PRE-TREATMENT ANALYSIS OF WOODY VEGETATION COMPOSITION AND STRUCTURE ON THE HARDWOOD ECOSYSTEM EXPERIMENT RESEARCH UNITS

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Abstract.—In long-term, large-scale forest management studies, documentation of pre-treatment differences among and variability within experimental units is critical for drawing the proper inferences from imposed treatments. We compared pre-treatment overstory and large shrub communities (diameters at breast height >1.5 cm) for the 9 research cores with the Hardwood Ecosystem Experiment (HEE) in south-central Indiana with a total of 683 0.1-ha sampling plots. There were many significant differences ($p < 0.05$) in stand structure among the cores for many attributes, but intra-core variability was not severe enough to lead to significant differences in structural attributes for the proposed management treatments (that is, when data were averaged across three replicates in each management treatment, there were no significant differences). Ordinations of plot-level data showed that all cores occupied much of the same ordination space, suggesting that forest structure was highly variable within cores but did not differ as much between cores. Plot-level maps of species composition and size structure also showed large degrees of variability within each research core and hinted at spatial patterning not yet captured well by HEE inventories. We suggest that future projects and subsequent analyses of the HEE better capture intra-stand variability in both abiotic and biotic components through spatially explicit methodologies.

INTRODUCTION

Before the early 1990s, much of the emphasis for management of public lands across the United States was on timber production (Curtis et al. 2007, Seymour et al. 2006). Silvicultural research questions often were concerned with growth and yield predictions, regeneration responses, thinning practices, and other stand-level responses (Puettmann et al. 2009). Researchers often used either small, very uniform plots—often 0.10 ha or less—in their designs to isolate the treatment responses (e.g., Cochran and Barrett 1999, D'Amato et al. 2011), or larger, unreplicated (or poorly replicated) areas to demonstrate harvest practices (e.g., Kolbe and McKay 1939, Sánchez Meador and Moore 2010, Sendak et al. 2003). Consequently, these plots and areas, even if maintained over long time periods, had limited use for analysis of broader environmental questions outside the scope of the original study (Curtis and DeBell 2010, Puettmann et al. 2009).

Contemporary silvicultural research has shifted its focus much more to balancing timber production objectives with wildlife, water, biodiversity, social, and a multitude of other objectives (Long 2009, Seymour et al. 2006). This change in focus has resulted in a shift to much larger experimental units, often on the order of 10 ha, that incorporate heterogeneous areas (Curtis and DeBell 2010, Seymour et al. 2006). Larger-scale experimentation allows linkages of forest structural

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response from treatment to wildlife habitat use and movement, nutrient cycling, natural disturbances, and other ecological processes that vary strongly temporally and spatially. Given the variability of the experimental units, however, these experiments are often poorly replicated because they are expensive to monitor and maintain (Curtis and DeBell 2010). Problems in documenting treatment responses may result as statistical power is often low, particularly if researchers and reviewers subscribe to the agricultural research model that summarizes treatment effects with a single mean value, thus ignoring intra-experiment unit variability (Puettmann et al. 2009).

Mixed-effects models, likelihood methods, spatial statistics, Bayesian approaches, and other tools can be used to help overcome some of these issues by explicitly incorporating variability into the statistical analysis. Regardless of the approach taken, documentation of pre-treatment differences in forest structure and composition among experimental units is essential to understanding how implemented treatments influence forest development over time (Ganio and Puettmann 2008, Kabrick et al. 1997). This documentation is particularly important for collaborative studies where comparative, pre-treatment analyses can inform subsequent wildlife and other ecological studies on potential additional needs for data collection.

The Hardwood Ecosystem Experiment (HEE) is such an example of a contemporary, large-scale, forest management study. This experiment, begun in 2006, is documenting the long-term ecological and social impacts of forest management on public lands in southern Indiana. The HEE experiment is in its infancy as pre-harvest data collection has been completed and early post-harvest data collection to quantify plant and animal responses to even- and uneven-aged management is ongoing.

During study site selection for HEE, researchers used blocks of management units that were thought to be rather uniform as a whole, but likely were variable in age, composition, and structure at finer scales (Kalb and Mycroft, this publication). Therefore, we approached the goal of documenting pre-treatment differences among units in two ways. First, we asked: In a spatially explicit context, are there differences in tree and large shrub community composition and structure among the HEE management units (i.e., research cores) that could mask overall treatment effects? Second, we asked: In a spatially implicit context, are there strong differences in the plot-level variability of the tree and large shrub communities among the cores?

STUDY AREA

The HEE study consists of nine management units throughout Morgan-Monroe and Yellowwood State Forests in south-central Indiana (Kalb and Mycroft, this publication: Fig. 1). Management units range from 303 to 483 ha (Kalb and Mycroft, this publication: Table 1), with each unit consisting of a buffer area and a research core. The buffer area around each research core is managed consistently across units using uneven-aged management, a typical management strategy used by the Indiana Department of Natural Resources-Division of Forestry at this time (Haulton, this publication). Research cores range in size from 78 to 110 ha (Kalb and Mycroft, this publication: Table 1) and are randomly assigned to one of three management regimes: an experimental control, even-aged management using three-stage shelterwood and clearcut approaches, and uneven-aged management using single-tree selection and patch cutting. There are, therefore, three replicates of each treatment, blocked roughly north to south across the two State Forests (Kalb and Mycroft, this publication: Fig. 1). Research cores contain most of the detailed inventory systems for the experiment.

MATERIALS AND METHODS

Sampling Design

From January 2008 to August 2010, 683 sampling plots were established on 75m x 150m grids within each of the nine HEE research cores. Sampling plots are circular and 0.1 ha in size. Sampling intensity ranges from 67 to 89 plots per unit, with an average area-based intensity of 8.5 percent (range: 8.0-9.2 percent). Plots are scheduled to be sampled again 4 years post-harvest (2013) and every 4 years thereafter.

Within each sampling plot, all overstory trees with diameters at breast height (d.b.h.; 1.37 m from ground) >11.5 cm are measured. Saplings, defined as all woody stems between 1.5 and 11.5 cm d.b.h., are sampled with a 0.025-ha circular subplot centered within the overstory sampling plot. For all overstory trees and saplings, species, d.b.h., condition (e.g., live, dead, cull, broken top, dying), light field (sensu Bechtold 2003), stratum, and spatial location (i.e., azimuth and distance from plot center) are recorded. Total tree height and height of the lowest live crown are subsampled on approximately four overstory trees and four saplings per sampling plot. These individuals are systematically selected as the first observed tree and sapling in each quarter of the circular plot as crews move clockwise from due north. If the individual is dead, species, d.b.h., total height, and decay class (Cline et al. 1980) are recorded.

Data Analysis

Using the data collected from the pre-treatment inventory, we tested for differences in several structural attributes among research cores using analysis of variance (ANOVA). These attributes were as follows: 1) number of species per plot, 2) density of stems per ha, 3) quadratic mean tree diameter, and 4) basal area per ha. Individual sampling plots were the experimental units for these comparisons. Analyses were conducted for only overstory trees with d.b.h. ≥30.0 cm, and for all overstory trees and saplings combined (i.e., all stems with d.b.h. ≥1.5 cm). We also tested for differences in these attributes for several key species groups (Table 1).

Table 1.—Scientific and common names of overstory trees and saplings recorded on the Hardwood Ecosystem Experiment sites. Species groups were defined based on their prevalence on the sites and the shade tolerance scale of Niinemets and Valladares (2006) with 1 = very intolerant, 2 = intolerant, 3 = moderately tolerant, 4 = tolerant, and 5 = very tolerant.

Scientific name	Common name	Shade tolerance	Species group
Acer negundo	boxelder	3.5	Tolerant
Acer nigrum	black maple	3.0	Tolerant
Acer rubrum	red maple	3.4	Tolerant
Acer saccharum	sugar maple	4.8	Tolerant
Alnus glutinosa	European black alder	2.7	Noncommercial
Amelanchier spp.	serviceberry	4.3	Noncommercial
Asimina triloba	paw paw	4.0	Noncommercial
Carpinus caroliniana	American hornbeam	4.6	Noncommercial
Carya tomentosa	mockernut hickory	2.4†	Oak & Hickory
Carya cordiformis	bitternut hickory	2.1	Oak & Hickory
Carya glabra	pignut hickory	2.7	Oak & Hickory
Carya ovata	shagbark hickory	3.4	Oak & Hickory
Celtis occidentalis	hackberry	3.2	Other Commer.
Cercis canadensis	eastern redbud	3.0	Noncommercial
Cornus alternifolia	alternate-leaf dogwood	4.0	Noncommercial
Cornus florida	flowering dogwood	4.9	Noncommercial
Cornus stolonifera	red-osier dogwood	3.8†	Noncommercial
Corylus americana	American hazelnut	3.5	Noncommercial

(Table 1 continued on next page)

Table 1 (continued).—Scientific and common names of overstory trees and saplings recorded on the Hardwood Ecosystem Experiment sites. Species groups were defined based on their prevalence on the sites and the shade tolerance scale of Niinemets and Valladares (2006) with 1 = very intolerant, 2 = intolerant, 3 = moderately tolerant, 4 = tolerant, and 5 = very tolerant.

Scientific name	Common name	Shade tolerance	Species group
Crataegus spp.	hawthorn	2.3†	Noncommercial
Diervilla lonicera	bush honeysuckle		Noncommercial
Elaeagnus umbellata	autumn olive	1.4†	Noncommercial
Fagus grandifolia	American beech	4.8	Tolerant
Fraxinus americana	white ash	2.5	Other Commer.
Fraxinus nigra	black ash	3.0	Other Commer.
Fraxinus pennsylvanica	green ash	3.1	Other Commer.
Gymnocladus dioicus	Kentucky coffee-tree	2.5	Other Commer.
Hamamelis virginiana	witch-hazel	3.0	Noncommercial
Juglans cinerea	butternut	1.9	Intolerant
Juglans nigra	black walnut	1.9	Intolerant
Juniperus virginiana	eastern red-cedar	1.3	Other Commer.
Lindera benzoin	spicebush	3.0	Noncommercial
Liriodendron tulipifera	tulip poplar	2.1	Intolerant
Lonicera maackii	amur honeysuckle	3.6†	Noncommercial
Maclura pomifera	osage orange	1.5	Noncommercial
Morus alba	white mulberry	1.4	Other Commer.
Nyssa sylvatica	blackgum	3.5	Other Commer.
Ostrya virginiana	eastern hophornbeam	4.6	Noncommercial
Pinus banksiana	jack pine	1.4	Other Commer.
Pinus resinosa	red pine	1.9	Other Commer.
Pinus strobus	eastern white pine	3.2	Other Commer.
Pinus virginiana	Virginia pine	2.0	Other Commer.
Platanus occidentalis	American sycamore	2.9	Other Commer.
Populus deltoides	eastern cottonwood	1.8	Other Commer.
Populus grandidentata	bigtooth aspen	1.2	Other Commer.
Populus tremuloides	quaking aspen	1.2	Other Commer.
Prunus americana	American plum	2.2†	Noncommercial
Prunus serotina	black cherry	2.5	Intolerant
Quercus alba	white oak	2.9	Oak & Hickory
Quercus coccinea	scarlet oak	2.1	Oak & Hickory
Quercus macrocarpa	bur oak	2.7	Oak & Hickory
Quercus muehlenbergii	chinkapin oak	2.2	Oak & Hickory
Quercus palustris	pin oak	2.5	Oak & Hickory
Quercus prinus	chestnut oak	2.9	Oak & Hickory
Quercus rubra	northern red oak	2.8	Oak & Hickory
Quercus velutina	black oak	2.7	Oak & Hickory
Rhus spp.	sumac	1.5	Noncommercial
Robinia pseudoacacia	black locust	1.7	Other Commer.
Sassafras albidum	sassafras	1.7	Intolerant
Staphylea trifolia	bladdernut		Noncommercial
Tilia americana	American basswood	4.0	Tolerant
Ulmus americana	American elm	3.1	Other Commer.
Ulmus rubra	red elm	3.3	Other Commer.
Viburnum prunifolium	smooth blackhaw	3.3†	Noncommercial
Viburnum recognitum	northern arrowwood	3.3†	Noncommercial
Vitis spp.	grape		Noncommercial

† Value for species was not given. Value is estimated from average of all listed North American species in that genus.

To evaluate differences among treatment units prior to harvesting, we used ANOVA with the core-level estimates (i.e., research cores were the experimental unit). For each structural attribute, we fit the fixed effects model:

$$Y_i = \mu + \alpha_i + \varepsilon_i , \qquad [1]$$

where μ is the overall mean of the response, α_i is the treatment effect (df = 2) on the response, and ε_i is the error (df = 6) independently distributed on $N(0,\sigma^2)$. Since variances were not equal for each core-level estimate, we weighted the ANOVA by σ^{-2}_{core}. A significance level of alpha = 0.05 was used for all former analyses.

Non-metric multidimensional scaling (NMDS) was used to graphically summarize pretreatment, plot-level differences in species importance values (IV) among both plots and the research core estimates. For the plot-level analysis, IV was calculated for each species as the percentage of total basal area in a sampling plot plus the percentage of total stem density in a sampling plot; therefore IVs could range from zero to 200. For the core-level analysis, IV includes percentage basal area, percentage stem density, and percentage of sampling plots where a species was recorded within the research core; therefore, IVs could range from zero to 300. To simplify the ordination, rare and isolated species (i.e., those found in only one research core or in <10 plots) were grouped for analysis. Both ordinations were run 250 times on both the real and randomized data using Sorensen distance measurements, random starting coordinates, and a stability criterion of 0.00001.

Lastly, we plotted plot-level, spatial summaries of basal area proportion by each species group using a geographic information system (ArcMap 10, ESRI, Redlands, CA) to evaluate within-research core variation in species composition. A similar analysis was conducted to assess within-research core variation in size class distributions after stratifying plot-level data into four, timber-based size classes: sapling (0–12.4 cm d.b.h.), pole (12.5–30.5 cm d.b.h.), small sawtimber (30.6–45.6 cm d.b.h.), and large sawtimber (≥45.7 cm d.b.h.).

Raw data were processed and summarized using the plyr package (version 1.4; Wickham 2011) in R 2.12 (R Development Core Team 2010). PC-ORD 5.0 (McCune and Grace 2002, McCune and Mefford 2006) was used for the NMDS analysis. Figures were produced using R 2.12 and the ggplot2 package (version 0.8.9; Wickham 2009).

RESULTS

Core-Level Differences

There were some differences in structure among the research cores. Total stem density averaged from 923 to 1,527 trees ha^{-1}, and overstory stem density (i.e., d.b.h. ≥30.0 cm) averaged from 93 to 150 trees ha^{-1} (Table 2; Fig. 1). Total basal area averaged from 21.7 to 29.9 m^2 ha^{-1}, with overstory trees making up 15.5 to 22.5 m^2 ha^{-1} (Table 2; Fig. 2). Although the cores were significantly different for many attributes (Appendix 1), differences were not pronounced aside from a few exceptions (Table 2). For example, Research Core 7 had significantly lower total and overstory stem density, and total and overstory basal area, than most other cores. Research Cores 3 and 8 had the highest total stem density and total basal area, respectively.

Diameter (Fig. 3) and basal area (Fig. 4) distributions were similar among most cores. Core 7 was notably different in having a less peaked basal area and fewer small sawlog-sized (i.e., 30-50 cm d.b.h.) trees than other research cores. Although all cores had negative exponential diameter distributions that suggested a balanced uneven-aged structure (Fig. 3), the bell-shaped basal area distributions suggested that the age structures were strongly irregular (Fig. 4), likely comprising an older oak-dominated cohort with multiple younger cohorts of differing species (Figs. 1 and 2).

Table 2.—Mean ± standard error and range of observations by research core for selected plot-level attributes. Density, quadratic mean diameter (QMD) and basal area are summarized across all size classes (Tot.; ≥1.5 cm d.b.h.) and for only overstory trees (Ovs.; ≥ 30 cm d.b.h.).

Attribute	Research core								
	1	2	3	4†	5	6	7	8	9
All Species									
No. of species per plot	9.5 ± 0.2 (5,16)	11.1 ± 0.3 (6,18)	11.6 ± 0.3 (5,19)	9.9 ± 0.3 (6,15)	10.3 ± 0.2 (6,15)	10.9 ± 0.3 (5,18)	8.4 ± 0.3 (4,17)	10.6 ± 0.3 (5,17)	9.8 ± 0.3 (4,17)
Tot. density (trees ha^{-1})	932 ± 36 (380,1780)	1420 ± 111 (470,4560)	1527 ± 90 (350,5140)	1156 ± 62 (420,2240)	1435 ± 63 (500,2860)	1161 ± 59 (390,3000)	923 ± 56 (210,3260)	1441 ± 68 (560,3030)	962 ± 53 (180,2830)
Ovs. density (trees ha^{-1})	140 ± 5 (60,240)	116 ± 6 (0,260)	103 ± 5 (10,250)	150 ± 6 (50,280)	113 ± 5 (40,260)	120 ± 5 (0,210)	93 ± 4 (10,180)	136 ± 6 (50,290)	121 ± 6 (0,290)
Tot. QMD (cm)	20.6 ± 0.5 (11.7,34.6)	17.7 ± 0.7 (6.9,29.3)	15.6 ± 0.5 (6.2,28.3)	19.0 ± 0.6 (11.4,31.0)	16.0 ± 0.4 (8.9,26.1)	17.7 ± 0.5 (8.4,29.0)	18.8 ± 0.6 (6.3,40.3)	17.0 ± 0.5 (10.6,31.6)	19.4 ± 0.7 (5.8,40.0)
Ovs. QMD (cm)‡	44.1 ± 0.5 (34.7,54.5)	45.6 ± 0.5 (36.5,62.3)	45.4 ± 0.5 (31.5,56.8)	44.2 ± 0.7 (34.8,58.0)	45.9 ± 0.6 (36.3,58.0)	43.5 ± 0.6 (43.5,57.7)	45.9 ± 0.6 (31.4,59.2)	44.6 ± 0.6 (32.6,57.7)	43.9 ± 0.6 (33.0,63.4)
Tot. Basal area (m^2 ha^{-1})	28.8 ± 0.7 (16.6,50.6)	27.8 ± 0.9 (13,42.5)	24.4 ± 0.7 (13.7,46.0)	29.6 ± 0.8 (17.8,44.7)	26.3 ± 0.7 (14.6,43.6)	25.4 ± 0.7 (12.6,38.5)	21.7 ± 0.7 (3.6,49.2)	29.9 ± 1.1 (10.9,56.1)	24.6 ± 0.8 (7.5,48.4)
Ovs. Basal area (m^2 ha^{-1})	21.1 ± 0.7 (6.9,44.9)	19.0 ± 1.1 (0,37.0)	16.9 ± 0.8 (0.8,37.5)	22.5 ± 0.8 (10.2,37.5)	18.5 ± 0.8 (5.4,35.4)	17.6 ± 0.7 (0,32.3)	15.5 ± 0.7 (2.3,33.8)	21.3 ± 1.1 (6.6,53.5)	18.4 ± 0.8 (0,39.6)
Oak & Hickory									
No. of species per plot	3.8 ± 0.2 (0,6)	3.6 ± 0.2 (0,6)	3.5 ± 0.2 (0,7)	3.6 ± 0.2 (0,6)	3.9 ± 0.1 (1,7)	4.2 ± 0.1 (1,8)	2.6 ± 0.1 (0,5)	3.2 ± 0.2 (0,6)	3.8 ± 0.2 (0,7)
Tot. density (trees ha^{-1})	235 ± 15 (0,680)	205 ± 29 (0,1440)	166 ± 17 (0,730)	204 ± 15 (0,530)	192 ± 15 (10,670)	219 ± 19 (10,1160)	85 ± 8 (0,430)	163 ± 13 (0,430)	186 ± 15 (0,500)
Ovs. density (trees ha^{-1})	120 ± 7 (0,230)	81 ± 8 (0,260)	63 ± 5 (0,170)	123 ± 8 (0,240)	92 ± 5 (10,220)	92 ± 6 (0,200)	48 ± 4 (0,150)	77 ± 6 (0,180)	105 ± 7 (0,270)
Tot. QMD (cm)	33.6 ± 1.1 (0,55.6)	34.8 ± 1.7 (0,64.3)	32.8 ± 1.5 (0,60.3)	37.2 ± 1.1 (0,53.8)	36.2 ± 0.9 (18.6,53.6)	33.8 ± 0.9 (10.7,61.3)	37.7 ± 1.5 (0,66.4)	32.2 ± 1.6 (0,51.1)	37.0 ± 1.3 (0,61.7)
Ovs. QMD (cm)‡	44.7 ± 0.6 (34.7,56.5)	46.3 ± 0.9 (33.0,64.3)	46.6 ± 0.7 (31.5,62.6)	44.8 ± 0.8 (34.6,61.1)	46.4 ± 0.7 (34.3,69.7)	43.9 ± 0.7 (33.3,65.0)	48.2 ± 0.9 (31.5,66.4)	45.6 ± 0.6 (34.7,57.2)	45.3 ± 0.8 (33.1,67.4)
Tot. Basal area (m^2 ha^{-1})	21.5 ± 1.0 (0,43.8)	15.7 ± 1.3 (0,39.8)	11.9 ± 0.9 (0,40.1)	21.7 ± 1.3 (0,37.9)	17.4 ± 0.9 (1.0,34.0)	16.8 ± 0.9 (0.3,34.0)	9.6 ± 0.7 (0,24.7)	14.4 ± 1.1 (0,37.6)	18.2 ± 1.2 (0,40.0)
Ovs. Basal area (m^2 ha^{-1})	18.3 ± 1.0 (0,41.3)	13.6 ± 1.2 (0,37.0)	10.6 ± 0.8 (0,36.3)	19.3 ± 1.2 (0,35.5)	15.3 ± 0.9 (0,32.0)	13.6 ± 0.8 (0,27.7)	8.6 ± 0.7 (0,22.8)	12.5 ± 1.0 (0,36.1)	16.0 ± 1.0 (0,37.3)

(Table 2 continued on next page)

Table 2 (continued).—Mean ± standard error and range of observations by research core for selected plot-level attributes. Density, quadratic mean diameter (QMD) and basal area are summarized across all size classes (Tot.; ≥1.5 cm d.b.h.) and for only overstory trees (Ovs.; ≥ 30 cm d.b.h.).

	Research core								
Attribute	1	2	3	4†	5	6	7	8	9
Tolerant									
No. of species per plot	1.9 ± 0.1 (0,4)	2.6 ± 0.1 (0,4)	2.6 ± 0.1 (1,4)	2.5 ± 0.1 (1,4)	2.6 ± 0.1 (1,4)	2.2 ± 0.1 (0,4)	2.1 ± 0.1 (0,3)	2.7 ± 0.1 (1,3)	2.3 ± 0.1 (1,4)
Tot. density (trees ha^{-1})	297 ± 22 (0,920)	607 ± 45 (0,1870)	556 ± 33 (20,1350)	583 ± 53 (80,1560)	736 ± 47 (10,1950)	469 ± 42 (0,1630)	529 ± 34 (0,1600)	784 ± 45 (110,1950)	394 ± 36 (10,1470)
Ovs. density (trees ha^{-1})	7 ± 1 (0,60)	12 ± 2 (0,80)	14 ± 2 (0,60)	5 ± 2 (0,80)	8 ± 1 (0,50)	7 ± 2 (0,60)	22 ± 2 (0,80)	14 ± 2 (0,90)	7 ± 2 (0,40)
Tot. QMD (cm)	10.3 ± 0.5 (0,23.1)	10.8 ± 0.6 (0,26.9)	10.7 ± 0.5 (0.2,30.2)	8.6 ± 0.5 (0.2,18.1)	9.6 ± 0.5 (5.3,26.6)	9.4 ± 0.5 (0,22.0)	13.3 ± 0.6 (0,33.7)	9.2 ± 0.5 (3.1,19.6)	10.9 ± 0.7 (4.3,31.4)
Ovs. QMD (cm)‡	40.9 ± 2.5 (30.5,82.3)	39.7 ± 1.4 (30.9,69.5)	40.0 ± 0.9 (30.5,53.5)	40.3 ± 2.5 (30.4,58.0)	43.2 ± 2.7 (30.1,101.1)	39.2 ± 1.2 (30.0,53.9)	40.7 ± 1.0 (30.2,72.1)	40.7 ± 1.3 (31.0,61.0)	42.7 ± 1.8 (32.4,65.0)
Tot. Basal area (m^2 ha^{-1})	2.9 ± 0.3 (0,12.9)	5.3 ± 0.4 (0,16.3)	4.7 ± 0.3 (0.2,14.4)	3.2 ± 0.4 (0.2,16.5)	4.7 ± 0.3 (0.2,16.5)	3.4 ± 0.4 (0,15.1)	6.5 ± 0.5 (0,20.7)	5.4 ± 0.5 (0.2,21.9)	3.1 ± 0.3 (0.1,12.8)
Ovs. Basal area (m^2 ha^{-1})	0.9 ± 0.2 (0,8.3)	1.6 ± 0.3 (0,11.3)	1.8 ± 0.3 (0,9.9)	0.6 ± 0.2 (0,9.7)	1.3 ± 0.3 (0,10.3)	1.0 ± 0.3 (0,11.4)	3.1 ± 0.4 (0,15.2)	2.0 ± 0.4 (0,17.3)	1.0 ± 0.2 (0,8.3)
Intolerant									
No. of species per plot	1.4 ± 0.1 (0,4)	1.7 ± 0.1 (0,4)	1.7 ± 0.1 (0,3)	1.2 ± 0.1 (0,3)	1.2 ± 0.1 (0,3)	1.3 ± 0.1 (0,3)	1.2 ± 0.1 (0,3)	1.1 ± 0.1 (0,4)	1.1 ± 0.1 (0,3)
Tot. density (trees ha^{-1})	161 ± 17 (0,700)	206 ± 30 (0,1240)	354 ± 48 (0,2010)	125 ± 21 (0,730)	208 ± 47 (0,1890)	141 ± 27 (0,1440)	88 ± 14 (0,810)	51 ± 12 (0,650)	132 ± 22 (0,720)
Ovs. density (trees ha^{-1})	8 ± 2 (0,110)	15 ± 2 (0,70)	18 ± 3 (0,160)	8 ± 3 (0,90)	5 ± 1 (0,70)	11 ± 2 (0,100)	13 ± 2 (0,90)	5 ± 1 (0,40)	4 ± 1 (0,40)
Tot. QMD (cm)	12.7 ± 1.1 (0,42.9)	20.8 ± 2.0 (0,74.2)	14.8 ± 1.5 (0,53.1)	12.5 ± 2.1 (0,55.1)	13.4 ± 1.6 (0,54.2)	17.6 ± 1.9 (0,62.3)	20.1 ± 1.8 (0,60.8)	12.3 ± 1.8 (0,49.8)	9.9 ± 1.3 (0,45.2)
Ovs. QMD (cm)‡	44.0 ± 2.0 (32.8,70.9)	48.0 ± 1.9 (31.8,74.2)	45.8 ± 1.7 (31.2,65.9)	45.7 ± 2.6 (34.8,61.7)	45.1 ± 2.1 (30.9,70.0)	46.8 ± 2.0 (32.1,83.8)	46.5 ± 1.5 (31.8,71.4)	44.5 ± 1.9 (32.0,69.9)	39.2 ± 1.9 (30.0,51.6)
Tot. Basal area (m^2 ha^{-1})	2.5 ± 0.5 (0,22.1)	4.5 ± 0.6 (0,16.7)	4.9 ± 0.7 (0,29.7)	2.1 ± 0.6 (0,19.6)	2.2 ± 0.4 (0,13.8)	2.8 ± 0.5 (0,22.2)	3.5 ± 0.6 (0,20.5)	1.2 ± 0.2 (0,6.6)	1.7 ± 0.3 (0,13.1)
Ovs. Basal area (m^2 ha^{-1})	1.2 ± 0.3 (0,16.2)	2.8 ± 0.5 (0,14.4)	2.9 ± 0.6 (0,24.0)	1.3 ± 0.4 (0,18.0)	0.9 ± 0.2 (0,9.0)	2.0 ± 0.4 (0,18.8)	2.5 ± 0.5 (0,18.1)	0.8 ± 0.2 (0,5.7)	0.6 ± 0.2 (0,8.4)

(Table 2 continued on next page)

Table 2 (continued).—Mean ± standard error and range of observations by research core for selected plot-level attributes. Density, quadratic mean diameter (QMD) and basal area are summarized across all size classes (Tot.; ≥1.5 cm d.b.h.) and for only overstory trees (Ovs.; ≥ 30 cm d.b.h.).

	Research core								
Attribute	1	2	3	4†	5	6	7	8	9
Other Commercial									
No. of species per plot	0.9 ± 0.1 (0,3)	1.3 ± 0.1 (0,5)	1.6 ± 0.1 (0,7)	1.2 ± 0.2 (0,5)	1.3 ± 0.1 (0,3)	1.5 ± 0.1 (0,5)	1.1 ± 0.1 (0,5)	1.6 ± 0.2 (0,6)	1.1 ± 0.1 (0,5)
Tot. density (trees ha^{-1})	95 ± 20 (0,920)	79 ± 14 (0,480)	137 ± 19 (0,850)	125 ± 21 (0,540)	106 ± 12 (0,460)	141 ± 21 (0,710)	45 ± 8 (0,440)	150 ± 28 (0,1290)	69 ± 15 (0,760)
Ovs. density (trees ha^{-1})	5 ± 1 (0,80)	7 ± 1 (0,50)	9 ± 2 (0,140)	13 ± 5 (0,170)	7 ± 3 (0,190)	9 ± 2 (0,70)	8 ± 3 (0,150)	39 ± 9 (0,290)	4 ± 1 (0,70)
Tot. QMD (cm)	8.9 ± 1.1 (0,44.4)	13.4 ± 1.7 (0,49.5)	12.5 ± 1.3 (0,81.3)	8.8 ± 1.2 (0,31.4)	14.1 ± 1.3 (0,59.0)	13.4 ± 1.2 (0,43.3)	12.3 ± 1.4 (0,46.5)	15.6 ± 1.7 (0,47.0)	12.3 ± 1.5 (0,51.6)
Ovs. QMD (cm)‡	42.8 ± 2.7 (30.5,74.7)	39.1 ± 1.3 (31.2,54.3)	44.8 ± 2.1 (31.2,81.3)	37.6 ± 1.9 (31.4,50.4)	41.4 ± 1.8 (30.0,59.0)	39.0 ± 1.1 (30.0,56.9)	39.6 ± 1.5 (31.8,56.6)	40.5 ± 1.4 (30.7,57.4)	42.7 ± 2.5 (30.2,55.7)
Tot. Basal area (m^2 ha^{-1})	1.2 ± 0.2 (0,10.7)	1.6 ± 0.4 (0,18.4)	2.2 ± 0.4 (0,25.3)	2.3 ± 0.7 (0,23.8)	1.7 ± 0.4 (0,30.4)	1.9 ± 0.3 (0,13.0)	1.7 ± 0.5 (0,31.1)	8.4 ± 1.9 (0,53.7)	1.3 ± 0.3 (0,15.0)
Ovs. Basal area (m^2 ha^{-1})	0.7 ± 0.2 (0,8.1)	0.9 ± 0.2 (0,8.3)	1.5 ± 0.4 (0,21.2)	1.3 ± 0.5 (0,17.9)	1.0 ± 0.4 (0,26.4)	1.1 ± 0.2 (0,10.1)	1.2 ± 0.4 (0,26.4)	6.0 ± 1.6 (0,53.5)	0.7 ± 0.2 (0,13.9)
Noncommercial									
No. of species per plot	1.5 ± 0.1 (0,5)	1.8 ± 0.2 (0,4)	2.2 ± 0.2 (0,6)	1.4 ± 0.2 (0,5)	1.4 ± 0.1 (0,4)	1.8 ± 0.1 (0,5)	1.4 ± 0.1 (0,6)	2.0 ± 0.2 (0,6)	1.5 ± 0.2 (0,7)
Tot. density (trees ha^{-1})	145 ± 18 (0,920)	324 ± 60 (0,2610)	314 ± 33 (0,1430)	119 ± 24 (0,920)	193 ± 34 (0,1480)	192 ± 21 (0,1100)	175 ± 40 (0,2920)	293 ± 32 (0,1120)	181 ± 40 (0,2080)
Ovs. density (trees ha^{-1})	1.2 ± 0.4 (0,10)	0.4 ± 0.3 (0,10)	0.4 ± 0.2 (0,10)	0.8 ± 0.4 (0,10)	0.1 ± 0.1 (0,10)	0.5 ± 0.3 (0,20)	1.1 ± 0.4 (0,20)	0.3 ± 0.2 (0,10)	0.3 ± 0.2 (0,10)
Tot. QMD (cm)	7.9 ± 0.8 (0,39.9)	6.7 ± 0.8 (0,38.5)	5.2 ± 0.3 (0,14.5)	4.3 ± 0.6 (0,21.3)	4.7 ± 0.4 (0,19.1)	5.9 ± 0.7 (0,43.9)	5.5 ± 0.7 (0,32.3)	4.2 ± 0.4 (0,21.9)	3.8 ± 0.3 (0,9.8)
Ovs. QMD (cm)‡	39.1 ± 2.1 (31.2,54.9)	44.6 ± 4.6 (38.5,53.6)	38.6 ± 2.9 (32.0,44.0)	36.1 ± 2.0 (33.5,42.0)	32.0 (32.0,32.0)	37.0 ± 3.6 (32.0,43.9)	40.0 ± 6.7 (30.7,80.0)	43.6 ± 0.4 (43.2,43.9)	34.1 ± 1.2 (32.8,35.3)
Tot. Basal area (m^2 ha^{-1})	0.68 ± 0.08 (0,39.9)	0.73 ± 0.11 (0,38.5)	0.76 ± 0.10 (0,14.5)	0.32 ± 0.06 (0,21.3)	0.35 ± 0.05 (0,19.1)	0.50 ± 0.06 (0,43.9)	0.48 ± 0.09 (0,32.3)	0.52 ± 0.07 (0,21.9)	0.30 ± 0.05 (0,9.8)
Ovs. Basal area (m^2 ha^{-1})	0.15 ± 0.05 (0,2.4)	0.07 ± 0.04 (0,2.3)	0.05 ± 0.03 (0,1.5)	0.08 ± 0.04 (0,1.4)	0.01 ± 0.01 (0,0.8)	0.05 ± 0.03 (0,1.9)	0.15 ± 0.07 (0,5.0)	0.04 ± 0.03 (0,1.5)	0.03 ± 0.02 (0,1.0)

† Data from 19 plots were discarded from this analysis, due to questionable plot-level basal areas far exceeding 50 m^2 ha^{-1}.

‡ Plots without overstory trees were ignored for this attribute.

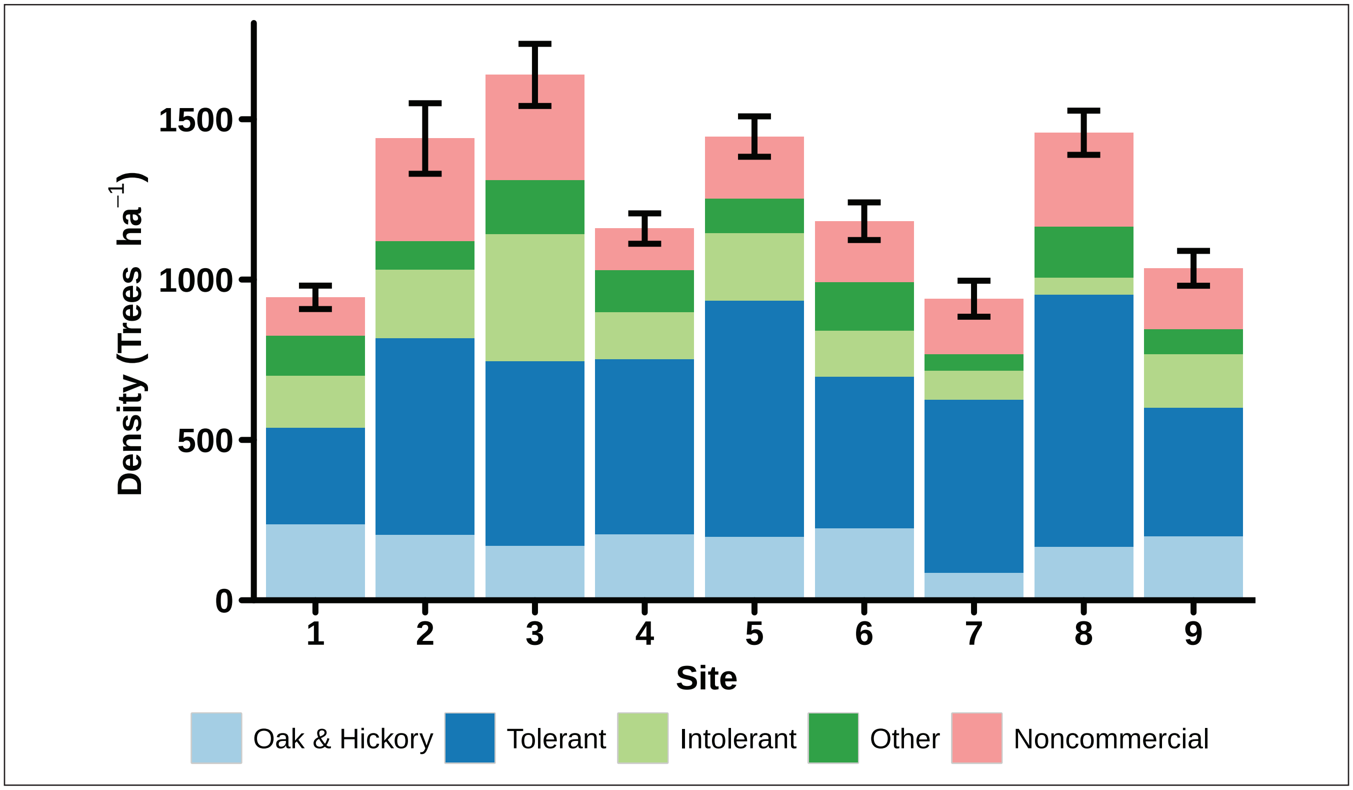

Figure 1.—Stand-level, average tree density of all stems >1.5 cm diameter at breast height by research core. Error bars approximate ± 1 standard error of the total, stand-level tree density. Species group definitions are given in Table 1.

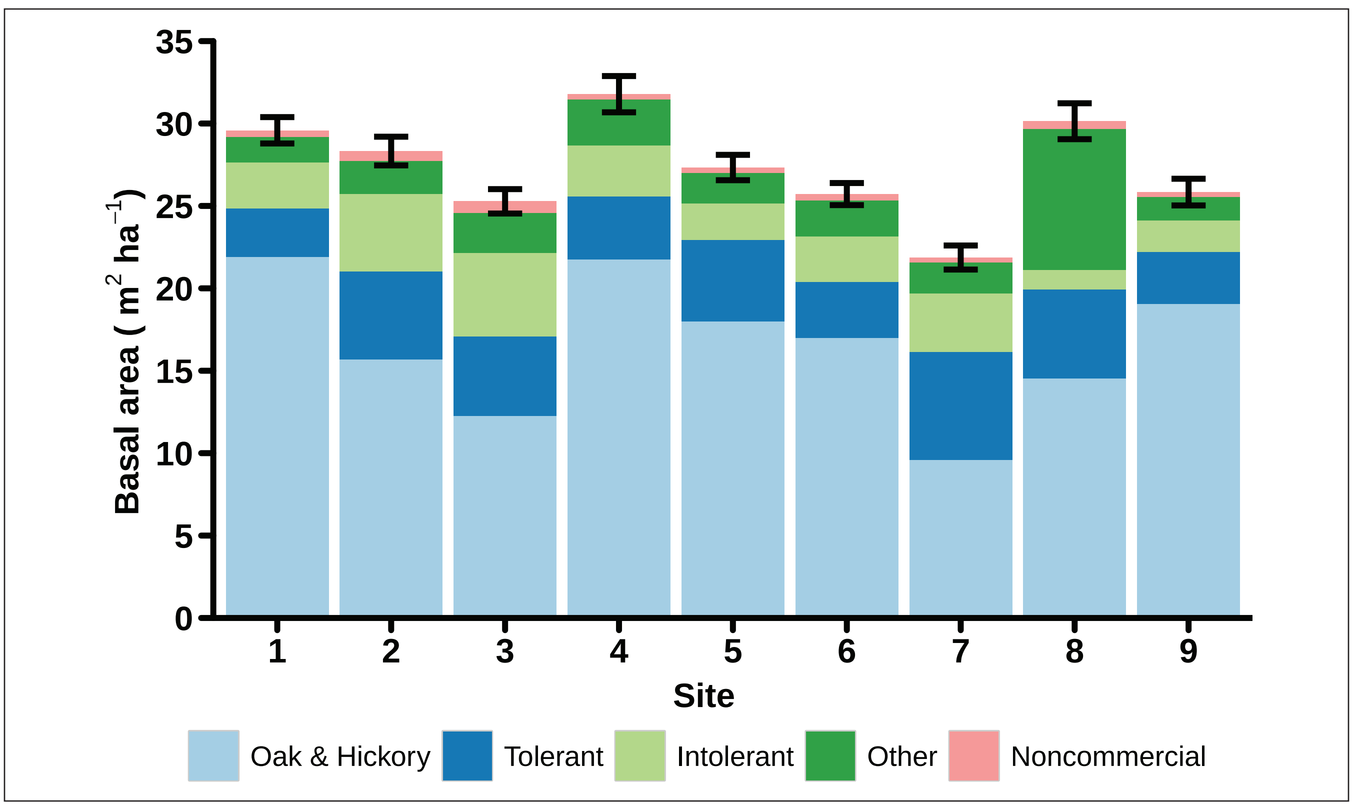

Figure 2.—Stand-level, average basal area of all stems >1.5 cm diameter at breast height by research core. Error bars approximate ± 1 standard error of the total, stand-level basal area. Species group definitions are given in Table 1.

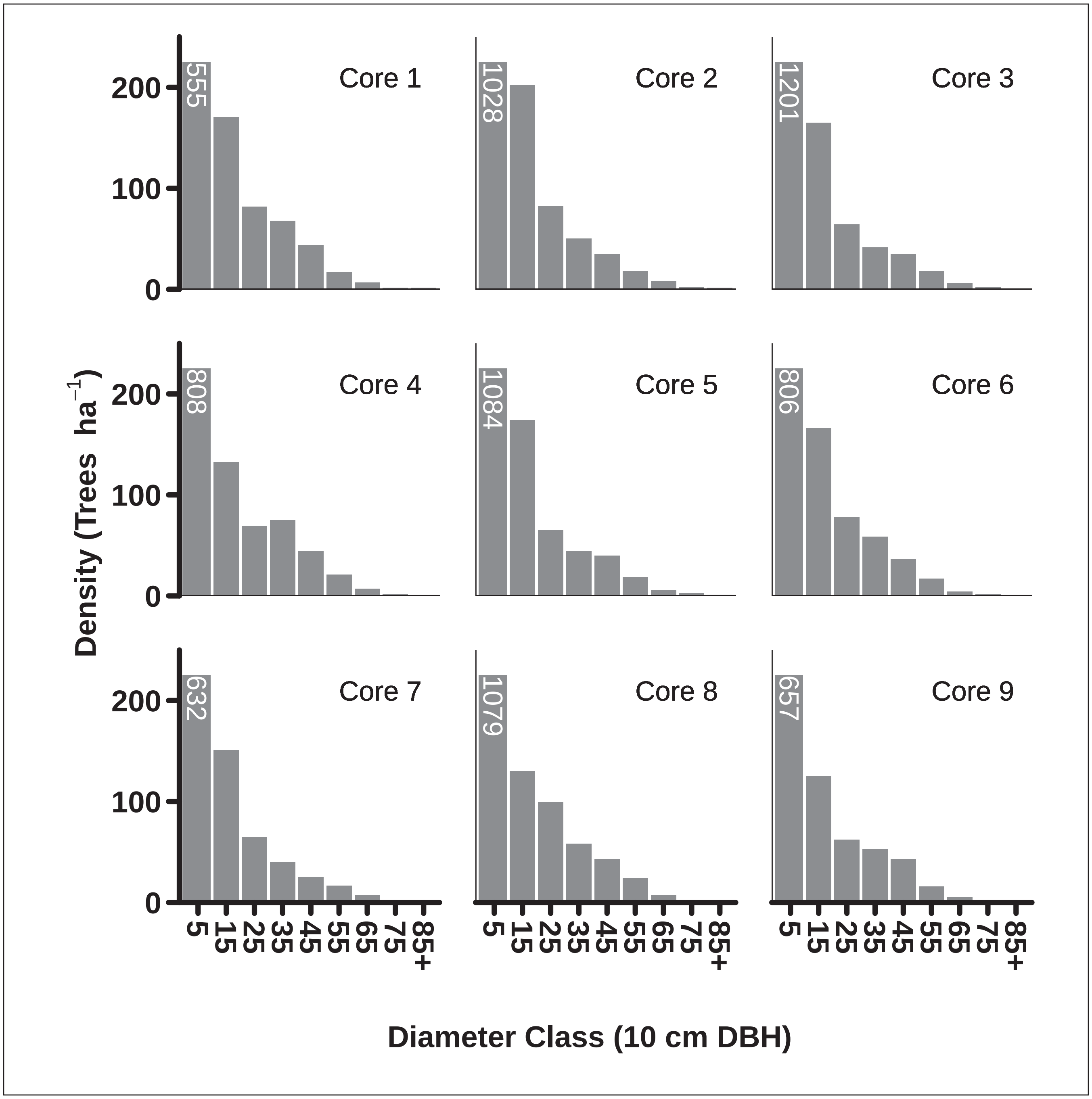

Figure 3.—Tree density distributions by 10-cm diameter classes (labeled at midpoint of each class) of all stems >1.5 cm diameter at breast height for each research core. The white number in the bar for the 0-10 cm diameter class for each core indicated observed density, as it far exceeded the density of all other diameter classes.

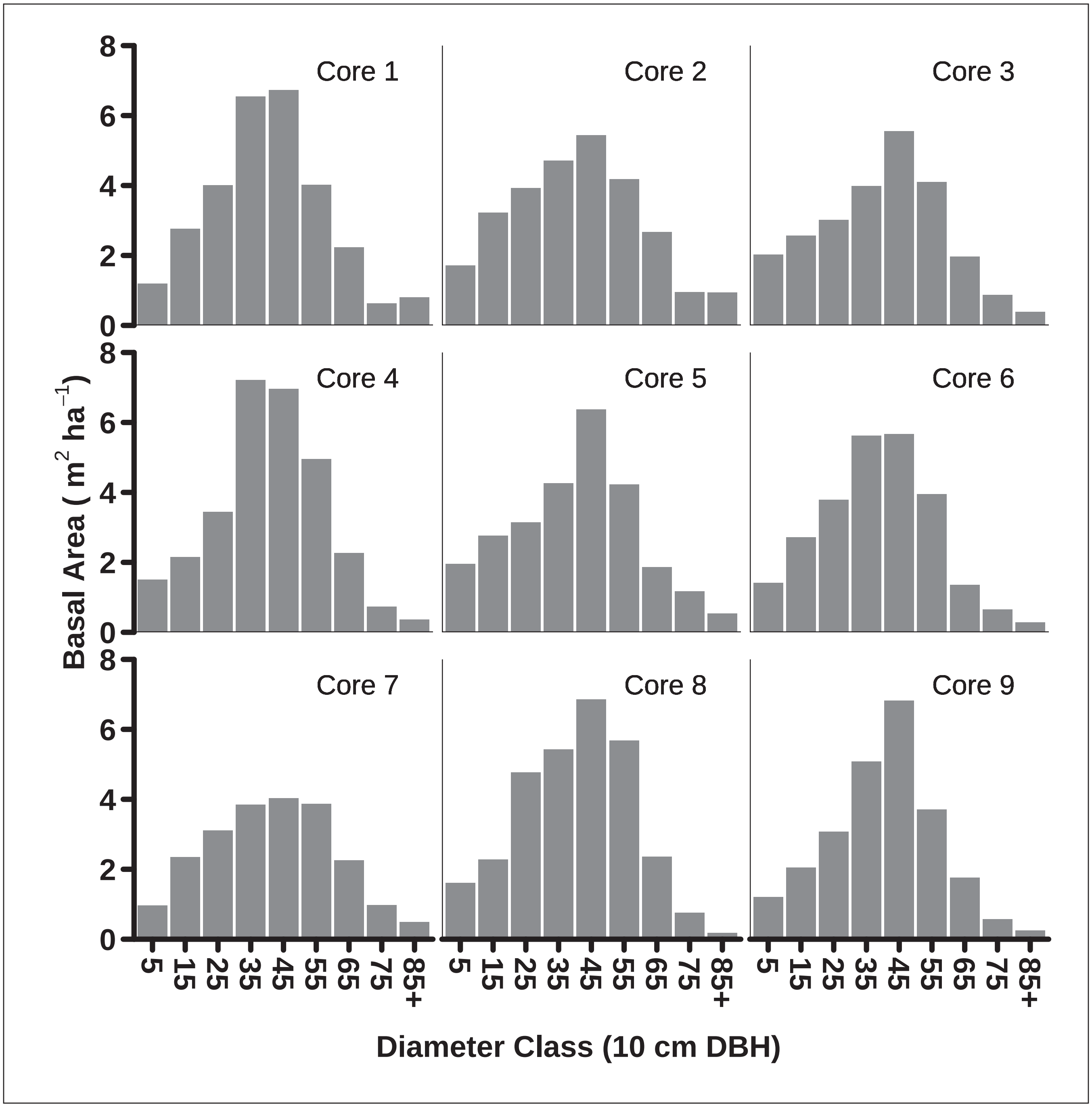

Figure 4.—Basal area distributions by 10-cm diameter classes (labeled at midpoint of each class) of all stems >1.5 cm diameter at breast height for each research core.

Tree species diversity differed significantly across the research cores, with species counts ranging between 4 and 19 species in a sampling plot (Table 2; Fig. 5; Appendix 1). Cores averaged between 2.6 and 4.2 oak (see Table 1 for list of common and scientific names) and hickory species per sampling plot (Table 2), with the most common species being chestnut (experiment averages: 5.0 m^2 ha^{-1} and 59 trees ha^{-1}), white (3.4 m^2 ha^{-1} and 33 trees ha^{-1}), black (2.8 m^2 ha^{-1} and 21 trees ha^{-1}), and northern red (2.7 m^2 ha^{-1} and 24 trees ha^{-1}) oaks; and pignut hickory (1.2 m^2 ha^{-1} and 28 trees ha^{-1}). Oak and hickory species dominated stand basal area in most cores, varying between 44 and 75 percent of total basal area (Fig. 2), but this basal area was concentrated in relatively few large overstory trees (Fig. 1). For example, across all research cores, the average d.b.h. of oaks and hickories in a plot was 36.0 ± 0.4 cm (mean ± standard error), whereas all other species averaged 11.2 ± 0.2 cm.

The majority of stems in all units were shade-tolerant and other commercial species groups. Tolerant species, mostly red and sugar maple, accounted for 297 to 784 trees ha^{-1} but averaged only 8.6 to 10.9 cm in diameter (Table 2). In fact, tolerant species were nearly absent from the overstory size class with only 5 to 22 trees ha^{-1} (Table 2). The noncommercial species group also made up a large percentage of the stems in most research cores, but like the tolerant group, was not particularly large (3.8 to 7.9 cm average diameter) nor numerous in the overstory size class (<1.0 trees ha^{-1}; Table 2). Shade-intolerant species were generally low in abundance in most cores (51 to 354 trees ha^{-1}) but made up a large amount of basal area in many (1.2 to 4.9 m^2 ha^{-1}) (Table 2, Figs. 1 and 2).

There were some significant differences in forest composition among the research cores. Research Core 7 was more heavily dominated by shade-tolerant

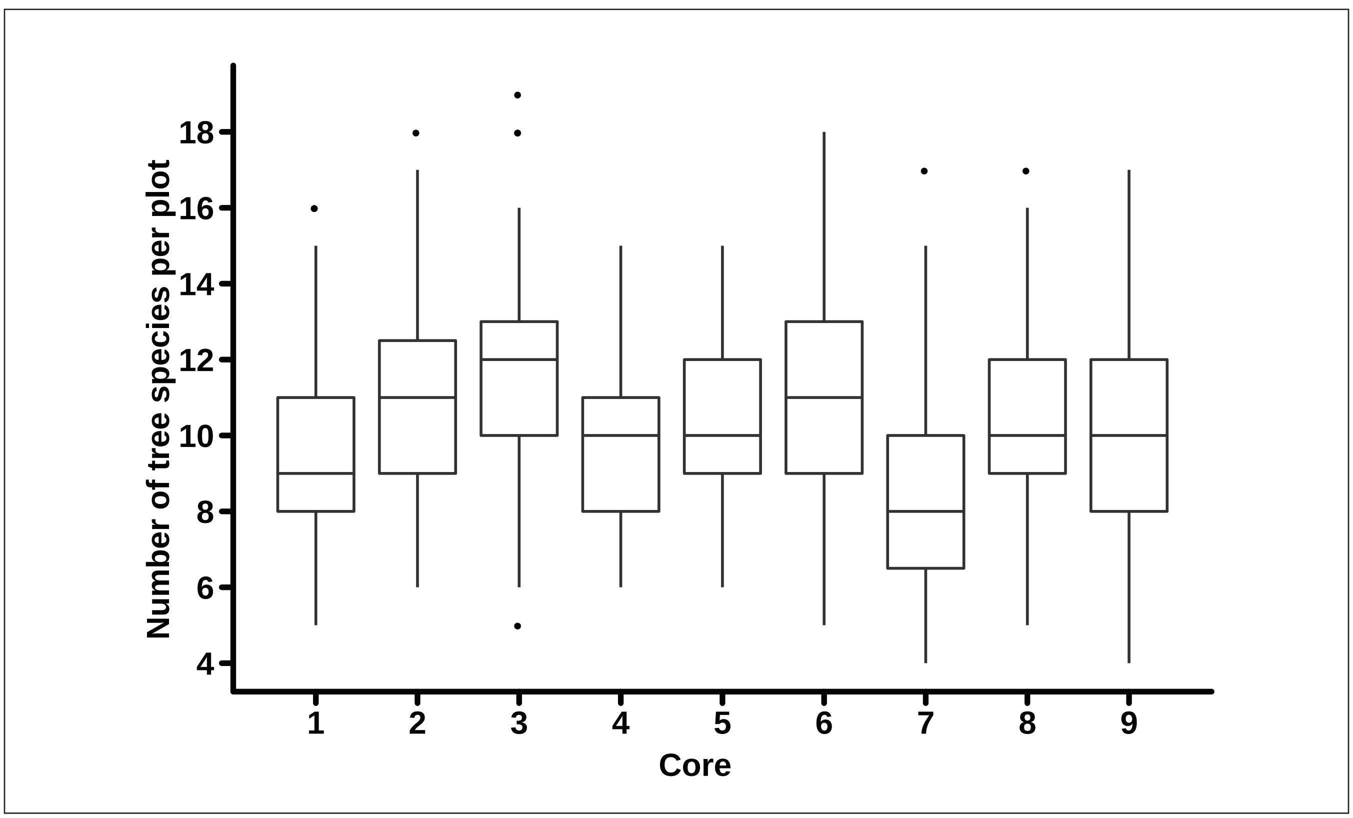

Figure 5.—Box plots of the number of species recorded in plots by research core. Boxes correspond to upper and lower quartiles of the data, with the horizontal line in each box showing the median, and the whiskers approximating the range of the data. Significant outliers in the distribution are shown as individual points.

species and had significantly less oak and hickory basal area and density than almost all other units (Table 2, Appendix 1). Further, it was significantly less diverse than almost any other core ($p < 0.05$; Appendix 1). Research Core 3, on the other hand, was the most diverse and had the highest basal area and density of intolerant species (Table 2, Figs. 1 and 2), suggesting that it had been disturbed more recently than other cores. Research Core 8 was notably different in composition in that it had a much higher density and basal area in the other commercial species group, in terms of both total and overstory stems ($p < 0.05$; Appendix 1). This core had numerous plantings of Virginia pine and eastern white pine throughout; pine species made up 66 percent of the stems and 70 percent of the basal area in this core. Other than Research Core 8, pine was represented well only in Research Core 4, where it composed 43 percent of the stems and 33 percent of the basal area in the overstory size class.

The plot-level NMDS ordination converged on a three-dimension solution after 500 iterations with a stress of 19.33, which is a marginal fit (Kruskal 1964). Nevertheless, this ordination hinted at these minor differences in species importance among research cores (Fig. 6a). The centroid for all plots within Research Core 7 was slightly separated from the other cores in this ordination, and Research Core 8 had several plots in ordination space outside plots of any other research core (i.e., the convex hull extended into quadrat 1 further than any other core). However, the convex hulls of all research cores strongly overlapped one another in ordination space, suggesting a significant overlap in species importance values among all cores (Fig. 6a).

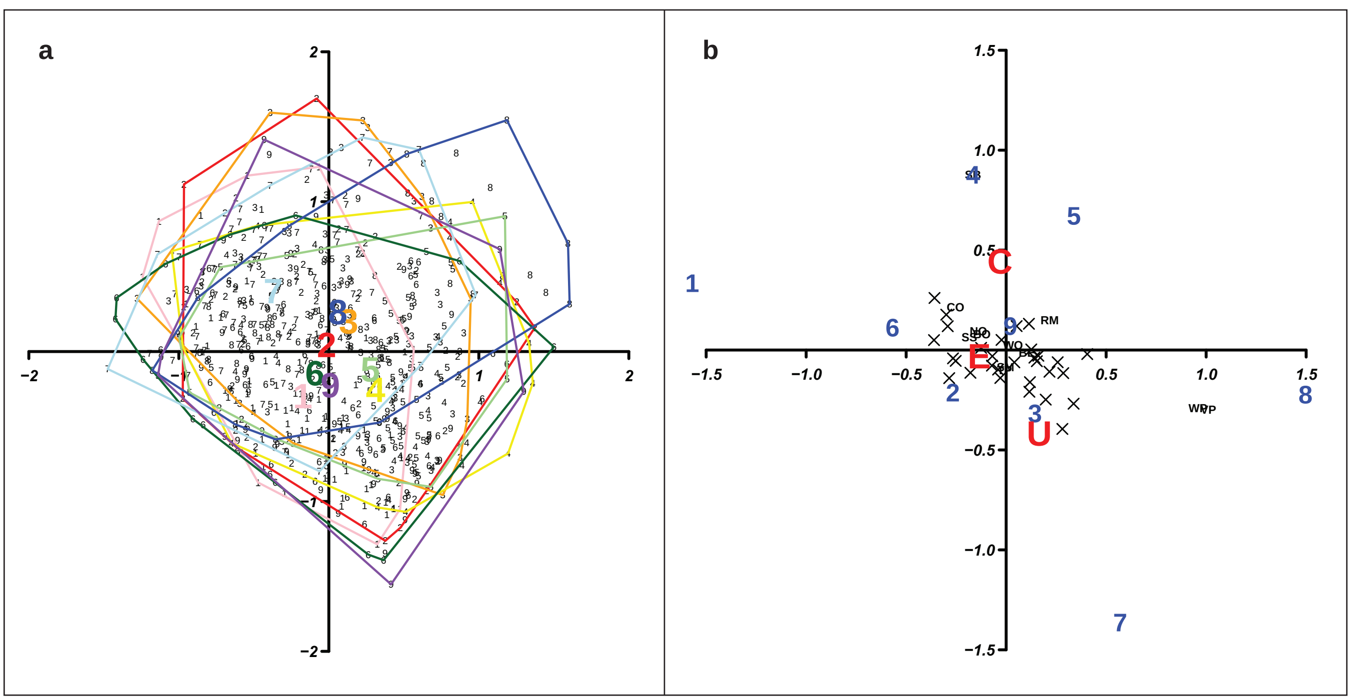

Figure 6.—Nonparametric multidimensional scaling ordinations of species importance values a) by individual plots and b) by research cores. In a), plots are labeled by research core, with centroids and convex hulls of each core shown by colored numbers and lines, respectively. In b), coordinates for individual species and species groups are represented by black “x” or species abbreviations as follows: BO = black oak, CO = chestnut oak, RO = northern red oak, WO = white oak, SM = sugar maple, RM = red maple, BE = American beech, TP = tulip poplar, SS = sassafras, WP = white pine, VP = Virginia pine, and SB = serviceberry. Treatment centroids are shown in red and are abbreviated as follows: C = control, E = even-aged, and U = uneven-aged.

Pre-Treatment Differences

Even though there were significant differences among research cores for many attributes, there were no significant treatment-level differences in tree species diversity, trees per hectare, quadratic mean diameter, or basal area across all treatments, either for all trees or overstory trees alone (p-values ranged from 0.23 to 0.76; Table 3). ANOVAs of major species groups also did not detect significant treatment-level differences in those response variables (p-values ranged from 0.15 to 0.92; Tables 4-8).

Core-level NDMS yielded much more usable results (Fig. 6b). Average stress after 56 iterations for this ordination was 0.045 on two axes, within the good fit zone suggested by Kruskal (1964). Centroids for each research core were distinct from one another in ordination space (e.g., Research Cores 1, 7, and 8), which may explain the significant core-level comparisons. Differences in importance values among cores for certain species caused some of this separation; for example, Research Core 8 was distinctly separated from the other cores because of the strong importance of pine species in that core. However, the centroids of the treatments (red letters, Fig. 6b) are separated much less and, thus, less distinct from one another.

Table 3.—Core means for all woody species by proposed management treatment. Density, quadratic mean diameter (QMD), and basal area are summarized across all size classes (Tot.; ≥1.5 cm d.b.h.) and for only overstory trees (Ovs.; ≥30 cm d.b.h.). Differences among treatments for each attribute were tested using Eq. 1.

	Proposed treatment				
Attribute	No harvest (cores 2, 4, 5)	Even-aged (cores 3, 6, 9)	Uneven-aged (cores 1, 7, 8)	F	p
No. of species per plot	10.4	10.8	9.5	1.89	0.23
Tot. density (trees ha^{-1})	1337	1217	1098	1.02	0.41
Ovs. density (trees ha^{-1})	126	115	123	0.28	0.76
Tot. QMD (cm)	17.6	17.6	18.8	0.46	0.65
Ovs. QMD (cm)†	45.3	44.5	44.8	0.61	0.57
Tot. basal area (m^2 ha^{-1})	27.9	24.8	26.8	1.11	0.39
Ovs. basal area (m^2 ha^{-1})	20.0	17.6	19.3	0.98	0.43

† Plots without overstory trees were ignored for this attribute.

Table 4.—Core means for the oak and hickory species group by proposed management treatment. Density, quadratic mean diameter (QMD), and basal area are summarized across all size classes (Tot.; ≥1.5 cm d.b.h.) and for only overstory trees (Ovs.; ≥30 cm d.b.h.). Differences among treatments for each attribute were tested using Eq. 1.

	Proposed treatment				
Attribute	No harvest (cores 2, 4, 5)	Even-aged (cores 3, 6, 9)	Uneven-aged (cores 1, 7, 8)	F	p
No. of species per plot	3.7	3.8	3.2	2.67	0.15
Tot. density (trees ha^{-1})	200	190	191	1.64	0.27
Ovs. density (trees ha^{-1})	99	87	82	0.80	0.48
Tot. QMD (cm)	37.0	35.1	36.1	0.98	0.42
Ovs. QMD (cm)†	45.8	45.3	46.2	0.11	0.90
Tot. basal area (m^2 ha^{-1})	18.2	15.6	15.2	0.80	0.49
Ovs. basal area (m^2 ha^{-1})	16.0	13.4	13.1	0.87	0.46

† Plots without overstory trees were ignored for this attribute.

Table 5.—Core means for the shade-tolerant species group by proposed management treatment. Density, quadratic mean diameter (QMD), and basal area are summarized across all size classes (Tot.; ≥1.5 cm d.b.h.) and for only overstory trees (Ovs.; ≥30 cm d.b.h.). Differences among treatments for each attribute were tested using Eq. 1.

	Proposed treatment				
Attribute	No harvest (cores 2, 4, 5)	Even-aged (cores 3, 6, 9)	Uneven-aged (cores 1, 7, 8)	F	p
No. of species per plot	2.6	2.4	2.2	0.56	0.60
Tot. density (trees ha^{-1})	642	473	537	1.03	0.41
Ovs. density (trees ha^{-1})	8	9	14	0.52	0.62
Tot. QMD (cm)	9.7	10.4	11.1	0.69	0.54
Ovs. QMD (cm)†	41.0	40.7	40.8	0.08	0.92
Tot. basal area (m^2 ha^{-1})	4.4	3.7	4.9	0.20	0.82
Ovs. basal area (m^2 ha^{-1})	1.2	1.3	2.0	0.33	0.73

† Plots without overstory trees were ignored for this attribute.

Table 6.—Core means for the shade-intolerant species group by proposed management treatment. Density, quadratic mean diameter (QMD), and basal area are summarized across all size classes (Tot.; ≥1.5 cm d.b.h.) and for only overstory trees (Ovs.; ≥30 cm d.b.h.). Differences among treatments for each attribute were tested using Eq. 1.

	Proposed treatment				
Attribute	No harvest (cores 2, 4, 5)	Even-aged (cores 3, 6, 9)	Uneven-aged (cores 1, 7, 8)	F	p
No. of species per plot	1.3	1.4	1.2	0.15	0.86
Tot. density (trees ha^{-1})	180	209	100	1.56	0.28
Ovs. density (trees ha^{-1})	10	11	9	0.10	0.90
Tot. QMD (cm)	17.8	17.0	19.6	0.17	0.85
Ovs. QMD (cm)†	46.3	43.9	45.0	1.04	0.41
Tot. basal area (m^2 ha^{-1})	2.9	3.1	2.4	0.78	0.50
Ovs. basal area (m^2 ha^{-1})	1.7	1.8	1.5	0.14	0.87

† Plots without overstory trees were ignored for this attribute.

Table 7.—Core means for the other commercial species group by proposed management treatment. Density, quadratic mean diameter (QMD), and basal area are summarized across all size classes (Tot.; ≥1.5 cm d.b.h.) and for only overstory trees (Ovs.; ≥30 cm d.b.h.). Differences among treatments for each attribute were tested using Eq. 1.

	Proposed treatment				
Attribute	No harvest (cores 2, 4, 5)	Even-aged (cores 3, 6, 9)	Uneven-aged (cores 1, 7, 8)	F	p
No. of species per plot	1.3	1.4	1.2	1.37	0.32
Tot. density (trees ha^{-1})	103	116	96	1.48	0.30
Ovs. density (trees ha^{-1})	9	7	17	0.10	0.90
Tot. QMD (cm)	15.3	15.9	18.4	1.13	0.38
Ovs. QMD (cm)†	39.4	42.2	41.0	0.65	0.55
Tot. basal area (m^2 ha^{-1})	1.9	1.8	3.8	0.19	0.83
Ovs. basal area (m^2 ha^{-1})	1.0	1.1	2.6	0.09	0.91

† Plots without overstory trees were ignored for this attribute.

Table 8.—Core means for the noncommercial species group by proposed management treatment. Density, quadratic mean diameter (QMD), and basal area are summarized across all size classes (Tot.; ≥1.5 cm d.b.h.) and for only overstory trees (Ovs.; ≥30 cm d.b.h.). Differences among treatments for each attribute were tested using Eq. 1.

	Proposed treatment				
Attribute	No harvest (cores 2, 4, 5)	Even-aged (cores 3, 6, 9)	Uneven-aged (cores 1, 7, 8)	F	p
No. of species per plot	1.5	1.8	1.6	1.03	0.41
Tot. density (trees ha^{-1})	212	229	204	0.48	0.64
Ovs. density (trees ha^{-1})	0.4	0.4	0.9	1.62	0.27
Tot. QMD (cm)	6.4	5.7	7.0	0.33	0.73
Ovs. QMD (cm)†	37.6	36.6	40.9	0.88	0.46
Tot. basal area (m^2 ha^{-1})	0.5	0.5	0.6	0.98	0.43
Ovs. basal area (m^2 ha^{-1})	0.05	0.04	0.11	2.30	0.18

† Plots without overstory trees were ignored for this attribute.

Intra-Core Variability

As highlighted by the plot-level NMDS (Fig. 6a), there was a large amount of intra-core variability across all research units. Figures 7 through 15 display plot-level relative basal area composition by species group and by size class for all nine research cores. These maps can be used to look for differences in forest development stages across each core, and by cross-referencing with topographic maps or aerial photography, riparian areas, and other features.

DISCUSSION

Research Core Differences

Even though great care was taken during site selection for the HEE, the woody communities still differed among individual research cores as measured by several structural attributes in this study. Several reasons may explain these differences. Although all the HEE cores are within the Brown County Section of the Highland Rim Natural Region, and all are underlain by the Wellston-Berks-Gillpin soil complex (Jenkins, this publication), some differences among cores may result from small-scale and/or more variable topographic and soil conditions within individual cores. For example, Research Cores 6 and 9 are characterized by much more extreme relief than most of the other cores, and all cores differ strongly by the amount of bottomland soil types distributed along the numerous ephemeral and perennial streams that dissect and/or border each site (Natural Resources Conservation Service 2011). Often these bottomland areas are characterized by a much larger proportion of the “other commercial” species group, which can be detected on Figures 7 through 15 as linear features within the cores (e.g., on Figure 9 from the northwest corner running southeast two-thirds of the way through the core).

Overall land use and disturbance histories were likely similar for most cores, as a significant part of each was likely tilled and/or grazed until Indiana acquired the Morgan-Monroe and Yellowwood State Forest lands in 1929 and 1947, respectively (Carman, this publication; Jenkins, this publication). For example, many overstory oaks within the research cores date to the mid- to late-1800s and have relatively rapid juvenile growth[2], suggesting that stands were originally at a much lower stem density. After State acquisition, stands likely slowly increased in density as more shade-tolerant species became established in the understory with fire suppression (Jenkins, this publication). Although a full stand reconstruction has not been done for the HEE cores, this development pattern was also seen in the nearby Hoosier National Forest (Jenkins and Parker 2000).

[2] Unpublished data on file with M.R. Saunders, Department of Forestry and Natural Resources, Purdue University, 715 West State St., West Lafayette, IN 47907.

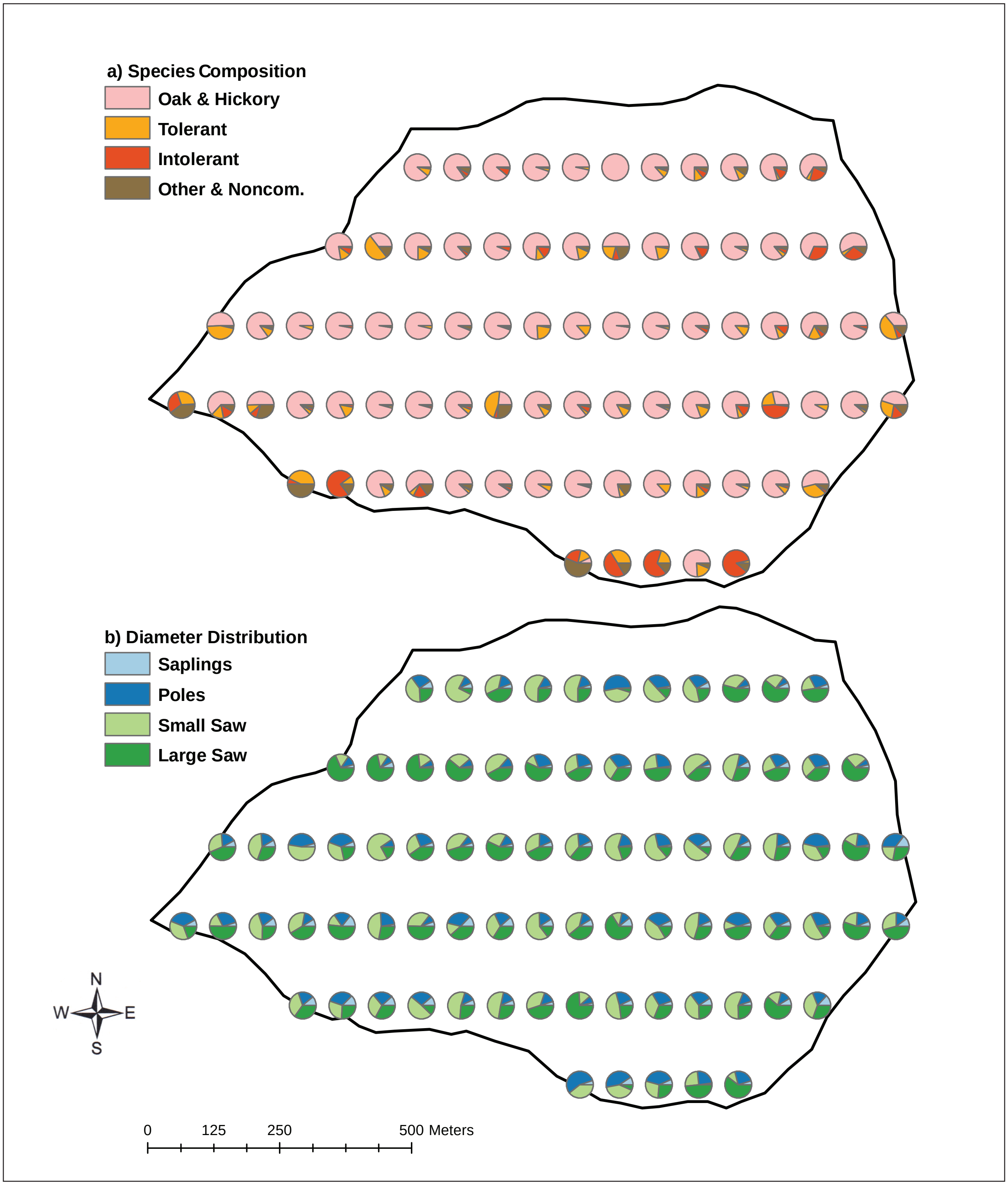

Figure 7.—Pre-treatment, plot-level a) species composition and b) diameter distribution of all stems >1.5 cm diameter at breast height within Research Core 1 at Morgan-Monroe State Forest in south-central Indiana. Individual pie charts are plotted over plot center positions and represent proportions of total plot basal area within each species group (a) or size class (b). Species group definitions are given in Table 1; diameter distributions are defined as saplings, 1.5 – 12.4 cm; poles, 12.5 – 30.5 cm; small sawtimber, 30.6 – 45.6 cm; and large sawtimber, 45.7 cm and above.

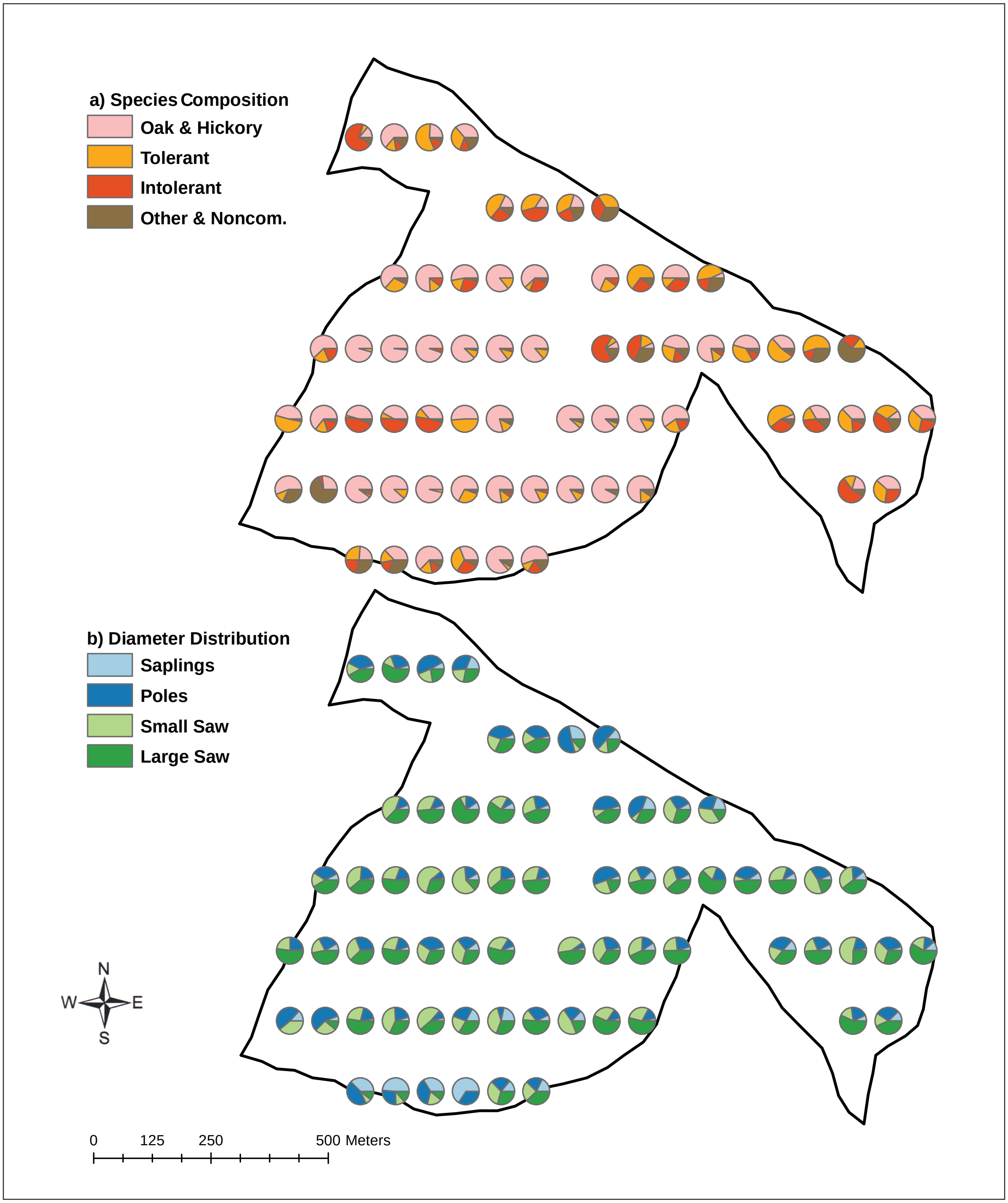

Figure 8.—Pre-treatment, plot-level a) species composition and b) diameter distribution of all stems >1.5 cm diameter at breast height within Research Core 2 at Morgan-Monroe State Forest in south-central Indiana. Information summarized as in Figure 7.

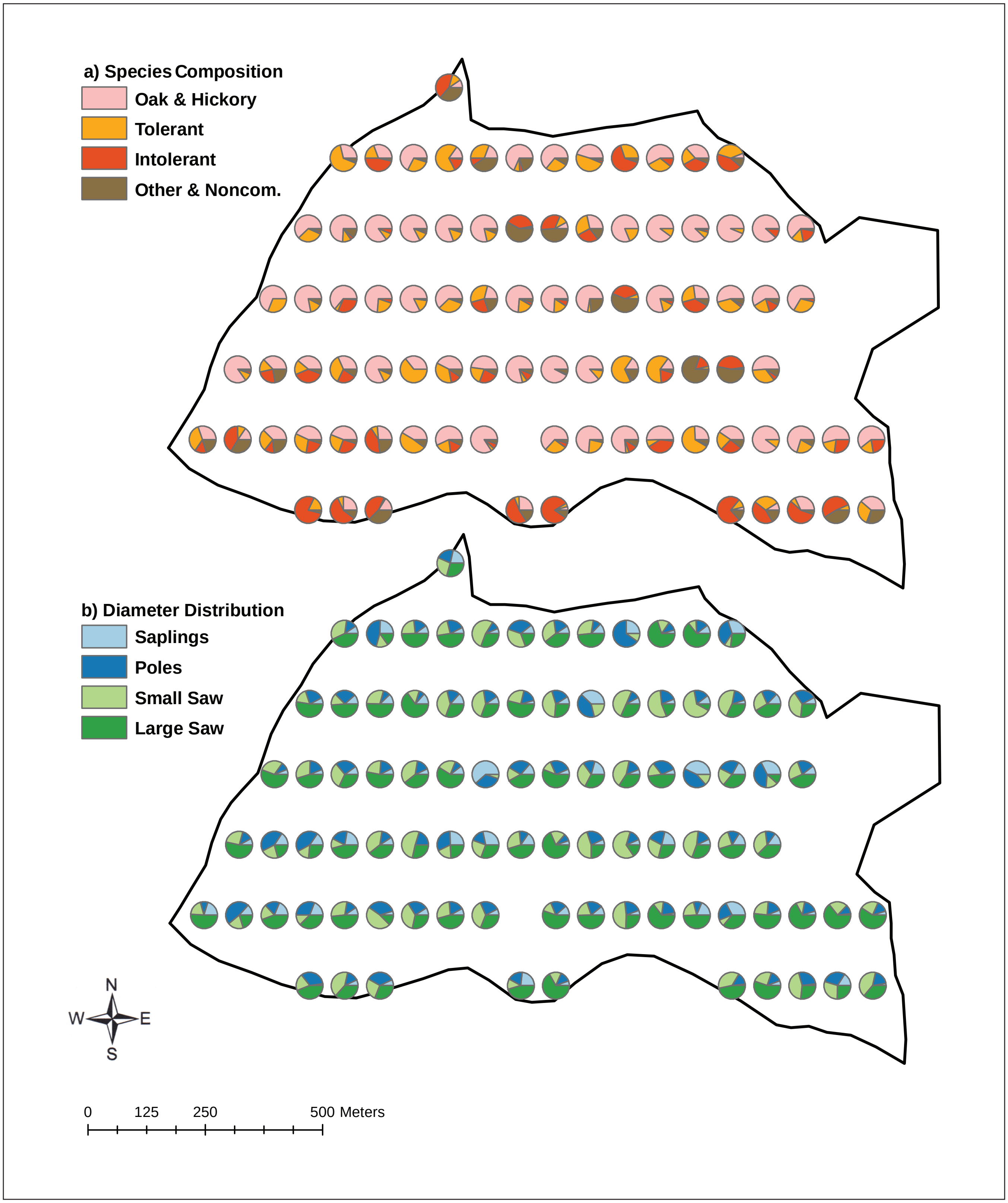

Figure 9.—Pre-treatment, plot-level a) species composition and b) diameter distribution of all stems >1.5 cm diameter at breast height within Research Core 3 at Morgan-Monroe State Forest in south-central Indiana. Information summarized as in Figure 7.

Figure 10.—Pre-treatment, plot-level a) species composition and b) diameter distribution of all stems >1.5 cm diameter at breast height within Research Core 4 at Morgan-Monroe State Forest in south-central Indiana. Information summarized as in Figure 7.

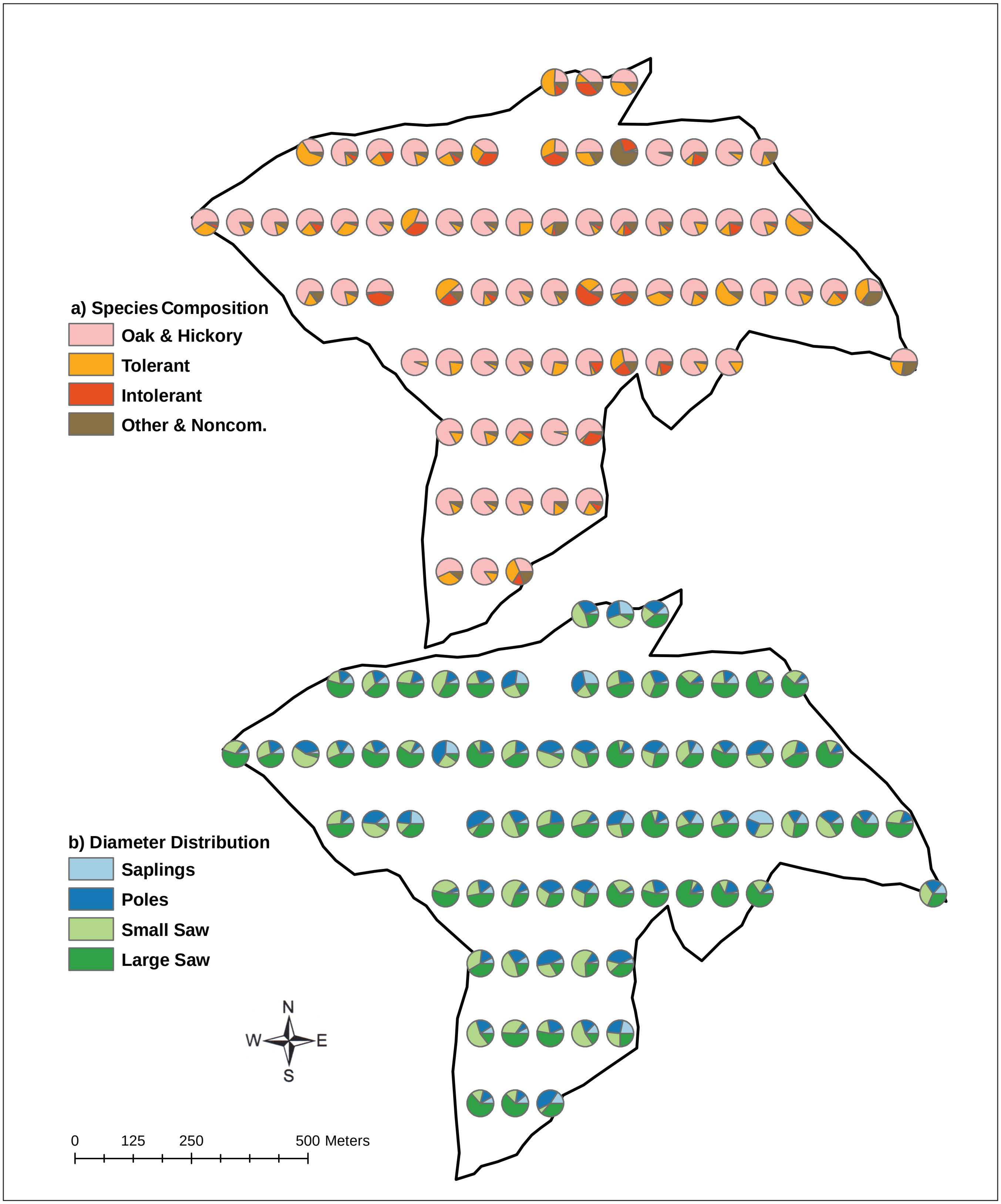

Figure 11.—Pre-treatment, plot-level a) species composition and b) diameter distribution of all stems >1.5 cm diameter at breast height within Research Core 5 at Morgan-Monroe and Yellowwood State Forests in south-central Indiana. Information summarized as in Figure 7.

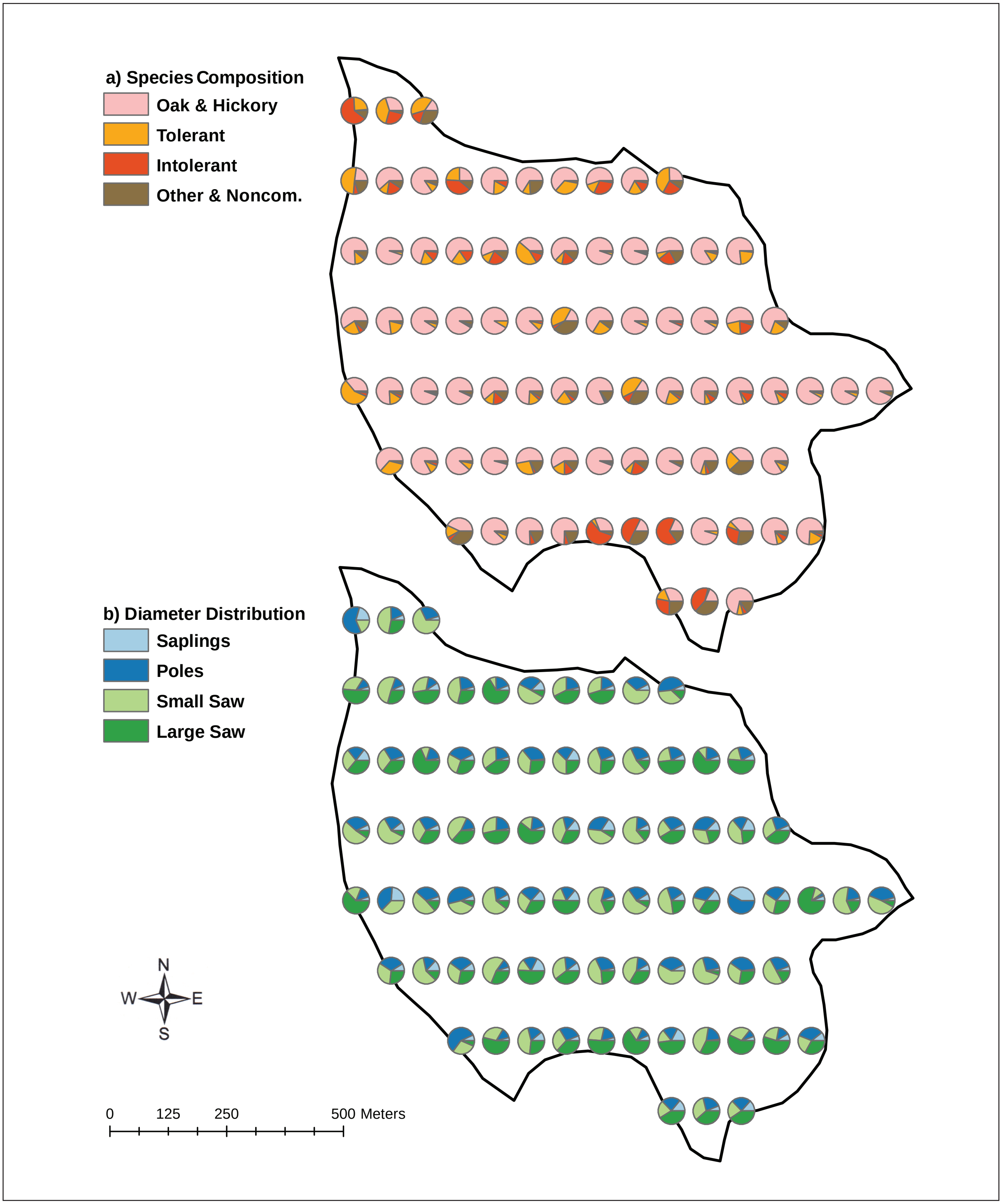

Figure 12.—Pre-treatment, plot-level a) species composition and b) diameter distribution of all stems >1.5 cm diameter at breast height within Research Core 6 at Morgan-Monroe and Yellowwood State Forests in south-central Indiana. Information summarized as in Figure 7.

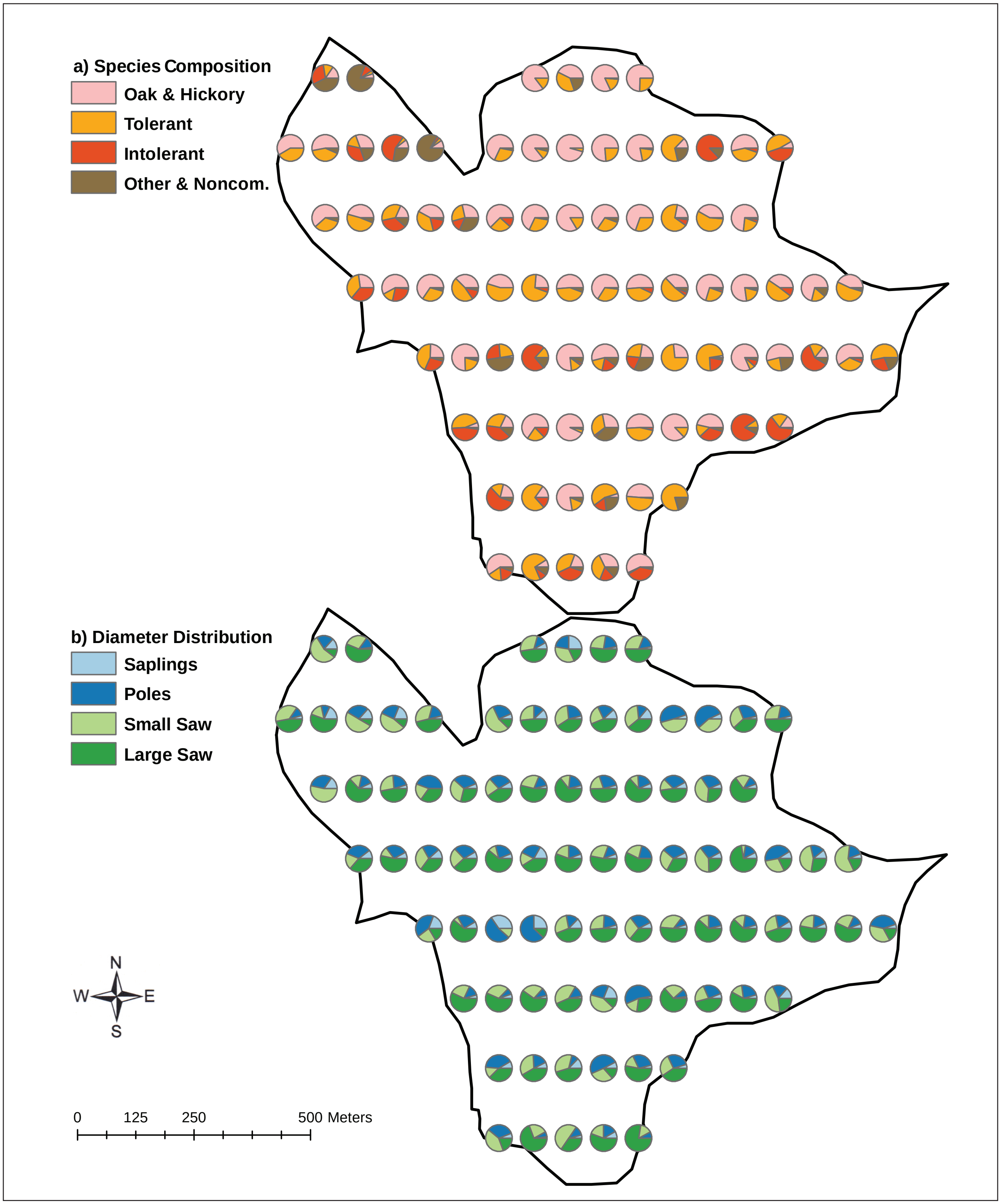

Figure 13.—Pre-treatment, plot-level a) species composition and b) diameter distribution of all stems >1.5 cm diameter at breast height within Research Core 7 at Yellowwood State Forest in south-central Indiana. Information summarized as in Figure 7.

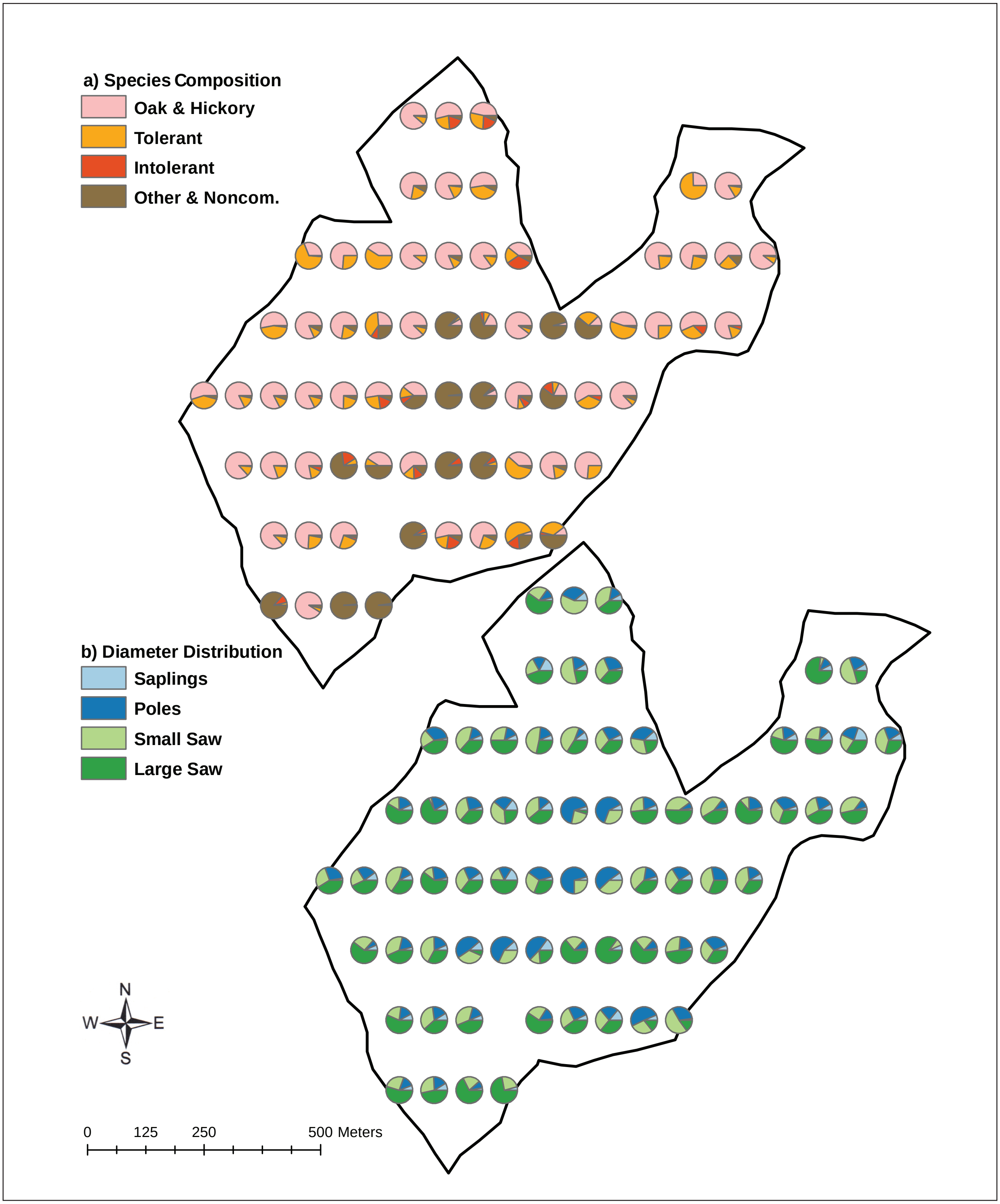

Figure 14.—Pre-treatment, plot-level a) species composition and b) diameter distribution of all stems >1.5 cm diameter at breast height within Research Core 8 at Yellowwood State Forest in south-central Indiana. Information summarized as in Figure 7.

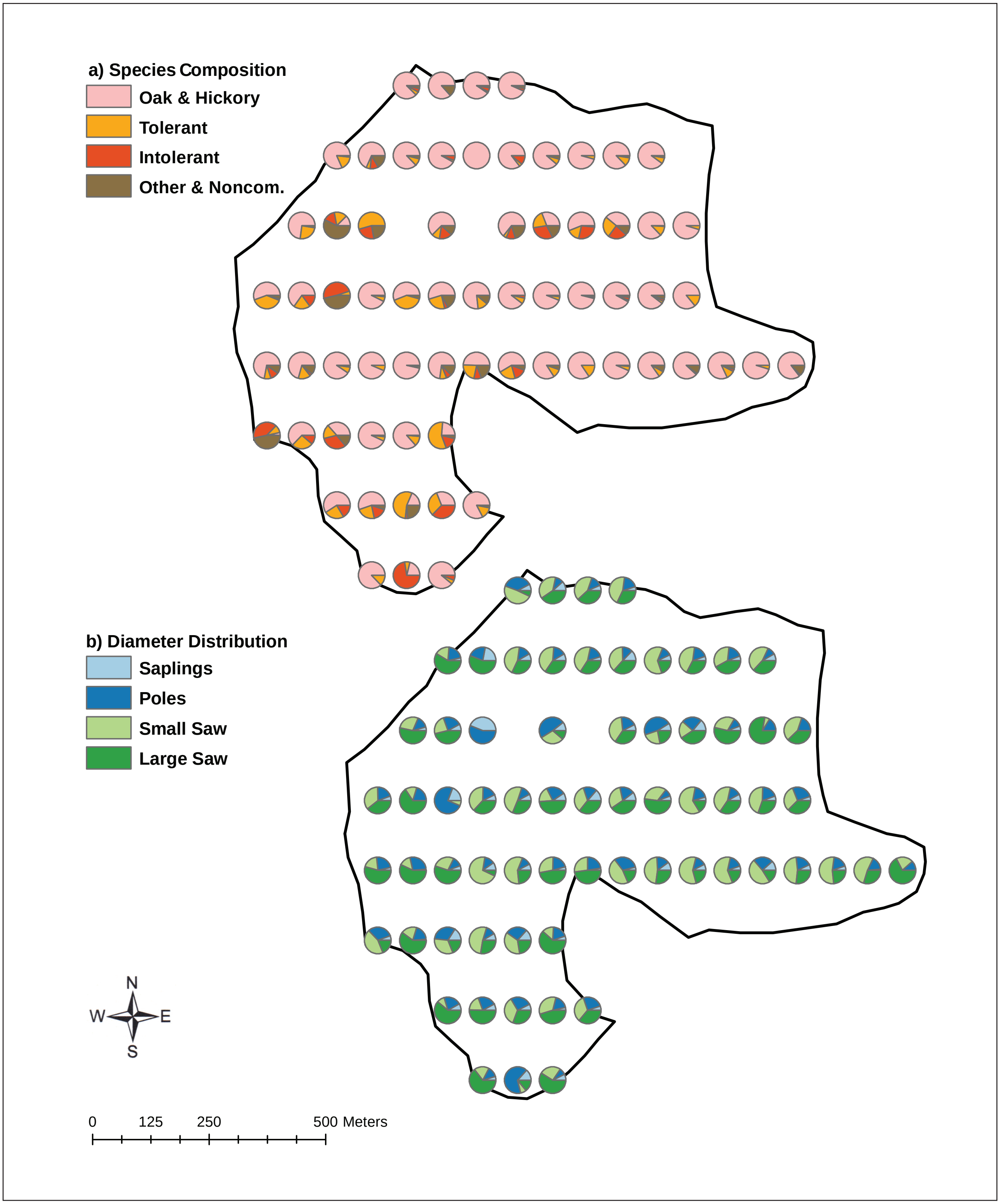

Figure 15.—Pre-treatment, plot-level a) species composition and b) diameter distribution of all stems >1.5 cm diameter at breast height within Research Core 9 at Yellowwood State Forest in south-central Indiana. Information summarized as in Figure 7.

Nevertheless, more recent differences in land use and disturbance histories likely have contributed to the structural and compositional differences among cores. For example in Research Core 8 (Fig. 14), the large block of plots with a higher proportion of "other commercial" species and a higher proportion of poles than elsewhere corresponds to the numerous white pine and Virginia pine plantings within that core. These plantings have been associated with a Depression-era homestead within a riparian area on the site. The more northern cores located within the Morgan-Monroe State Forest (i.e., Research Cores 1-4) have been disturbed more frequently from windstorms and tornados than the southern sites over the last 20 years.[3] These events resulted in a significantly higher component of intolerant tree species in some of these cores, particularly for Research Core 3 (Table 1, Appendix 1).

Implications for Future Research

Fortuitously, differences among the research cores offset one another when averaged across the three replicates of each treatment. We can say confidently—at the proposed treatment level—that there are no significant pre-treatment differences in overstory and large shrub communities. However, we recommend that researchers be cognizant of potentially strong site-to-site differences that could mask treatment effects, particularly if only subsets of the experimental units are used in the analysis. For example, the most northern set of replicates, Research Cores 1–3, may likely respond very differently from the other units because of the higher proportion of intolerant stems.

Blocking may be effective, in this case, to alleviate these concerns, although the geographical isolation of Research Cores 4 and 5 may make them difficult to use as experimental controls for the southern cores (Kalb and Mycroft, this publication: Fig. 1). Blocking was used a posteriori to account for harvesting differences among contractors (Kalb and Mycroft, this publication), as the time frame allowed for the harvest and the total area was deemed too difficult for one contractor to do alone. Research Cores 1 and 3, 6 and 7, and 8 and 9 were bid separately, although the last two sets were purchased by the same contractor. Analysis after the first complete post-treatment inventory in 2013 should clarify whether a contractor effect exists and whether blocking will be necessary in those analyses.

Lastly, Figures 7 through 15 highlight the high degree of variability in structure within each core. As Puettmann et al. (2009) point out, understanding this variability is critical to assessing post-treatment tree regeneration, herbaceous diversity, and other variables, as mean values alone may mask the true environmental and ecological drivers resulting from treatment. Resources need to be dedicated to finer scale, plot-level modeling of abiotic factors, most notably soil type, and past disturbance and land use history. Spatially explicit sampling and analysis should allow better linkage of pattern with process, particularly at finer scales than the research core. With that intent, we encourage individuals to overlay sampling designs on this grid of overstory plots, thereby providing benefits to other researchers involved in the project.

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[3] Jim Allen, Indiana Department of Natural Resources-Division of Forestry, Yellowwood/Morgan-Monroe State Forest, personal communication

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APPENDIX 1.

Denominator degrees of freedom (n), F statistics, and p-values for one-way analysis of variance tests for differences among research cores for the following attributes. Research cores with the same letter are not significantly different for that attribute using a Tukey's HSD test at α = 0.05. Means, standard errors, and ranges for each attribute are found in Table 2.

				Research Core								
Attribute	n	$F_{8,n}$	p	1	2	3	4†	5	6	7	8	9
All Species												
No. of species per plot	654	12.01	<0.001	cd	ab	a	bc	bc	ab	d	abc	bc
Tot. density (trees ha^{-1})	654	12.83	<0.001	c	ab	a	bc	ab	bc	c	ab	c
Ovs. density (trees ha^{-1})	654	12.10	<0.001	ab	cde	de	a	de	bcd	e	abc	bcd
Tot. QMD (cm)	654	9.56	<0.001	a	bc	c	ab	c	bc	ab	bc	ab
Ovs. QMD (cm)‡	651	2.46	0.012	a	a	a	a	a	a	a	a	a
Tot. Basal area (m^2 ha^{-1})	654	12.40	<0.001	abc	abcd	de	ab	bcd	cd	e	a	de
Ovs. Basal area (m^2 ha^{-1})	654	7.18	<0.001	ab	abc	c	a	bc	bc	c	ab	bc
Oak and Hickory												
No. of species per plot	654	8.54	<0.001	ab	ab	ab	ab	a	a	c	bc	ab
Tot. density (trees ha^{-1})	654	7.23	<0.001	a	a	a	a	a	ab	b	a	a
Ovs. density (trees ha^{-1})	654	16.82	<0.001	ab	cde	ef	a	bcd	bc	f	de	abc
Tot. QMD (cm)	654	2.29	0.020	a	a	a	a	a	a	a	a	a
Ovs. QMD (cm)‡	609	3.14	0.002	b	ab	ab	b	ab	b	a	ab	ab
Tot. Basal area (m^2 ha^{-1})	654	15.78	<0.001	a	bc	cd	a	ab	bc	d	bc	ab
Ovs. Basal area (m^2 ha^{-1})	654	13.46	<0.001	a	bc	cd	a	ab	bc	d	bcd	ab
Tolerant												
No. of species per plot	654	13.20	<0.001	e	ab	ab	abc	abc	cde	de	a	bcd
Tot. density (trees ha^{-1})	654	15.24	<0.001	e	bc	cd	bc	ab	cde	cd	a	de
Ovs. density (trees ha^{-1})	654	8.89	<0.001	bc	bc	b	c	bc	bc	a	ab	bc
Tot. QMD (cm)	654	6.59	<0.001	b	b	b	b	b	b	a	b	ab
Ovs. QMD (cm)‡	276	0.59	0.785	a	a	a	a	a	a	a	a	a
Tot. Basal area (m^2 ha^{-1})	654	10.37	<0.001	d	ab	bc	cd	bc	cd	a	ab	cd
Ovs. Basal area (m^2 ha^{-1})	654	7.20	<0.001	bc	bc	abc	c	bc	bc	a	ab	bc

(Appendix 1 continued on next page)

APPENDIX 1 (continued).

Denominator degrees of freedom (n), F statistics, and p-values for one-way analysis of variance tests for differences among research cores for the following attributes. Research cores with the same letter are not significantly different for that attribute using a Tukey's HSD test at α = 0.05. Means, standard errors, and ranges for each attribute are found in Table 2.

				Research Core								
Attribute	n	$F_{8,n}$	p	1	2	3	4†	5	6	7	8	9
Intolerant												
No. of species per plot	654	5.40	<0.001	abc	ab	a	c	abc	abc	bc	c	c
Tot. density (trees ha^{-1})	654	8.87	<0.001	bc	b	a	bc	bc	bc	bc	c	bc
Ovs. density (trees ha^{-1})	654	4.47	<0.001	abc	ab	a	abc	abc	abc	abc	bc	c
Tot. QMD (cm)	654	4.86	<0.001	bcd	a	abcd	cd	abcd	abc	ab	cd	d
Ovs. QMD (cm)‡	228	1.27	0.308	a	a	a	a	a	a	a	a	a
Tot. Basal area (m^2 ha^{-1})	654	6.26	<0.001	bcd	ab	a	cd	cd	abcd	abc	d	cd
Ovs. Basal area (m^2 ha^{-1})	654	5.19	<0.001	abc	a	a	abc	bc	abc	ab	bc	c
Other Commercial												
No. of species per plot	654	3.63	<0.001	b	ab	a	ab	ab	a	ab	a	ab
Tot. density (trees ha^{-1})	654	4.00	<0.001	ab	ab	a	ab	ab	a	b	a	ab
Ovs. density (trees ha^{-1})	654	8.43	<0.001	b	b	b	b	b	b	b	a	b
Tot. QMD (cm)	654	2.42	0.014	b	ab	ab	b	ab	ab	ab	a	ab
Ovs. QMD (cm)‡	182	1.64	0.117	a	a	a	a	a	a	a	a	a
Tot. Basal area (m^2 ha^{-1})	654	9.62	<0.001	b	b	b	b	b	b	b	a	b
Ovs. Basal area (m^2 ha^{-1})	654	7.95	<0.001	b	b	b	b	b	b	b	a	b
Noncommercial												
No. of species per plot	654	4.77	<0.001	b	ab	a	b	b	ab	b	ab	b
Tot. density (trees ha^{-1})	654	4.42	<0.001	bc	a	a	c	abc	abc	abc	ab	abc
Ovs. density (trees ha^{-1})	654	1.69	0.098	a	a	a	a	a	a	a	a	a
Tot. QMD (cm)	654	4.97	<0.001	a	ab	bc	bc	bc	abc	abc	bc	c
Ovs. QMD (cm)‡	27	0.37	0.929	a	a	a	a	a	a	a	a	a
Tot. Basal area (m^2 ha^{-1})	654	4.90	<0.001	ab	a	a	c	bc	abc	abc	abc	c
Ovs. Basal area (m^2 ha^{-1})	654	1.54	0.139	a	a	a	a	a	a	a	a	a

† Data from 19 plots were discarded from this analysis due to questionable plot-level basal areas far exceeding 50 m^2 ha^{-1}.
‡ Plots without overstory trees in the species group were ignored.

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.