PAST IS PROLOGUE: A SYNTHESIS OF STATE FOREST MANAGEMENT ACTIVITIES AND HARDWOOD ECOSYSTEM EXPERIMENT PRE-TREATMENT RESULTS

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Abstract.—Disturbance plays an important role in forest development processes. Present-day forest condition can be viewed as the cumulative result of various historical disturbance events; therefore, an understanding of disturbance history is important when describing overall forest condition. Pre-treatment studies of the Hardwood Ecosystem Experiment (HEE) have described various ecological and social aspects of portions of two State Forests in south-central Indiana that serve as the study area for the HEE. This paper describes the timber harvesting history for the HEE study area and how this history relates to HEE studies and current forest condition. Additionally, pre-treatment results of HEE studies are discussed in the context of past state forest management activities to highlight important emerging issues in state forest management that could be addressed by future HEE research.

INTRODUCTION

Disturbance events can have a dramatic, sometimes long-lasting, effect on forest structure and composition. The overall impact on forest development, ecosystem processes, community structure, and recovery from these events varies depending on such attributes as disturbance intensity, frequency, and spatial scale. Disturbances play a particularly important role in shaping the development of managed forests, where anthropogenic disturbance agents are prescribed alongside natural events to achieve predictable outcomes. Often, forest managers base this predictability upon an understanding of how events and manipulations in the past have affected the present-day condition of a forest. Furthermore, a thorough understanding of how historical disturbance events have shaped a forest may better inform future decisionmaking and help adapt management trajectories accordingly.

The Hardwood Ecosystem Experiment (HEE) is a long-term, landscape-scale collaborative project designed to explore the ecological effects and social aspects of forest management in the heavily forested region of south-central Indiana (Kalb and Mycroft, this publication). The HEE is based upon a comparative before-and-after experimental design using replicated treatments defined by even-age and uneven-age silvicultural methods and unharvested control areas. A “pre-treatment” study period began in 2006 to allow researchers to collect baseline data until the treatment harvests were implemented starting in the summer of 2008. Post-treatment data collected after harvesting will be compared to baseline conditions to quantitatively evaluate the response of various attributes to the harvests. Researchers have also used baseline data to evaluate the pre-treatment condition of the HEE research sites, known as “cores” (Kalb and Mycroft, this publication). Similarity among cores, and particularly among the three treatment types (i.e.,

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cores designated for uneven-age, even-age, or control treatments), is important in a before-and-after study because post-treatment effects will be easier to identify if pre-treatment conditions were similar.

Given that HEE study areas exist on two state forests, each with an extensive management history, an assessment of each core's timber harvest history would help to provide a more complete understanding of its condition before implementation of the HEE experimental treatments. In this paper, I summarize a review of state forest records that documented inventories and harvests at the present-day HEE research cores. My goals for this review were to: 1) evaluate the degree of similarity in timber harvest history among the HEE research cores and treatment types, 2) provide an historical context to the HEE pre-treatment results, and 3) offer suggestions for future research to address important questions raised during the pre-treatment assessment process regarding forest management on state forests and in southern Indiana in general.

STUDY AREA

The study area and experimental design of the HEE project is described in detail by Kalb and Mycroft (this publication). The historical documents reviewed pertained to inventories and harvests that took place at Morgan-Monroe (MMSF) and Yellowwood State Forests (YSF), where the HEE study areas (i.e., research cores) have been established.

State forest stands are classified using the forest type nomenclature of the U.S. Department of Agriculture, Forest Service (U.S. Forest Service 2011: Appendix 2). Indiana Department of Natural Resources-Division of Forestry continuous forest inventory data[2] indicate the Mixed Upland Hardwood forest type accounts for 46 percent of both MMSF and YSF, and is the single largest forest type at each property. On MMSF and YSF, stands are often dominated by a mix of species that may include yellow-poplar, sugar maple, and at least one oak species (see Appendix 1 for listing of scientific names). Oak-hickory forest types account for 43 percent of both properties, with white oak-red oak-hickory the largest single forest type in the oak-hickory group at the MMSF (32 percent) and YSF (22 percent). Conifer or mixed forest types account for <5 percent of either property.

Division of Forestry inventory data[3] also indicate approximately 2 percent of MMSF and YSF is <20 years old, and stands >80 years old occur across >50 percent of these two state forests, combined. Across MMSF and YSF, 74 percent of stands classified as oak-hickory are >80 years old, and <0.5 percent are <20 years old.

MATERIALS AND METHODS

Inventory and harvest records, as well as other supporting documents, were reviewed and summarized for each of the state forest management tracts occurring within a HEE research core. HEE cores were established across 27 management tracts in 2006; cores contain two or three tracts, each ranging from 17 to 53 ha. Records reviewed dated from 1971 to when pre-treatment surveys began on HEE research cores in 2006.

Although records were largely complete (with the exception of one missing file for a tract in core 8), inconsistencies in how information was recorded over the 35-year period limited the scope of the review and made certain compromises necessary in data analysis. For instance, though some records indicated the number and size of each regeneration opening (i.e., patch cut or group selection) associated with a harvest, other records simply provided a range in sizes

[2] Data on file with the Indiana Department of Natural Resources-Division of Forestry, Indianapolis, IN

[3] Data on file with the Indiana Department of Natural Resources-Division of Forestry, Indianapolis, IN

and an overall number of acres that were included in openings. Therefore, rather than estimating mean opening size associated with each harvest, the mean size of the largest opening is presented.

Inconsistencies in data recording also limited the scope of analysis, especially considering the relatively few harvests that had occurred within cores (mean 2.3, range 1-4). Due to low sample sizes within cores, differences were tested among treatment types (i.e., uneven-age, even-age, and control) using pooled tract-level harvest data within each treatment type. Mean differences were tested using multi-response permutation procedures in program Blossom (Cade and Richards 2005). These procedures are analogous to one-way analysis of variance when comparing differences among >2 groups, and are more effective for testing small sample sizes than many parametric and nonparametric alternatives. A significance level of alpha = 0.05 was used for analyses.

RESULTS

A review of management records spanning 35 years indicated 21 harvests have taken place in the MMSF and YSF tracts that became HEE research cores in 2006 (Table 1). Seven harvests occurred in each treatment type. The overall proportion of core area harvested was similar across treatment types, with 60, 56, and 61 percent harvested in uneven-aged, even-aged, and control cores, respectively (Table 1). Among cores, historical harvest rates ranged from 14 percent of the area in core 4 to 95 percent in core 2, both designated as control cores (Table 1).

Even-aged and control cores received most of their harvests from 1985 through 1995, with no harvests occurring after 1995 (Table 1, Fig. 1). In uneven-aged cores 60 percent of core area had been harvested by 1995, similar to the other two treatment types; however, 30 percent of core 7 was harvested again in 2003, 3 years before the HEE pre-treatment period (Table 1). Overall, the mean number of years between a tract's last harvest and the start of the HEE pre-treatment period was similar among the three treatment types, ranging from 18 years at even-aged and control cores to 22 years at uneven-aged cores (Table 1).

Three state forest management tracts within HEE cores received >1 harvest during the 35-year review period,

Table 1.—Number of harvests, proportion of unit harvested by time period, and the mean age of harvests in cores (range of observations) and treatment type (standard error, range of observations) at the initiation of the HEE.

HEE unit	No. of harvests	Proportion (%) harvested 1971-1984	1985-1995	1996-2006	Total (1971-2006)	Harvest age (years)
1	1	28.3	0.0	0.0	28.3	35
7	4	73.5	20.1	30.7	93.7	18.8 (3-23)
8	2	0.0	58.3	0.0	58.3	15 (14-16)
Uneven-age	7	35.0	24.7	10.6	59.7	20 (4.2, 3-35)
3	4	0.0	78.9	0.0	78.9	15.5 (15-17)
6	2	0.0	46.9	0.0	46.9	13
9	1	32.5	0.0	0.0	32.5	22
Even-age	7	9.2	46.4	0.0	55.7	15.7 (1.2, 13-22)
2	3	0.0	94.5	0.0	94.5	15.7 (15-17)
4	1	13.5	0.0	0.0	13.5	24
5	3	0.0	78.5	0.0	78.5	13.7 (11-17)
Control	7	4.7	56.3	0.0	61.0	16 (1.6, 11-24)
HEE overall	21	16.4	42.4	3.5	62.3	17.2 (1.5, 3-35)

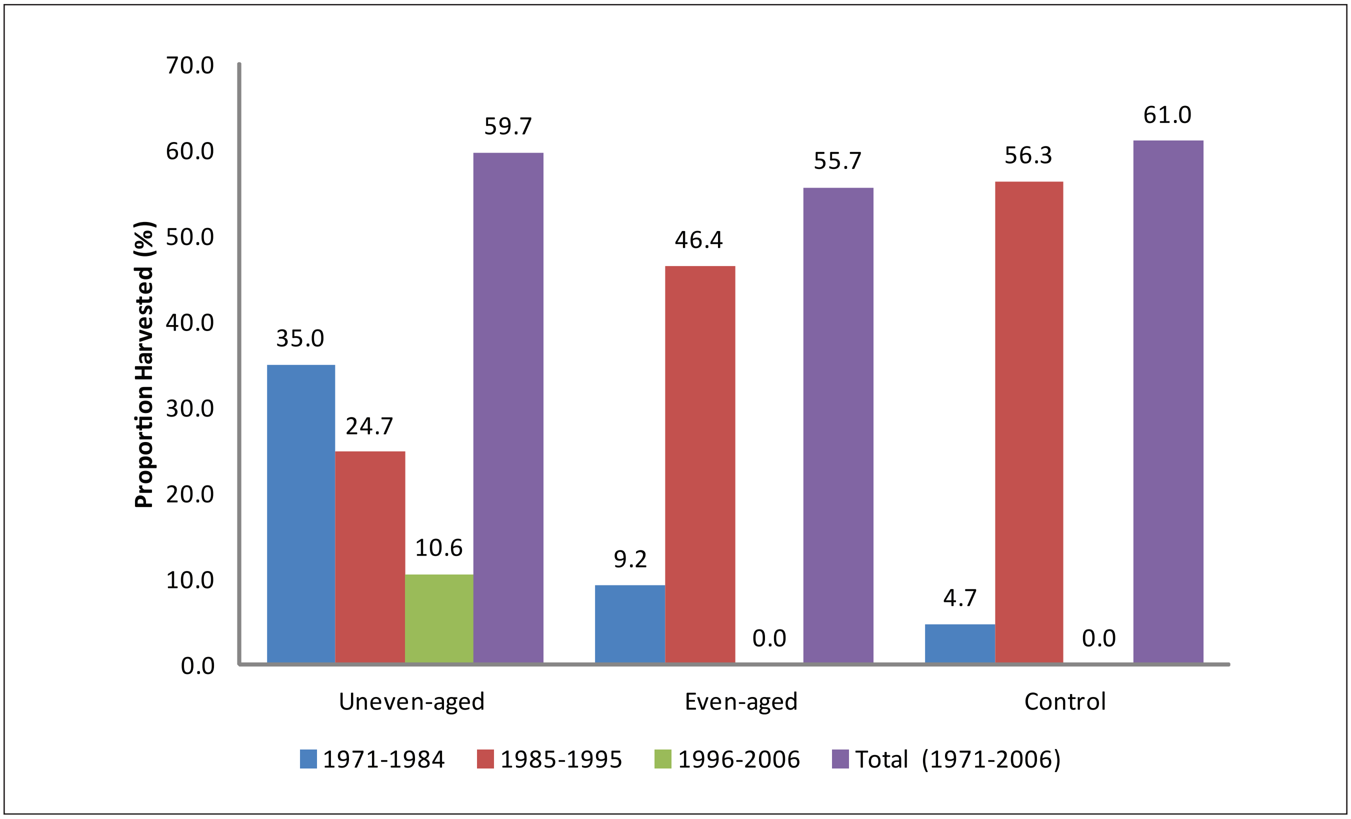

Figure 1.—Proportion of HEE treatment types harvested by time period. Labels over bars indicate treatment value.

and with the exception of the 2003 improvement harvest in core 7, additional harvests were due to salvage harvesting in previously harvested tracts that had experienced high wind damage at MMSF during the summer of 1990 (Table 2). Salvage harvesting was limited to areas in cores 2 and 3, affecting 17 percent of the overall HEE study area (Table 2).

Historically, non-regenerative, intermediate harvests (e.g., selection thinning, improvement harvests) were the most often employed harvesting method in core tracts, with 96, 89, and 92 percent of harvests in uneven-aged, even-aged, and control cores, respectively, using this cutting method (Table 2). Harvest records indicated that these techniques were typically prescribed to thin overstocked stands, release suppressed crop trees, and remove poorly developed individuals to reduce competition with trees of higher quality. Additionally, similar selective techniques were used during salvage harvests to remove damaged trees with commercial value. Most improvement harvest prescriptions mentioned removing fire-scarred trees of poor quality, indicating that, historically, the occurrence of fire was not uncommon on HEE cores.

Across all cores, regeneration harvests (e.g., patch cut and group selection) accounted for 7.4 percent of harvesting (Table 2). Among treatment types, even-aged cores had the highest proportion of regeneration harvests (11.7 percent), mostly associated with portions of salvage harvests where heavy damage resulted in a total loss of standing timber. The size of the largest patch cuts and group openings ("regeneration openings") was similar across treatment types, ranging from 0.9 hectares in uneven-aged cores to 1.4 hectares in even-aged cores (Table 3). Additionally, the mean age of regeneration openings was similar among treatment types, ranging from 15 years in uneven-aged and even-aged cores to 16 years in control cores (Table 3).

Table 2.—Proportion of HEE units salvage harvested and the proportion of harvests using patch cutting or group selection (Patch/Group) and single-tree harvesting techniques. Harvesting occurred at present-day HEE research cores, 1971-2003. n = number of harvests in unit; NA = no determination made due to incomplete records.

HEE unit			Proportion of harvests (%)	
(core/treatment)	n	Salvage harvested[a] (%)	Patch/Group	Single-tree
1	1	0.0	NA	NA
7	4	0	5.1	94.9
8	2	0	2.3	97.7
Uneven-age	7	0	4.3	95.7
3	4	66.6	13.9	86.1
6	2	0	5.5	94.5
9	1	0	NA	NA
Even-age	7	26.7	11.7	88.3
2	3	72.2	11.7	88.3
4	1	0	1.0	99.0
5	3	0	4.6	95.4
Control	7	23.4	8.3	91.7
HEE overall	21	16.7	7.4	92.6

[a] Includes patch cuts, group harvests, and single-tree harvesting done during salvage harvests.

Table 3.—Mean maximum regeneration opening area and the mean age of regeneration openings at the initiation of the HEE. For both attributes, means are presented by core (range of observations) and treatment type (standard error, range of observations). Harvesting occurred at present-day HEE research cores, 1980-2003. n = number of harvests in unit; NA = no determination made due to incomplete records.

HEE unit (core/treatment)	n	Maximum regeneration opening[a] area (ha)	Regeneration opening age (years)
1	0	NA	NA
7	3	1.2 (0.5-1.5)	14.3 (3-23)
8	2	0.4 (0.3-0.4)	15 (14-16)
Uneven-age	5	0.9 (0.24,0.3-1.5)	14.6 (3.26,3-23)
3	4	2.0 (0.8-2.8)	15.5 (15-17)
6	2	0.4 (0.3-0.4)	13
9	0	NA	NA
Even-age	6	1.4 (0.45,0.3-2.8)	14.7 (0.61,13-17)
2	2	2.3 (0.8-3.7)	16 (15-17)
4	1	0.1	24
5	2	0.5	12 (11-13)
Control	5	1.1 (0.65,0.1-3.7)	16 (2.23,11-24)
HEE overall	16	1.1 (0.24, 0.1-3.7)	15.2 (1.17,5-26)

[a] The largest opening created during a single harvest when multiple openings were created.

Mean volume harvest rates (i.e., mean proportion of pre-harvest volume harvested) differed among treatment types (T = -1.93, A = 0.14, p = 0.048), with uneven-aged cores having higher rates of volume removal than control cores, and even-aged cores intermediate to and not different from the other two treatment types (Table 4). Across cores, mean proportion of volume harvested ranged from 10 to 40 percent, with the highest tract-level volume harvest rate (52 percent) occurring in core 7 (Table 4).

The mean density of trees harvested per hectare was similar across treatment types, ranging from 21.6 trees ha^{-1} in control cores to 29.5 trees ha^{-1} in even-aged cores. In all treatment types, the oak-hickory species group provided the majority of trees harvested (Table 5; Fig. 2). Along with scarlet oak, a shade-intolerant species, moderately shade-intolerant oaks, such as chestnut oak, black oak, and white oak were among the most harvested species in each treatment type (Table 5). Relatively abundant non-oak species harvested across all HEE cores included yellow-poplar, large-toothed aspen, hickories, American beech, and sugar maple (Table 5).

Table 4.—Mean proportion of volume harvested by core (range of observations) and treatment type (standard error, range of observations). Harvesting occurred at present-day HEE research cores, 1971-2006. n = number of harvests in unit; NA = no determination made due to incomplete records.

HEE unit (core/treatment)	n	Volume harvested[a] (%)
1	0	NA
7	4	40.2 (24.7-52.9)
8	2	26.9 (24.7-29.1
Uneven-age	6	38.8 (4.9,24.7-52.9)
3	4	21.7 (15.5-26.7)
6	1	29.8
9	0	NA
Even-age	5	23.3 (3.2,15.5-26.7)
2	3	19.0 (13.7-27.5)
4	1	30.9
5	1	9.8
Control	5	19.6 (4.0,9.8-30.9)
HEE overall	16	26.8 (2.9,9.8-52.9)

[a] Proportion of pre-harvest volume removed during harvest.

DISCUSSION

Historically, cores in each of the HEE treatment types were similarly managed, with the exception of marginally higher rates of volume removal in uneven-aged cores compared to control cores. Driving this difference were harvests in core 7, where the mean proportion of volume harvested was 40 percent and harvesting had occurred as recently as 2003, just 3 years before the pre-treatment research period began. Interestingly, Saunders and Arseneault (this publication) reported core 7 had lower total and overstory tree density, and lower total and overstory basal area than most other cores. They also reported that relative to the other HEE cores, core 7 had

Table 5.—Relative density (trees ha^{-1}) of trees harvested 1982-2003 at present-day HEE cores by treatment type. Species ranked by relative density pooled across all HEE cores. Scientific names presented in Appendix 1.

	Relative density of trees harvested (%)[†]			
Common name	HEE overall	Uneven-age	Even-age	Control
Chestnut oak	22.9[ab]	10.2[ab]	24.2[ab]	36.7[ab]
Scarlet oak	17.5[ab]	10.9[ab]	27.5[ab]	10.3[ab]
Black oak	14.8[ab]	13.3[ab]	13.1[a]	12.7[ab]
White oak	8.7[a]	10.6[ab]	7.8[a]	7.0[a]
Northern red oak	6.8[a]	4.2	7.5[a]	5.5[a]
Yellow- poplar	6.6[a]	5.8[a]	5.6	4.2[a]
Bigtooth aspen	4.5[a]	6.4[a]	2.8	4.2[a]
Hickory spp.	4.3	7.0[a]	3.0	2.9
American beech	3.6	10.0[ab]	0.5	4.0
Sugar maple	3.4	9.9[a]	2.2	2.0
White ash	1.7	2.3	0.8	1.6
Sassafras	1.2	1.1	0.9	2.5
Red maple	1.1	1.7	0.6	2.2
American basswood	1.1	0.6	0.8	1.9
Blackgum	0.9	1.9	0.1	1.2
Black cherry	0.4	0.3	0.3	0.5
Red elm	0.1	0.2	0.1	0.2
Black walnut	0.1	----	0.1	0.1
Black locust	0.1	----	0.2	0.1
Elm spp.	0.1	----	----	0.2
American elm	< -0.1	< -0.1	----	----
Kentucky coffee-tree	< -0.1	----	< -0.1	----
Hackberry	< -0.1	< -0.1	----	----
Virginia pine	< -0.1	----	< -0.1	----

[†] Superscript “a” ([a]) denotes species that collectively account for 80 percent of treatment type total, superscript “b” ([b]) denotes species that collectively account for 50 percent of total.

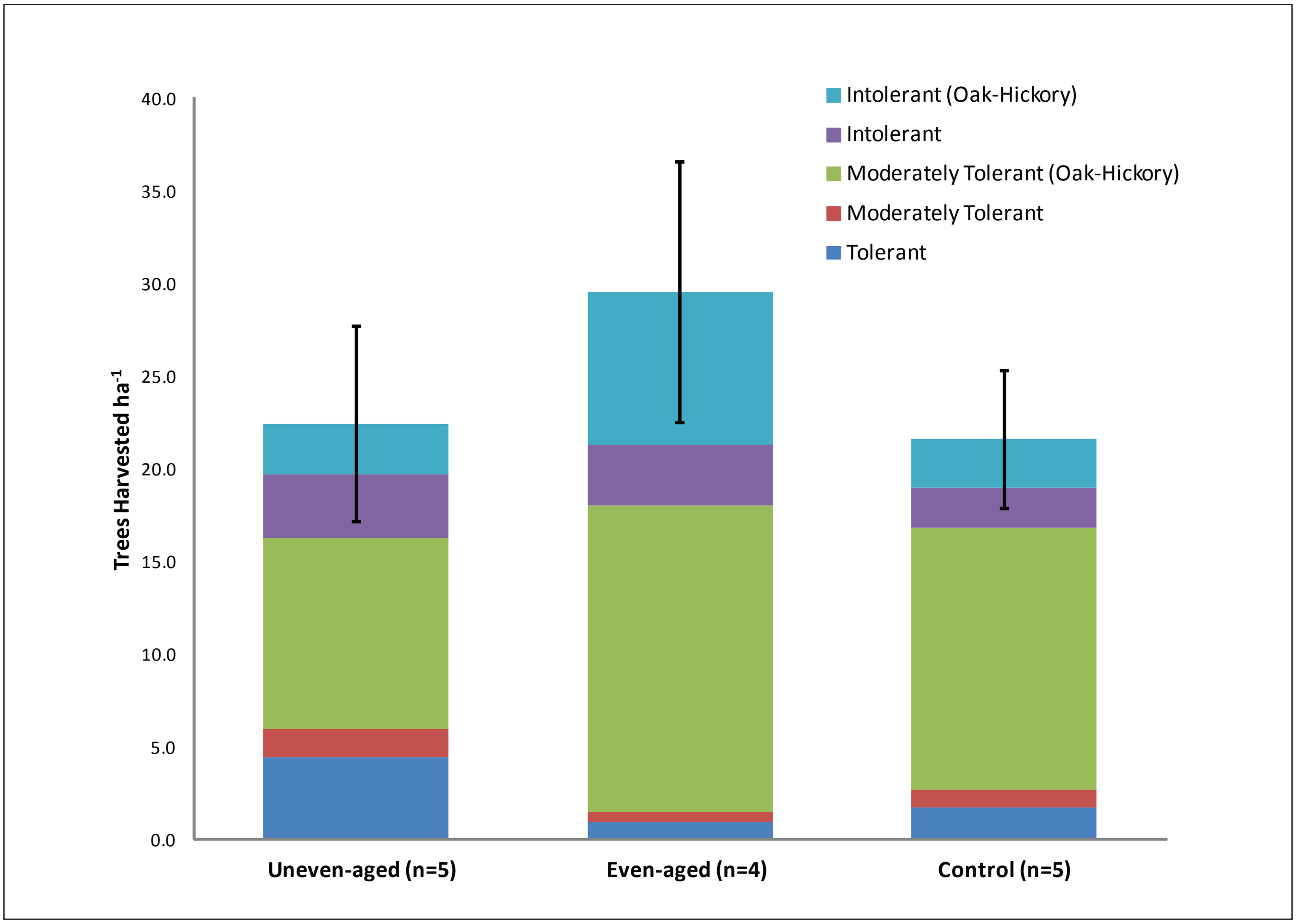

Figure 2.—Density (trees ha^{-1}) of trees harvested by HEE treatment type. Error bars approximate ±1 standard error of the total. n = number of harvests. Definitions of shade tolerance are given in Appendix 1.

irregular diameter and basal area distributions, suggesting the core contained fewer small sawlog-sized trees (i.e., 30 to 50 cm diameter at breast height). The findings of Saunders and Arseneault (this publication) are consistent with the effects expected from harvest records, and it is likely that during the pre-treatment study period stands in core 7 were still recovering from relatively recent and heavier-intensity harvests than stands had experienced in the other HEE cores.

Other authors in this volume found differences in pre-treatment conditions between uneven-aged cores and those of the other treatment types. Sheets, Duchamp, et al. (this publication) found HEE cores destined for uneven-aged treatments had a greater probability of high bat activity, compared to cores of other treatment types. Although these authors were unable to explain this result due to the limited scope of their study, they predicted forest structure likely had strong implications on bat activity and habitat use in the HEE study area (Sheets, Duchamp, et al., this publication). MacNeil and Williams (this publication) found mean encounter rates for salamanders were lower in uneven-aged cores compared to control and even-aged cores when a quadrat survey technique was used (but similar when cover object arrays were used), a result they attributed to relatively low encounter rates for two species. Future HEE research will provide a better understanding of how these species are affected by timber harvesting and whether pre-treatment results reflect historical harvest activities or are more strongly associated with other factors. Despite these few noted differences, however, most authors in this volume found no difference among the treatment types, suggesting harvests may affect species differently and providing further justification for simultaneously studying harvest effects across communities, rather than just at the single-species level.

Although timber harvesting has occurred on all HEE research cores over the last 35 years, authors in this volume report that pre-treatment conditions reflect mature forest suitable for experimental, before-and-after comparisons of timber harvest effects. Because managers have primarily relied on selection silviculture and intermediate harvesting methods, as opposed to stand-replacing even-age techniques, cores have generally maintained overstory structure characteristic of mature forest (Saunders and Arseneault, this publication). Malloy and Dunning (this publication) report the most abundant avian species encountered on HEE cores were those that use mature forest habitat, whereas species dependent on early-successional habitats were found less often. Other studies, too, have found that bird species associated with mature forest habitats are typically abundant in selectively harvested forest (Haulton 2008), further suggesting that historical management of core tracts was consistent with the habitat requirements of mature forest bird species.

Malloy and Dunning (this publication) also report that two mature forest species listed in Indiana as “species of special concern,” Hooded and worm-eating warblers, were among the most abundant species found on HEE cores during the pre-treatment period. The state-endangered cerulean warbler was found on all HEE cores during the pre-treatment study period, and densities were similar or slightly higher than those reported from other Indiana locations (Islam et al., this publication). Earlier research at MMSF and YSF also indicated that state forest harvesting practices appear to be compatible with the breeding habitat needs of cerulean warblers (Register and Islam 2008).

Bat studies on HEE sites indicated that pre-treatment conditions favor the northern myotis, which is typically found in mature forests (Sheets, Duchamp, et al. this publication; Sheets, Whitaker, et al., this publication). Sheets, Whitaker, et al. (this publication) suggested that the forest structure produced by selection harvesting at MMSF and YSF created interior forest conditions suitable for this “clutter-adapted” species. Indiana myotis, a federally endangered species that also uses interior forests, was also found on several HEE cores but prefers more open woodland conditions, which may explain why it was found less frequently than other forest bat species (Sheets, Whitaker, et al., this publication). Future HEE research will provide more insight into Indiana myotis’ habitat use and preferences relative to various treatment types and harvesting techniques.

HEE cores historically were managed primarily using intermediate harvesting techniques, such as selection thinning and improvement harvests. Reliance on these methods over the history of MMSF and YSF reflects the developmental stage of most stands at these state forests. Much of the forest land composing these two properties was acquired in a depleted, and often cut-over, condition when it was placed into public ownership beginning around 1930 and continuing through the 1940s (Carman, this publication). Many of these second-growth stands were coming into maturity in the decades preceding the HEE pre-treatment period, requiring selective thinning and improvement harvests to release better-quality trees from competition and to remove damaged and poorly developed trees from the mature stand.

In these developing forests, stand improvement, rather than regeneration, was the priority; however, when regeneration opportunities were available, foresters typically prescribed group selection or larger patch cuts. Pre-treatment forest conditions at HEE sites reflect this philosophy; Saunders and Arseneault (this publication) found that even though oak and hickory species dominated core overstories, more shade-tolerant species—often red and sugar maple—accounted for most of the smaller stems found in cores. Lack of large forest canopy openings to encourage the regeneration of less shade-tolerant species, such as oaks, has had ramifications for wildlife habitat as well; species requiring early-successional forest were encountered far less frequently than those that use late-successional, interior forest (Malloy and Dunning, this publication; Sheets, Duchamp, et al., this publication; Sheets, Whitaker, et al., this publication). Furthermore, given that the mean age of openings across all HEE cores was 15 years, many regeneration openings that were created on HEE cores have since succeeded beyond the stage where they would be attractive to early-successional species that use only recently created openings.

These results illustrate a major challenge for Indiana state forests in the coming years: as these forests continue to mature and require less maintenance through intermediate techniques, new management systems will need to be employed to regenerate and maintain oak-dominated forests. Summerville et al. (this publication) and Holland et al. (this publication) reported that oak was an important predictor of invertebrate species assemblage and diversity on HEE cores; loss of oak would undoubtedly have long-reaching effects throughout all levels of the forest community (Kellner et al., this publication). The HEE will play an important role in the transition on state forests from primarily single-tree management to a system that incorporates more regeneration methods and balances the habitat requirements of species that use late-successional interior forests with those that use early-successional forest communities.

FUTURE CONSIDERATIONS

Development of Oak Regeneration System

One of the primary research objectives of the HEE is to develop silvicultural systems that maintain oak-dominated communities and landscapes (Kalb and Mycroft, this publication). Even-age techniques, such as clearcutting and shelterwoods, have traditionally been favored for oak regeneration (Johnson et al. 2002); however, they are currently not widely used in Indiana and their effectiveness and ecological impact have not been thoroughly studied in the state. HEE research will provide a better understanding of how these cutting methods affect forest regeneration response on Indiana state forests and in Midwestern forests in general while also providing information on the social and ecological effects of these harvest types. Given the historical reliance on single-tree harvesting at HEE cores, and the pre-treatment conditions that suggest an overall lack of oak regeneration in cores, these prescriptions will provide much needed guidance toward the development of management systems that work to sustain oak as a dominant and ecologically important species group in Indiana forests.

Fire has played an important role in the development of Indiana's forests, and is believed to have influenced the dominance by oak and hickory prior to European-American settlement (Jenkins, this publication). Historical state forest records indicated that many improvement harvests were prescribed on core tracts to remove fire-scarred trees, suggesting that fires were not uncommon in these oak-dominated forests prior to public ownership. Other research has indicated that use of prescribed fire may provide an efficient and effective way to reduce competition from less fire-tolerant species, such as red maple and beech (Johnson et al. 2002). Given the history of fire in southern Indiana forests and its purported role in oak regeneration, HEE researchers should investigate further how prescribed fire might fit into an oak regeneration system for southern Indiana and what the community-level effects of such a system might be.

Balancing Habitat Requirements

Indiana state forests are managed to provide habitat for all native forest species. HEE pre-treatment results indicate, however, that mature forest communities dominate core tracts, conditions that reflect the overall trend across MMSF and YSF and, more generally, all

Indiana state forests. Recent data from the Division of Forestry's continuous forest inventory indicate approximately 2 percent of state forests is <20 years old.[4] These conditions have developed partly due to a reliance on intermediate harvesting methods that maintain canopy cover, enhance stand-level structural heterogeneity, and facilitate the development of old forest characteristics (Franklin et al. 2007), but they are also due to decades of actively limiting the effects of other disturbance agents through both fire suppression and insect pest control.

Although relatively homogenous mature forest conditions are preferred by many species and are desirable for pre-treatment cores in a comparative before-and-after harvesting-effects study such as the HEE, such landscape-scale homogeneity could occur at the expense of excluded assemblages and communities (Summerville et al., this publication). Forest managers would benefit from a better understanding of where appropriate thresholds exist between landscape heterogeneity and homogeneity. Specifically, at what point does the creation of early-successional forest habitat across a landscape negatively affect habitat suitability for interior, mature forest species (e.g., Becker et al. 2011)? Given the landscape-scale approach of the HEE and opportunities for community-level research, future HEE studies should provide a better understanding of impact thresholds, allowing forest managers to balance habitat opportunities for all species.

Maintaining Structural Habitat

During pre-treatment studies, HEE researchers identified several structural habitat features that may be especially important to forest species on HEE cores, including snags (Sheets, Whitaker, et al., this publication); unmerchantable harvest residue, such as tops and limbs (slash) (MacGowan and Walker, this publication); and other down coarse woody debris (Holland et al., this publication; Urban and Swihart, this publication). Sheets, Whitaker, et al. (this publication) indicated that retention of snags suitable for Indiana myotis' day-roosting will help reduce negative impacts that may occur during harvests. Similarly, MacGowan and Walker (this publication) reported that creation of early-successional habitat and retention of woody debris following harvest could enhance habitat for timber rattlesnakes. Holland et al. (this publication) noted that coarse woody debris serves as habitat to many wood-boring beetles, and retention of this structural component should be a consideration for sustainable forest management.

In the coming years, emerging technologies, such as the use of harvest residues and other forms of woody biomass for alternative energy sources, may compete with forest communities for these important structural resources (Indiana Department of Natural Resources-Division of Forestry 2011). Forest managers facing choices between the utilization of harvest residues and pre-existing coarse woody debris for energy production and retention of these materials for community sustainability and resilience will look to researchers for guidance on how to balance all needs sustainably. Although guidelines have been established in Indiana for the retention of harvest residue (Indiana Department of Natural Resources-Division of Forestry 2011) and structural forest habitat elements (Indiana Department of Natural Resources-Division of Forestry 2008), there are opportunities to rigorously test their impacts and effectiveness on managed forest communities. The long-term, multi-disciplinary, experimental approach of the HEE makes it well suited to investigate where appropriate structural retention thresholds exist in Indiana forests and what effects these new harvesting technologies may have on forest communities in the years to come.

[4] Data on file with the Indiana Department of Natural Resources-Division of Forestry, Indianapolis, IN

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LITERATURE CITED

Becker, D.A.; Wood, P.B.; Keyser, P.D.; Wigley, T.B.; Dellinger, R.; Weakland, C.A. 2011. **Threshold responses of songbirds to long-term timber management on an active industrial forest.** Forest Ecology and Management. 262(3): 449-460.

Cade, B.S.; Richards, J.D. 2005. **User manual for Blossom statistical software.** Open-File Report 2005-1353. Fort Collins, CO: U.S. Geological Survey, Fort Collins Science Center. 124 p.

Franklin, J.F.; Mitchell, R.J.; Palik, B.J. 2007. **Natural disturbance and stand development principles for ecological forestry.** Gen. Tech. Rep. NRS-19. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 44 p.

Haulton, S. 2008. **Effects of silvicultural practices on bird communities in deciduous forests of eastern and central North America.** Available: http://www.in.gov/dnr/forestry/files/fo-ManagedForestBirdReview.pdf. (Accessed 4 October 2012).

Indiana Department of Natural Resources-Division of Forestry. 2008. **Management guidelines for compartment-level wildlife habitat features.** Available: http://www.in.gov/dnr/forestry/files/fo-Guidelines_WildlifeHabitatFeatures.pdf. (Accessed 4 October 2012).

Indiana Department of Natural Resources-Division of Forestry. 2011. **Harvesting biomass, a guide to best management practices.** Available: http://www.in.gov/dnr/forestry/files/fo-BiomassGuide.pdf. (Accessed 4 October 2012).

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

Niinemets, Ü.; Valladares, F. 2006. **Tolerance to shade, drought, and waterlogging of temperate northern hemisphere trees and shrubs.** Ecological Monographs. 76(4): 521-547.

Register, S.M.; Islam, K. 2008. **Effects of silvicultural treatments on cerulean warbler (*Dendroica cerulea*) abundance in southern Indiana.** Forest Ecology and Management. 255(8-9): 3502-3505.

U.S. Forest Service. 2011. **Forest Inventory and Analysis national core field guide. Volume 1, field guide collection procedures for phase 2 plots.** Version 5.1. Available: http://fia.fs.fed.us/library/field-guides-methods-proc/. (Accessed 4 October 2012).

APPENDIX 1.

Species' scientific names used in the text. Shade tolerance groups shown for tree species; tolerance groups were defined based on the shade tolerance scale of Niinemets and Valladares (2006) with intolerant and intolerant oaks and hickories <2.5, moderately tolerant and moderately tolerant oaks and hickories 2.5-3.5, and tolerant >3.5.

Common name	Scientific name	Shade tolerance	Tolerance group
Red maple	*Acer rubrum*	3.4	Moderately Tolerant
Sugar maple	*Acer saccharum*	4.8	Tolerant
Hickory spp.	*Carya* spp.	2.7*	Moderately Tolerant (Oak-Hickory)
Hackberry	*Celtis occidentalis*	3.2	Moderately Tolerant
American beech	*Fagus grandifolia*	4.8	Tolerant
White ash	*Fraxinus americana*	2.5	Moderately Tolerant
Kentucky coffee-tree	*Gymnocladus dioicus*	2.5	Moderately Tolerant
Black walnut	*Juglans nigra*	1.9	Intolerant
Yellow-poplar	*Liriodendron tulipifera*	2.1	Intolerant
Blackgum	*Nyssa sylvatica*	3.5	Tolerant
Virginia pine	*Pinus virginiana*	2.0	Intolerant
Bigtooth aspen	*Populus grandidentata*	1.2	Intolerant
Black cherry	*Prunus serotina*	2.5	Moderately Tolerant
White oak	*Quercus alba*	2.9	Moderately Tolerant (Oak-Hickory)
Scarlet oak	*Quercus coccinea*	2.1	Intolerant (Oak-Hickory)
Chestnut oak	*Quercus prinus*	2.9	Moderately Tolerant (Oak-Hickory)
Northern red oak	*Quercus rubra*	2.8	Moderately Tolerant (Oak-Hickory)
Black oak	*Quercus velutina*	2.7	Moderately Tolerant (Oak-Hickory)
Black locust	*Robinia pseudoacacia*	1.7	Intolerant
Sassafras	*Sassafras albidum*	1.7	Intolerant
American basswood	*Tilia americana*	4.0	Tolerant
American elm	*Ulmus americana*	3.1	Moderately Tolerant
Red elm	*Ulmus rubra*	3.3	Moderately Tolerant
Hooded warbler	*Setophaga citrina*		
Worm-eating warbler	*Helmitheros vermivorum*		
Cerulean warbler	*Setophaga cerulea*		
Northern myotis	*Myotis septentrionalis*		
Indiana myotis	*Myotis sodalis*		
Timber rattlesnake	*Crotalus horridus*		

* Average shade tolerance value for all species in genus occurring on HEE

The content of this paper reflects the views of the author(s), who are responsible for the facts and accuracy of the information presented herein.