other stand-level disturbances. Both basal area and stem density in undisturbed sites are also likely to increase in the foreseeable future, as shade-tolerant species continue to regenerate and recruit into multiple understory strata (Lorimer 1993, Nowacki and Abrams 2008).

Harvesting will produce obvious and dramatic changes in stem density and species composition. Following harvest, timber stand improvement within the clearcuts in the EA cores and patch cuts in the UEA cores removed most woody competitors >2.5 cm from those sites (Kalb and Mycroft, this publication). Future composition of these sites, therefore, will be determined by the combination of propagules from seed fall, advanced regeneration and sprouting of harvested stumps. Given that there was little advanced regeneration of oak, outside of chestnut oak (*Q. prinus* L.) on very dry ridgetops, and that the harvests were not timed with a mast year, clearcuts and patch cuts will likely be dominated for several years by shade-intolerant species such as tulip poplar (*Liriodendron tulipifera* L.) and sassafras (*Sassafras albidum* [Nutt.] Nees) that seed in from adjoining stands, with a few stems of oak and hickory arising from stump sprouts (Johnson et al. 2002). As is typical during stand initiation (sensu Oliver and Larson 1996), stem densities will increase until all growing space is occupied within these cuts, which will occur within 20 years in most oak-dominated forests (Johnson et al. 2002). Stem densities will then decline rapidly with competition-induced mortality during stem exclusion (Oliver and Larson 1996), with the survivors likely being the more numerous shade-intolerant species (Jenkins and Parker 1998, Morrissey et al. 2010).

In the UEA cores outside of the patch cuts, the single-tree selection harvests may accelerate successional development toward maple dominance (Abrams and Nowacki 1992, Jenkins and Parker 1998). Oak has not been regenerating in these stands for several years; therefore, most understory advanced regeneration consists of shade-tolerant species. Removing individual oaks across the site does not create large enough openings in the canopy to regenerate and sustain oak populations, even if shade-tolerant stems are removed as well (Johnson et al. 2002, Lorimer 1993). Continual single-tree selection likely will just thin overstory oaks more rapidly than the overstory oaks decline in the control stands, reducing oak dominance in the UEA cores until the maple and beech in the subcanopy strata recruit into the overstory (Sander and Graney 1993).

Within the shelterwood areas in the EA cores, removal of the midstory and many small overstory canopy trees through a preparatory harvest increased light levels at the forest floor and may allow development of a seedling bank of oak and hickory if overstory trees mast repeatedly before the understory fills again with shade-tolerant regeneration (Johnson et al. 2002). However, success of the shelterwood treatment can be hampered by deer herbivory to a greater extent than for clearcuts or patch cuts. Repeated browsing from high deer populations may quickly overwhelm the lower seedling densities that establish under an overstory as compared to the higher densities in full-light environments. In any case, researchers will need to be patient and schedule the next harvest of the shelterwood sequence (the establishment cut) when there is an established bank of oak seedlings throughout much of each site and, ideally, a bumper crop of mast in the overstory (Brose 2011, Loftis 1990).

Terrestrial salamanders generally are predicted to respond negatively to timber harvest, due to the hotter and drier conditions created by opening of the canopy and reduction in leaf litter (Herbeck and Larsen 1999) coupled with limited dispersal ability (Welsh and Droege 2001). However, negative effects may be ameliorated by leaving some basal area at a site (Knapp et al. 2003). Thus, salamanders are likely to be less negatively affected by initial entries into three-stage shelterwoods, and by smaller patch cuts. However, additional entries into shelterwoods could interfere with recovery (Morneault et al. 2004). Secondarily, site aspect may play a role, with a reduced effect of a particular silvicultural treatment predicted for northeast-facing sites.

Similar responses are predicted for species of small mammals that rely on humid sites with well-developed litter layers, including shrews and pine voles (Urban and Swihart 2011). In contrast, eastern chipmunks are predicted to increase in the dense, shrubby conditions characterizing southwest-facing openings with low basal areas shortly after harvest, irrespective of opening size (Urban and Swihart 2011). The presence of basking sites and abundant prey could also make these sites popular for timber rattlesnakes.

Following harvest, declines in the vicinity of openings are expected in abundance of birds and bats characterized by mature, interior forest habitat, including acadian flycatcher (*Empidonax virescens*), cerulean warbler (*Setophaga cerulea*), ovenbird (*Seiurus aurocapilla*), red-eyed vireo (*Vireo olivaceus*), scarlet tanager (*Piranga olivacea*), worm-eating warbler (*Helmitheros vermivorum*), wood thrush (*Hylocichla mustelina*), and northern long-eared bat (Malloy and Dunning, this publication; Sheets, Duchamp, et al., this publication; Sheets, Whitaker, et al., this publication). Increases in abundance or activity are predicted in early successional species or those with preferences for foraging in open areas, including brown-headed cowbird (*Molothrus ater*), Carolina wren (*Thryothorus ludovicianus*), indigo bunting (*Passerina cyanea*), eastern towhee (*Pipilo erythrophthalmus*), Indiana bat, little brown myotis (*Myotis lucifugus*), eastern red bat (*Lasiurus borealis*), hoary bat (*L. cinereus*), big brown bat (*Eptesicus fuscus*), and possibly tri-colored bat. Area effects are likely for most of these species, although some of the bats (e.g., Indiana bat) may be more responsive to the amount of edge created than to the size of an opening.

Moth communities did not vary predictably during the pre-treatment phase of the HEE. However, forest disturbances that alter microclimates and facilitate shifts in plant species composition can provide colonization opportunities for moth species that previously were absent from a site (Summerville et al. 2009). Shifts in moth assemblages thus are expected to follow shifts in plant species composition and/or microclimates. Short-term shifts could include addition of species associated with forbs and early successional woody vegetation. Short-term shifts also are anticipated in wood-boring beetle assemblages, as down logs and snags of various species attract beetles that rely on these resources for larval habitat. As with bird and bat communities, these responses are likely to be area-dependent, as the zone of attraction created is presumed to be correlated with the volume of harvested trees.

Nearly all of the respondents to the statewide survey conducted by Witter et al. (this publication) approved of timber harvest to improve forest health (defined as fire or disease). However, one-third of respondents preferred that the state's woodlands be untouched by humans. Ratings of visual acceptability also indicated that users of Morgan-Monroe State Forest prefer forest scenes with dense, unburned stands (Rogers et al. this publication). Thus, we predict negative responses to silvicultural prescriptions that deviate most from the unmanaged norm, i.e., greatest opposition to clearcutting, followed by patch cutting and then the midstory removal stage of shelterwood harvest. We also predict that educational efforts about the ecological and other benefits associated with these silvicultural treatments will reduce negative perceptions. However, we suspect that effects of education will be greatest for those individuals who have the least emotional connection to MMYSF.

CHALLENGES AND OPPORTUNITIES

The HEE has progressed from infancy to toddler stage, with post-treatment responses beginning to be quantified. Still, a great deal of work remains to characterize both the biotic and abiotic variables related to community responses. Spatially explicit databases need to be built from pre-treatment data, and additional data layers, such as soils, canopy cover, and land-use history, need to be summarized from existing management records and available remotely sensed data. These data need to include not only research cores and units, but also the landscape context within which MMYSF lies. HEE databases can then more effectively inform the design of new studies, increase the efficiency of sampling, and allow more adaptive management in response to the harvest treatments.

As is the case for many large-scale, long-term forest management studies, the scope of inference for HEE—to describe the effects of forest management in the Central Hardwood Region—is broad and complex and involves investigation of ecological, economic, and social responses at an operational scale (Ganio and Puettmann 2008). A broad scale of inference is a strength of studies such as the HEE, because results collected are directly applicable at the scale of management activities, thereby leading to relatively rapid transfer of knowledge (Curtis et al. 2004, Puettmann 2005) and increasing the credibility of the research (Seymour et al. 2006) to land managers. Furthermore, large-scale, long-term studies allow the opportunity to superimpose smaller-scale, shorter-term studies of components or processes of the ecosystem that cannot be investigated across larger extents. If these fine-scale studies are done in a manner that explicitly recognizes the broader spatial context, they can be exceedingly valuable to quantify the scale dependency in process (Levin 1992) and identify emergent properties of the system (Puettmann et al. 2009).

Unfortunately, large-scale, long-term studies create a set of challenges, and we discuss five important challenges here. First, shortsightedness can mortgage the long-term value of studies such as the HEE. The short-term, ancillary experiments described above could have been superimposed onto the HEE project in a way that compromised the original objectives of the larger study. Shortsightedness can occur in research programs funded partially or entirely by "soft money"; a sudden infusion of cash from a large grant can direct the focus of researchers and administrators from the original objectives of the larger study. Similarly, political or social pressure to focus on taxa that are of most management concern at the time can distract attention or effort from longer-term objectives. Finally, monitoring programs can be tempting targets to cut during periods of fiscal duress, even though they are critical to describing the long-term trends of the larger study. While there is no one "right" or "wrong" approach to the influence of external pressures, development of a strong objective tree is critical to long-term success of large-scale forest management studies (Ganio and Puettmann 2008). The HEE has been proactive in this respect; the full HEE objective tree is provided as an appendix in Kalb and Mycroft (this publication).

Second, minimal replication of landscape treatments results in low statistical power in large-scale studies. The size of experimental units, and costs of maintaining monitoring programs and other ecological studies, limited HEE researchers to installation of three replicates. Consequently, investigators may have difficulty detecting small or moderate treatment effects for the various taxa (Ganio and Puettmann 2008, Gram et al. 1997). Harrington and Carey (1997[2], as cited in Monserud 2002), for example, estimated that it would take 8-10 replications to detect a 20-percent treatment effect in small animal populations within their study ecosystem. Further, several research units in the HEE abut one another, so there is a possibility that responses for wide-ranging taxa (e.g., birds) might be pseudoreplicated as populations within each unit may not be spatially independent (Hurlbert 1984, Monserud 2002).

Although these deficiencies in experimental design can limit inference, researchers studying silvicultural systems and ecological phenomena at an operational scale often have no choice (Seymour et al. 2006). Use of mixed modeling, Bayesian hierarchical models, or other statistical approaches that explicitly account for spatial and/or temporal autocorrelation may help in this regard. Furthermore, HEE researchers should pursue the use of meta-analysis across multiple similar, but independent, large-scale studies to increase statistical power and inference (Monserud 2002). One such sister study is the Missouri Ozark Forest Ecosystem Project (Brookshire and Shifley 1997, Shifley and Kabrick 2002), which is similar to HEE in forest type, scale, and research objectives. Other opportunities likely exist for comparisons that extend beyond the boundaries of the HEE. For example, a post-treatment study of white-tailed deer impacts on herbaceous communities and tree regeneration included the installation of thirty-two 22m × 22m paired plots in clearcuts, shelterwoods, patch cuts, single-tree selection, and uncut matrix. In each pair, a 2.5-m tall exclosure was constructed. These exclosure plots are proposed to be included within a meta-analysis of deer impacts across the eastern United States.[3]

A third and imminent challenge facing the HEE team is to sustain momentum and commitment. Studies of manipulations to ecosystems need to persist at least long enough for transient dynamics to fade and the system to stabilize (Tilman 1989). In forests, transient dynamics can last for decades, with long-term treatment outcomes differing from or even contradicting the short-term treatment responses (Monserud 2002). Maintaining investigator and institutional momentum over this period can be difficult even with adequate funding sources. Academic demands for short-term, sharply focused, reductionist studies can discourage long-term participation by early-career scientists (Monserud 2002). Since forest development trajectories change slowly soon after the initial treatment, meaningful change in forest ecosystem structure or processes may not occur for a decade—well beyond a 3-year granting cycle or even a 7-year faculty tenure window. Consequently, university scientists often must relegate the study to a minor portion of their research portfolio.

Likewise, educational and outreach opportunities risk decline over this period, if prior events satiate public and professional consumers of project-related information. The “adolescent” stage of projects such as the HEE can be a dangerous period because the natural flow of products associated with long-term objectives can ebb or be perceived as stagnant before the study has matured enough to show long-term treatment effects and non-transient dynamics. Addressing the challenge of project adolescence will require project administrators to be actively engaged with researchers

[2] Harrington, C.A.; Carey, A.B. 1997. The Olympic Habitat Development Study: conceptual study plan. Unpublished manuscript on file at the Olympia Forestry Sciences Laboratory. Olympia, WA: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 38 p.

[3] Chris Webster (professor, Michigan Technological University) and Mike Jenkins (associate professor, Purdue University), personal communication

in identifying emerging research topics and new opportunities for collaboration.

Flexibility is a fourth challenge to the future success of the HEE. Planning documents for many large-scale forest management studies, including the HEE, state that an adaptive management framework will be used to guide future treatment prescriptions (e.g., Curtis et al. 2004, Franklin et al. 1999). However, adaptive management can become a nightmare for individuals asked to analyze results from the study. For instance, researchers and project administrators may choose to split experimental units to study a new treatment array that is being superimposed on the original study. From a management viewpoint, splitting can provide a powerful demonstration of individual treatment effects within a silvicultural system. From a research perspective, however, these splits can further reduce the statistical power of an already "power-starved" study, thereby weakening inference.

We are not asserting that an adaptive framework is unnecessary. On the contrary, researchers must be able to change treatment prescriptions when those treatments do not achieve their respective goals. This is the hallmark of a study comparing management or silvicultural "systems", which are planned sets of "treatments" used to accomplish some desired structural condition (Smith et al. 1997). By establishing benchmarks for individual treatment success a priori (e.g., Curtis et al. 2004), follow-up treatments can be done in a manner that does not compromise the original objectives of the study (Ganio and Puettmann 2008).

Unfortunately, these decisions often happen well after study establishment (Abbott et al. 1999), making application of follow-up treatments a contentious issue among researchers on an interdisciplinary team. For example, the use of prescribed fire in the HEE was deemed both too costly and administratively difficult to coordinate immediately after the first harvest entry across multiple research cores. However, advanced oak regeneration within shelterwoods is almost nonexistent, even 2 years after midstory removal and a subsequent mast year in those areas. Thus, project administrators and researchers will need to decide on the use of prescribed fire in areas slated for harvest during the next entry in 2028, largely as a way to build up a seedling bank of regeneration well ahead of overstory harvests. The use of prescribed fire will have to be carefully considered against the costs of increasing sampling effort to document its effects.

A fifth challenge of a long-term study is to maintain scientific, managerial, and social relevance. Many large-scale forest management studies, like the HEE, are often installed to fill a knowledge gap for management. The widely-cited Demonstration of Ecosystem Management Options study established in Washington and Oregon is a good example; Franklin et al. (1999: 4) explain that the study was conceived "to integrate ecological and commodity objectives." Studies that are inherently applied can still address fundamental research questions, but not without ingenuity and progressive thinking. The "hot-button" topic in science that may have helped drive the conception of a study will, in all likelihood, have long faded from scientific concern by the time the long-term results are known. HEE researchers will thus need to "re-think, re-analyze, and re-package" their long-term results to frame and answer emerging questions of basic interest.

Maintaining science of high relevance is a necessary but not sufficient condition for success of projects such as the HEE. Relevance to land managers and the public must also be maintained. Monserud (2002: 176) wrote: "As scientists, it is tempting to believe that the world will wait patiently for our well-designed experiments to be completed before conclusions can be reached." Practicing foresters, wildlife biologists, and other resource managers recognize that sound ecological and social science is only one small piece of a large list of information used to make policy and management decisions. Regulatory, economic, social, and political pressures often drive the decisionmaking process in the management of publicly owned natural resources. Managers and the public often do not have the luxury of waiting on definitive answers and thus routinely make decisions based on short-term results.

In this regard, the HEE has the potential to be an exemplar for integrating ecologic and social research. The HEE's primary objectives explicitly state that economic and social ramifications of timber harvesting will be quantified, and that the HEE will be an outdoor laboratory for public engagement (Kalb and Mycroft, this publication). We have established a baseline in public attitudes regarding forest harvesting (Rogers et al., this publication; Witter et al., this publication); we now need to track changes in social attitudes and norms in response to ongoing research, education, and outreach efforts. Incorporating a longitudinal social science component into the HEE is perhaps the biggest challenge, and biggest opportunity, of all.

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