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Short-term Effects of Silvicultural Treatments and White-tailed Deer Exclusion on Oak and Hickory Regeneration in Southern Illinois

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ABSTRACT

Many forested regions in the U.S. are experiencing a lack of oak (*Quercus* spp.) and hickory (*Carya* spp.) regeneration, which may be partially due to high levels of white-tailed deer (*Odocoileus virginianus*) browsing. We assessed the impact of deer on oak and hickory regeneration in 5 forest management units in southern Illinois during 2015 and 2016. We established 30 paired plots (fenced exclosures and open reference plots) within each unit and quantified several habitat variables therein. We then compared presence, number, and height of oak and hickory seedlings, species richness, and competition from other species between enclosures and reference plots. Oak seedlings were present more often and in higher numbers within enclosed plots. White oak seedling numbers responded positively to deer exclusion while red oak seedling numbers responded positively to midstory thinning. Mean height of oak seedlings and the presence, number, and mean height of hickory seedlings did not differ in enclosed versus reference plots. Species richness was lower in reference plots while midstory thinning positively affected both species richness and competition from less desirable species. Deer suppressed oak regeneration in reference plots after only 1 year, suggesting that managers must incorporate deer management into forest management plans to best encourage oak regeneration. Specifically, managers may have to consider implementing higher levels of deer harvest in areas lacking regeneration to decrease deer populations and mitigate damage.

Keywords: white-tailed deer; herbivory; oak; regeneration; exclosure

INTRODUCTION

Oak (*Quercus*) and hickory (*Carya*) species are valued for their high-quality timber and for their importance to wildlife (Fralish, 2002; Fralish and McArdle, 2009; Brose et al., 2013; Kellner et al., 2014; Olson et al., 2015). For example, white oak (*Q. alba*) lumber is particularly economically valuable, while northern red oak (*Q. rubra*) grows at a faster rate, making both much desired in large industries such as construction of buildings and furniture (Loftis, 1990; Abrams, 2003). Many species of plants and animals depend on these large overstory trees for the structure, micro-environment conditions, and nutrients they create (Abrahamson and Layne, 2002; Fralish, 2002; Brose et al., 2014). However, in many forests, oak and hickory regeneration is insufficient to feasibly maintain their dominance in the canopy. In some places, seedlings are extremely rare, while in others seedlings are abundant and saplings are lacking (Abrams, 2003; Ozier et al., 2006; Brudvig and Asbjornsen, 2008).

Across eastern North America, oaks and hickories are slowly being replaced by more shade tolerant species such as maples (*Acer* spp.), American beech (*Fagus grandifolia*), and black cherry (*Prunus serotina*) (Fralish, 2002; McShea et al., 2007; Brudvig and Asbjornsen, 2008; Dech et al., 2008; Fralish and McArdle, 2009; Brose et al., 2013). Many of the suggested drivers of this decrease in oak and hickory regeneration are anthropogenic in nature, including (but not limited to) the cessation of natural fire and disturbance regimes, the introduction of harmful insects and diseases, and the increased populations of species who feed on seeds and seedlings, such as white-tailed deer (*Odocoileus virginianus*) (Abrams, 2003; McShea et al., 2007; Hass and Heske, 2005; Brose et al., 2013; Holm et al., 2013).

Forest management practices such as prescribed burning and thinning have been used widely to address the issue of poor oak and hickory regeneration. Oaks are well adapted to growing in areas that burn regularly and as such, are able to outcompete faster growing, more shade-tolerant species that attempt to spread into such areas (Abrams, 2003; Bellocq et al., 2005; Hutchinson et al., 2012; Brose et al., 2014). Since the early 1900s, however, programs implemented to eliminate fire have negated this advantage (Fralish 2002; Dech et al., 2008; Brose et al., 2013). Thinning decreases competition and increases light availability, thereby increasing the competitiveness of oak and hickory seedlings (Lorimer et al., 1994; Boerger et al., 2013; Leonardsson et al., 2015). Burning and thinning are generally more effective in promoting oak and hickory regeneration when performed in combination (Hutchinson et al., 2012; Holzmueller et al., 2014; Thomas-Van Gundy et al., 2014). Planning for these methods must take into consideration many variables, including the negative impact of frequent browse by deer.

In many areas, deer are present in high enough densities to affect oak and hickory regeneration through the browsing of seedlings (Russell et al., 2001). Deer populations have become overabundant in many areas due to decades of harvest and habitat management and the elimination of natural predators (Russell et al., 2001; Côté et al., 2004; Adams et al., 2011). Food preference by deer has been shown to alter stand characteristics such as species diversity (Russell et al., 2001; Horsley et al., 2003; Côté et al., 2004; Ruzicka et al., 2010; McShea, 2012). Where deer densities are high for a prolonged period, they may alter the composition of species in various structural levels of the forest, thus shifting the path of succession (Stromayer and Warren, 1997; Urbanek et al., 2012; Holm et al., 2013). Many of the tree species that are valued in human industries, including oaks and hickories, are also favored by deer (Stromayer and Warren, 1997; Holm et al., 2013). Even low levels of deer browsing may slow the growth of seedlings necessary for regeneration of these species (thus increasing the rotation age of stands); repeated browsing for prolonged periods may lead to reduced stocking as fewer seedlings make it to the sapling stage (Stromayer and Warren, 1997; Russell et al., 2001; Côté et al., 2004; Kern et al., 2012). As preferred species decline due to browsing, undesirable species such as maples and ferns become more abundant, which will eventually result in an environment that is not favorable for either timber production or for wildlife, including deer (Horsley et al., 2003).

Trail of Tears State Forest in southern Illinois recently began silvicultural treatments aimed at increasing oak and hickory regeneration, including burning, understory thinning, and overstory cutting (Snyder, 2015). We use the term “treatment” to refer to the use of silvicultural practices to change the current stand structure to meet management goals. While similar treatments have been shown to successfully increase oak regeneration in other forests, research suggests that management plans should consider possible deer effects alongside implementation of such procedures (Holm et al., 2013; Kern et al., 2012; Thomas-Van Gundy et al., 2014). Our research examined both forestry and deer-use aspects of oak and hickory regeneration to provide land managers in the Central Hardwoods Region with information to support forest regeneration. Specifically, we quantified the impact of deer and silvicultural treatments on the presence, number, and height of oak and hickory seedlings, and the composition of other vegetation. We hypothesized deer would have a negative impact on the presence, number, and height of oak and hickory seedlings, species richness, and amount of herbaceous material while having a positive impact on the number of non-oak/hickory seedlings. We hypothesized that thinning and burning treatments would have a positive impact on the presence, number, and height of oak and hickory seedlings, species richness, and the amount of herbaceous material within 1 year. We expected to observe a greater initial response from red oak seedlings because they are generally faster growing than white oaks (Abrams, 2003) and therefore more likely to show a significant growth response in 1 year.

METHODS

Study Area. Trail of Tears State Forest (TTSF) consists of 2,088 ha in Union County, Illinois (Figure 1), and is managed by the Illinois Department of Natural Resources (IDNR) for timber, wildlife, and recreation. In 2015, temperatures in the area averaged 13.8° C, with a maximum of 33.7° C and a minimum of -22.7° C, while precipitation for the year was 159.9 cm (Weather Underground, Inc., Ann Arbor, MI). In 2016, temperatures averaged 15.2° C, with a maximum of 38.3° C and a minimum of -13.9° C, with 125.5 cm of precipitation (Weather Underground, Inc., Ann Arbor, MI). The steep, hilly terrain at TTSF is home to a dense overstory of trees established in the late 1800s to early 1900s (Ozier et al., 2006). TTSF was inventoried in 2000 by Ozier at al. (2006); they described an overstory dominated by *Quercus* and *Carya* species and an understory dominated by sugar maple (*A. saccharum*) and American beech (*F. grandifolia*). Ozier et al. (2006) noted the presence of oak and hickory seedlings, but suggested that the closed canopy and lack of understory disturbance were responsible for the lack of saplings and young trees of these species.

The IDNR recently began several silvicultural treatments at TTSF (Figure 1), in what they have designated a “Demonstration Forest,” to determine the most effective method of promoting the growth of oak and hickory seedlings and saplings (Snyder, 2015). The Demonstration Forest is comprised of 374.5 ha which have been divided into 5 management units based on treatment type: 2 reference units (East Control hereafter EC, West Control hereafter WC), burn first unit (hereafter BF), and 2 cut first units (East Cut First hereafter ECF, West Cut First hereafter WCF; Figure 1, Table 1). The EC and WC units account for 112.7 and 81.6 ha, respectively, and will be allowed to follow a natural course of succession (Snyder, 2015). Topography differs between the 2 reference units, as well as the surrounding landscape. The WC unit is fully surrounded by Trail of Tears State Forest land while the EC unit is bordered by private land to the east. The BF unit, 61.7 ha, was burned in November 2014. Prior to the burn, fire lines were established using hand rakes and backpack blowers. Backing fires were used to strengthen fire lines and once they were deemed sufficient, the ignition sequence was completed using ring head fires and interior ignition strips. Managers plan to burn the area several more times over 10 years (Snyder, 2015). The cut first units together consist of 118.5 ha of land. An overstory cut was planned for the WCF unit, but was not performed prior to the analysis of this research; therefore, this unit was treated as a third reference. A timber stand improvement (TSI) cut was performed in the ECF unit in March 2015, removing trees of undesirable species with a diameter at breast height (DBH) of <15.2 cm and reducing basal area by 15 m/ha (Snyder, 2015). Shade tolerant species such as sugar maple, elm (*Ulmus* spp.), and American beech were targeted during the TSI, while oak and hickory species were maintained. Despite the redundancy of having 3 reference units, all 5 units were included in the data reported here to ensure that baseline data was available for future studies and to ensure that all aspects of the research area were adequately represented

Plot locations. We used ArcGIS 10.3 (Environmental Systems Research Institute, Inc., Redlands, CA) to randomly select 150 plot locations across the research area (30 from each management unit, minimum 100 m apart) for sampling for a total of 300 individual plots. In June 2015, we constructed a 1×1 m plot marked by PVC piping and orange paint surrounded by a 1.2 m high welded-wire exclosure at each plot location. Exclosures were circular, with diameters of 2.5 m and reinforced with rebar stakes to minimize the chance of deer damaging vegetation inside the plot by reaching through the fencing (Urbanek et al., 2012). They were designed to exclude deer, but not smaller animals that may have impacted conditions within plots. We constructed an identical, though unfenced, reference plot 10 m west of the each exclosure plot. In contrast to other exclosure studies, our plots were relatively small to maximize sample size and ensure that plots were well spaced throughout management units (Asnani et al., 2006; Urbanek et al., 2011; Urbanek et al., 2012). The spacing between pairs of plots allowed us to treat them as independent from each other while the uniformity of landscape conditions between pairs made it likely that any differences seen would be a result of silvicultural treatment rather than stand-level differences.

Seedling plots. We inventoried exclosure and reference plots in August 2015 and in April and August 2016. We measured elevation, slope, aspect, basal area, canopy coverage (via densitometer), density of vegetation (via Robel pole), and mean and maximum heights

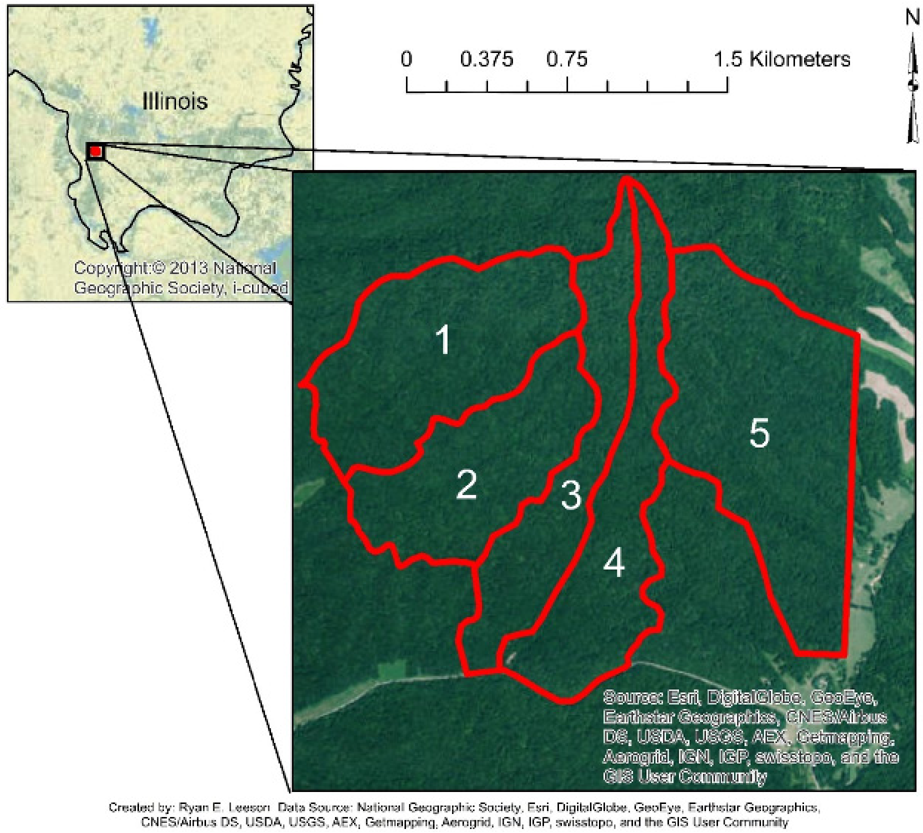

Figure 1. Map of demonstration forest units within Trail of Tears State Forest, southern Illinois, 2015-16: 1) west control (WC), 2) burn first (BF), 3) west cut first (WCF), 4) east cut first (ECF), and 5) east control (EC).

Table 1. Explanation of units within the study area, their size and prescribed treatments.

Unit	Size	Treatment
Control Unit (East and West)	194.3 ha	No treatment implemented.
Burn First Unit	61.7 ha	Repeated prescribed burns over the next 10 years.
Cut first Units (East and West)	118.5 ha	TSI cut of all undesirable tree species with a DBH < 15.2cm and reduction in basal area by 15m/ha.

of live vegetation once (August 2015) for each plot (Lemmon, 1956; Robel et al., 1970; Interagency Technical Team, 1999). For all sampling periods, we recorded frequently observed substrates and vegetation in terms of percentage cover of the plot; these included bare ground, water, litter, rock, seedling, sapling, tree, fern, grass, miscellaneous herbaceous plants, poison ivy (*Toxicodendron radicans*), Virginia creeper (*Parthenocissus quinquefolia*), and giant cane (*Arundinaria gigantea*) (Interagency Technical Team, 1999; Asnami et al., 2006; Urbanek, 2012). We counted and identified all seedlings (≤1.5 m tall), saplings (>1.5 m tall and <10 cm DBH), and trees (>10 cm DBH) within each plot. We used the number of individual woody seedling species as a measure of species richness and the number of individual non-oak/hickory species seedlings as a measure of competition. Oak seedlings were recorded as red or white due to important differences in their life history. When analyzing differences in red oak and white oak seedlings, only August data were used because of the difficulty in categorizing the seedlings during April. We measured all oak and hickory seedlings present in each plot from the point where the seedling entered the ground to the tallest point of woody growth on the plant, then calculated an average height (∑heights/n) and a cumulative height (∑heights) for oak and hickory seedlings within each plot (Urbanek et al., 2011).

Data Analysis. We compared data within and among treatment types and management units between August 2015, April 2016, and August 2016. We used generalized linear mixed models with seedling presence, numbers, mean heights, and cumulative heights as response variables. When analyzing seedling numbers, mean heights, and cumulative heights, only pairs of plots where ≥1 seedling of the species in question was found in ≥1 of the plots during ≥1 sampling period. We tested habitat measurements taken within and around plots as fixed effect covariates to determine other differences between plots. We examined differences in response variables among reference and exclosure plots (exclosure), sampling periods (period), and their interactions (e.g., treatment by period, exclosure by treatment). We considered plot ID (sample plot) alone or residual (error term) with plot ID as the subject as random effects in the models to preserve sample plot as the statistical sampling unit. We used autoregressive 1 covariance structure (AR1); except when analyzing differences in the number of several grouped non-oak/hickory seedling species, where we used an unstructured (UN) covariance structure. The default covariance structure (Variance Components) was only used when convergence would not occur with AR(1) or UN. We performed post-hoc Tukey tests or a Tukey adjusted analysis of simple effects to investigate pairwise differences. We evaluated model fit using generalized chi-square/DF; where values <1 indicate under-dispersion and values >1 indicate over-dispersion. Response variables were only ever dependent on exclosure, treatment, sampling period, or their interactions. All other variables were always either collinear or non-significant and thus removed from analysis and evaluation. All assumptions of normality, dispersion, and homogeneity of variance were assessed, met, or addressed. We analyzed all data using SAS 9.4 software (SAS Institute, Inc., Cary, NC, USA; α=0.05 throughout).

RESULTS

Oaks. Oak seedling presence was low during all 3 sampling periods, with 60.3%, 64.7%, and 71.0% of all plots having zero seedlings in August 2015, April 2016, and August 2016, respectively. Oak seedling presence was affected by exclosure and period (Table 2). Oak seedlings were present in exclosure plots more often than reference plots (t_{145}=-2.14, P=0.034; Figure 2). Presence was lower in August 2016 than in August 2015 (t_{290}=3.98, P<0.001) and April 2016 (t_{290}=2.84, P=0.013; Figure 2).

An initial estimate of 7,733 oak seedlings/ha was calculated for all plots, though there was some variation between management units (Table 3). The number of oak seedlings/plot varied from 0 to 12, with a mean of 0.61 ± 0.04 (SE throughout) seedlings/plot. When analyzing only pairs of plots with ≥1 oak seedling present during ≥1 period, the mean increased to 0.94 ± 0.06 seedlings/plot. Where present, oak seedling abundance was affected by treatment and period (Table 2). While treatment type did not vary across levels of period or exclosure during sampling, the EC unit had fewer oak seedlings than the WCF unit (t_{93}=-3.45, P=0.008). Across all management units and plot types, there were more oak seedlings in August 2015 than August 2016 (t_{186}=3.29, P=0.004; Figure 3).

Red oak seedling number was affected by period and the interaction of period and treatment (Table 2). Where oak seedlings were present, there were more red oak seedlings in August 2015 than August 2016 (t_{93}=2.49-4.08, P<0.001-0.015); this was true for all units except for the ECF unit (P>0.050; Figure 4). White oak seedlings were affected by the interaction of exclosure and treatment as well as the interaction of exclosure and period (Table 2). In all units, where oak seedlings were present, white oak numbers inside of exclosures were higher in August 2016 than

Table 2. Parameters and results (F, df, P) of generalized linear mixed models performed in reference to exclosure and reference plots[a] sampled for oak seedling presence and height in a central hardwood forest in southern Illinois, 2015-2016.

Model Parameters	Presence	*n* – All Plots	*n* – Red Oak Present	*n* – White Oak Present	Cumulative Height	Mean Height
Fixed Effect						
Enclosure	$4.59_{1,145}$, 0.034	$1.59_{1,93}$, 0.210	$0.37_{1,93}$, 0.542	$0.61_{1,93}$, 0.435	$1.84_{1,41}$, 0.183	$0.45_{1,41}$, 0.504
Treatment	$0.31_{4,145}$, 0.873	$3.41_{4,93}$, 0.012	$1.88_{4,93}$, 0.121	$2.95_{4,93}$, 0.024	$2.47_{4,93}$, 0.050	$1.87_{4,93}$, 0.123
Period	$8.04_{2,290}$, <0.001	$5.47_{2,186}$, 0.005	$42.5_{1,93}$, <0.001	$3.32_{1,93}$, 0.072	$1.00_{2,131}$, 0.369	$1.32_{2,131}$, 0.271
Exclosure X Treatment	$1.85_{4,145}$, 0.123	$2.00_{4,93}$, 0.100	$0.64_{4,93}$, 0.636	$2.64_{4,93}$, 0.038	-	-
Treatment X Period	$1.43_{8,290}$, 0.182	$0.61_{8,186}$, 0.766	$2.89_{4,93}$, 0.027	$1.90_{4,93}$, 0.116	-	-
Exclosure X Period	$0.83_{2,298}$, 0.435	$0.96_{2,194}$, 0.384	$0.00_{1,97}$, 0.968	$4.54_{1,97}$, 0.036	-	-
Random Effect	Residual	Residual	Residual	Residual	Residual	Residual
Subject	Site ID	Site ID	Site ID	Site ID	Site ID	Site ID
Covariance[b]	AR(1)[c]	Variance Comp[d]	AR(1)[c]	AR(1)[d]	AR(1)[c]	AR(1)[c]
Gen. X^2/DF	1.00	1.60	1.30	1.54	0.74	0.23
Distribution	Binomial	Poisson	Poisson	Poisson	Gamma	Gamma
Link	Logit	Log	Log	Log	Identity	Identity

[a]n=150 for both exclosure and reference plots for a total of n=300
[b]Measurement of relationship between 2 variables
[c]First order autoregressive - assumes correlation in the response error between sampling periods
[d]Variance components – assumes variances differ while covariance=0

August 2015 (t_{97}=-2.82, *P*=0.006), however, this difference was not significant for reference plots (*P*>0.050; Figure 5). Where oak seedlings were present, there were more white oak seedlings in exclosure plots than reference plots in the WCF unit (t_{93}=-2.65, *P*=0.010), but this relationship was not significant for other units (*P*>0.050).

Cumulative oak seedling height for each plot ranged from 0 cm to 214.5 cm and was affected by treatment (Table 2), such that seedling height was higher in the WCF unit than in the ECF unit (t_{93}=-2.98, *P*=0.030). Mean oak seedling height for each plot ranged from 0 cm to 64.8 cm and was not affected by exclosure, treatment, or period (Table 2).

Hickories. As with oak seedlings, hickory seedling presence was low during all 3 sampling periods, with 77.7%, 79.0%, and 78.0% of all plots having zero seedlings in August 2015, April 2016, and August 2016, respectively. An initial estimate of 3,333 hickory

Table 3. Pearson product moment correlations for conventional tillage (CT) means of sites 2-8.

	Reference		Enclosure	
	Aug 2015	Aug 2016	Aug 2015	Aug 2016
All Oak				
BF	7,000	2,000	6,667	5,000
EC	7,000	4,000	5,333	3,333
ECF	4,667	3,667	4,667	5,000
WC	8,333	3,667	6,333	6,000
WCF	10,333	5,667	17,000	9,667
White Oak				
BF	333	667	1000	3333
EC	1333	1000	667	1333
ECF	333	667	333	667
WC	3667	2667	667	2667
WCF	3667	2333	7000	7000
Red Oak				
BF	6667	1333	5333	1000
EC	5000	2667	4667	2000
ECF	4333	3000	4333	4333
WC	4333	1000	5667	3000
WCF	6667	3333	9667	2667
Hickory				
BF	2,667	2,667	3,333	2,667
EC	1,333	1,000	2,000	2,667
ECF	4,333	3,000	3,000	2,667
WC	3,667	3,000	5,333	5,667
WCF	4,333	5,667	3,333	3,333

[a]n=150 for both reference and exclosure plots for a total of n=300

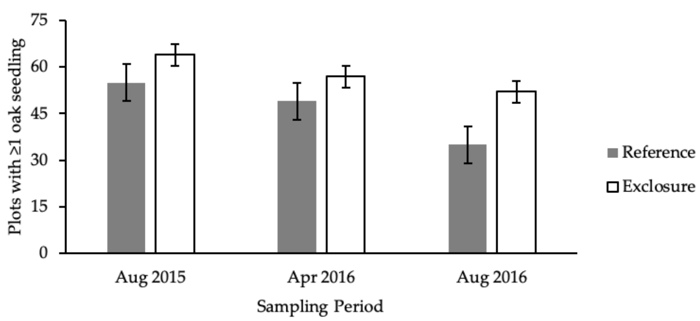

Figure 2. Presence of oak seedlings in reference (n=150) and exclosure (n=150) plots by period (error bars indicate standard error) in a central hardwood forest in southern Illinois, 2015-16.

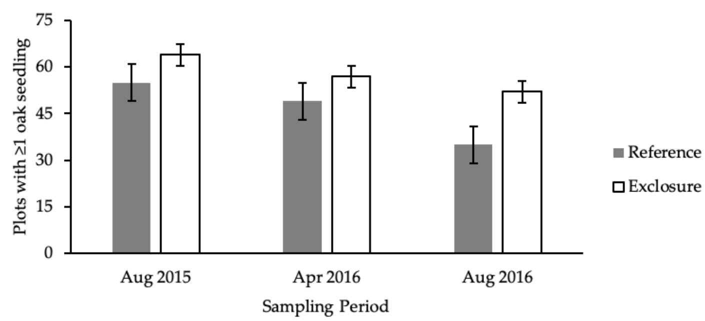

Figure 3. Mean number of oak seedlings/plot for sample sites with oak seedlings present in reference (n=98) and exclosure (n=98) plots by sampling period (error bars indicate standard error) in a central hardwood forest in southern Illinois, 2015-16.

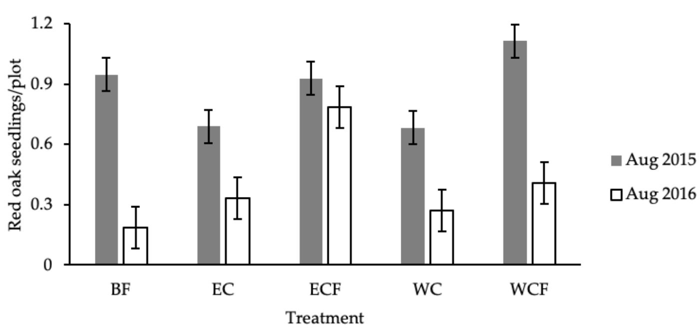

Figure 4. Mean number of red oak seedlings/plot for sample sites with oak seedlings present (n=98) by sampling period and treatment (BF=burn first, EC=east control, ECF=east cut first, WC=west control, and WCF=west cut first; error bars indicate standard error) in a central hardwood forest in southern Illinois, 2015-16.

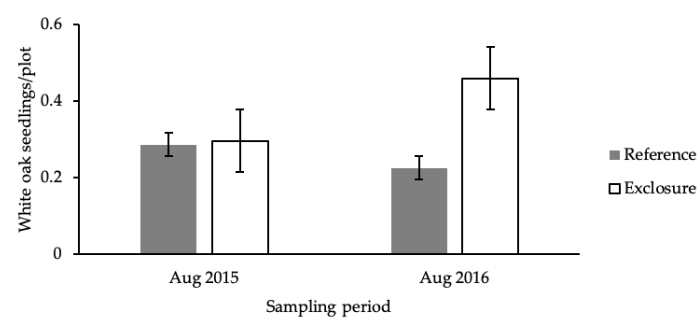

Figure 5. Mean number of white oak seedlings/plot for sample sites with oak seedlings present in reference (n=98) and exclosure (n=98) plots by sampling period (error bars indicate standard error) in a central hardwood forest in southern Illinois, 2015-16.

seedlings/ha was calculated for all plots, though there was some variation among management units (Table 3). Number of hickory seedlings/plot varied from 0 to 5, with a mean of 0.31 ± 0.02 seedlings/plot. Considering only pairs of plots with ≥1 hickory seedling present during ≥1 period, the mean increased to 0.69 ± 0.04 seedlings/plot. Hickory seedling presence and number were not dependent on exclosure, treatment, or period (Table 4).

Cumulative hickory seedling height for each plot ranged from 0 cm to 127.2 cm. Despite a significant *P*-value for treatment, there were no differences in cumulative hickory seedling heights based on treatment pairwise comparisons (Table 4). Mean hickory seedling height for each plot ranged from 0 cm to 127.2 cm and was not affected by exclosure, treatment, or period (Table 4).

Other Vegetation at Seedling Plots. We recorded woody seedlings of 23 non-oak/hickory species. We recorded ≥ 1 seedling of a non-oak/hickory species in 73.9% of plots, with a range of 0 to 47 seedlings/plot and a mean of 3.14 ± 0.13 seedlings/plot. The number of non-oak/hickory seedlings was affected by period and by the interaction of treatment and period (Table 5) and did not differ among treatments in August 2015 or April 2016. However, in August 2016, there were more non-oak/hickory seedlings in the ECF unit than in others (t_{145}=-3.80 to 4.47, *P*<0.001-0.012; Figure 6).

Table 4. Parameters and results (F, df, P) of generalized linear mixed models performed in reference to exclosure and reference plots[a] sampled for hickory seedling presence and height in a central hardwood forest in southern Illinois, 2015-2016.

Model Parameters	Presence	*n* – Hickores	Cumulative Height	Mean Height
Fixed Effect				
Enclosure	$1.14_{1,149}$, 0.287	$0.36_{1,66}$, 0.552	$0.56_{1,9}$, 0.474	$0.29_{1,12}$, 0.603
Treatment	$0.74_{4,145}$, 0.565	$0.81_{4,62}$, 0.525	$2.85_{4,62}$, 0.031	$1.09_{4,60}$, 0.371
Period	$0.38_{2,298}$, 0.685	$2.73_{2,132}$, 0.069	$0.20_{2,88}$, 0.820	$0.00_{1,47}$, 0.946
Exclosure X Treatment	-	-	$3.40_{4,9}$, 0.059	-
Treatment X Period	-	-	$0.24_{8,88}$, 0.982	-
Exclosure X Period	-	-	-	-
Random Effect	Residual	Residual	Residual	Residual
Subject	Site ID	Site ID	Site ID	Site ID
Covariance[b]	AR(1)[c]	AR(1)[c]	Variance Comp[d]	AR(1)[c]
Gen. X^2/DF	0.99	1.06	0.48	0.55
Distribution	Binomial	Poisson	Gamma	Gamma
Link	Logit	Log	Identity	Identity

[a]n=150 for both exclosure and reference plots for a total of n=300
[b]Measurement of relationship between 2 variables
[c]First order autoregressive - assumes correlation in the response error between sampling periods
[d]Variance components – assumes variances differ while covariance=0

Table 5. Parameters and results (F, df, P) of generalized linear mixed models performed in reference to exclosure and reference plots[a] sampled for non-oak/hickory species and miscellaneous herbaceous cover in a central hardwood forest in southern Illinois, 2015-2016.

Model Parameters	Non-oak/hickory	*n* – Species	Misc-Herb Cover
Fixed Effect			
Enclosure	$0.72_{1,145}$, 0.398	$5.85_{1,145}$, 0.017	$0.26_{1,114}$, 0.612
Treatment	$2.50_{4,145}$, 0.045	$1.68_{4,145}$, 0.158	$4.79_{4,142}$, 0.001
Period	$9.37_{2,145}$, <0.001	$4.49_{2,290}$, 0.012	$2.14_{2,242}$, 0.120
Exclosure X Treatment	$1.03_{4,145}$, 0.395	$0.98_{4,145}$, 0.421	$2.10_{4,114}$, 0.085
Treatment X Period	$7.20_{8,145}$, <0.001	$2.59_{8,290}$, 0.010	$1.80_{8,242}$, 0.079
Exclosure X Period	$1.95_{2,145}$, 0.146	$7.05_{2,298}$, 0.001	$1.55_{2,126}$, 0.217
Random Effect	Residual	Residual	Residual
Subject	Site ID	Site ID	Site ID
Covariance[b]	Unstructured[c]	AR(1)[d]	AR(1)[c]
Gen. X^2/DF	1.00	1.02	1.16
Distribution	Binomial	Poisson	Gamma
Link	Logit	Log	Identity

[a]n=150 for both exclosure and reference plots for a total of n=300
[b]Measurement of relationship between 2 variables
[c]Unstructured - assumes every variance and covariance relationship is independent
[d]First order autoregressive - assumes correlation in the response error between sampling periods

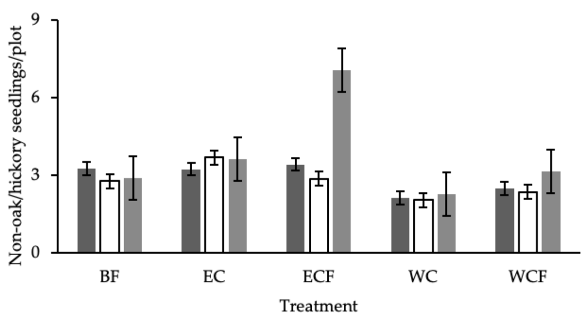

Figure 6. Mean number of red oak seedlings/plot for sample sites with oak seedlings presentnon-oak/hickory seedlings in all plots (n=900) by treatment (BF=burn first, EC=east control, ECF=east cut first, WC=west control, and WCF=west cut first; error bars indicate standard error) and sampling period in a central hardwood forest in southern Illinois, 2015-16.

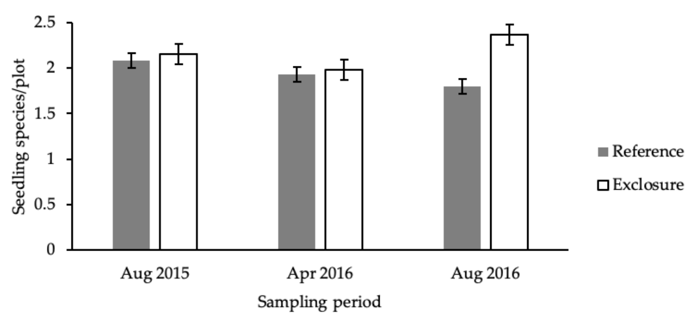

Figure 7. Mean number of seedling species in all plots (n=900) by sampling period and plot type (error bars indicate standard error) in a central hardwood forest in southern Illinois, 2015-16.

We recorded woody seedling species richness of ≥1 in 85.0% of plots, with a range of 0 to 9 species/plot and a mean of 2.06 ± 0.05 species/plot. The woody seedling species richness was affected by exclosure, period, the interaction of treatment and period, and the interaction of exclosure and period (Table 5). There was less seedling species richness in April 2016 than August 2016 in the ECF unit (t_{290}=-3.14, *P*=0.005). In the WCF unit, there was less seedling species richness in April 2016 than in either August 2015 (t_{290}=2.93, *P*=0.010) or August 2016 (t_{290}=-2.75, *P*=0.017). There was greater seedling species richness in exclosure than reference plots in August 2016 (t_{298}=-4.34, *P*<0.001), which was not the case in earlier sampling periods (*P*>0.050; Figure 7).

We recorded miscellaneous herbaceous material in 71.8% of plots, with values ranging from 1 to 62% coverage/plot. The amount of miscellaneous herbaceous coverage/plot was affected by treatment (Table 5), such that the WCF unit had less miscellaneous herbaceous coverage/plot across all periods and plot types than the EC unit (t_{142}=3.82, *P*=0.002) and the BF unit (t_{142}=3.47, *P*=0.006).

We recognize that our definition of seedling was rather broad and that many of the seedlings present in the plots were small and will not likely graduate into the overstory. Other studies classify seedlings by height according to either the height at which regeneration overtops other vegetation or the height of browse preferred by deer (Nix, 2003; Iverson et al., 2008; Cunningham, 2015; Leonardsson et al., 2015). Seedlings ≤30 cm in height generally escape browse damage and upon reaching 2 m are thought to have outgrown browse range (Götmark et al., 2005; Krueger and Peterson, 2006; Götmark, 2007; Leonardsson et al., 2015). We were unable to divide oak or hickory seedlings into categories due to the lack of seedlings ≥30 cm. In all 300 plots sampled, we only counted 18 oak and 17 hickory seedlings ≥30 cm, and of those, only 4 oaks and 2 hickories measured ≥50 cm and none measured ≥2 m (Figure 8). This can likely be attributed to the lack of time following treatment establishment.

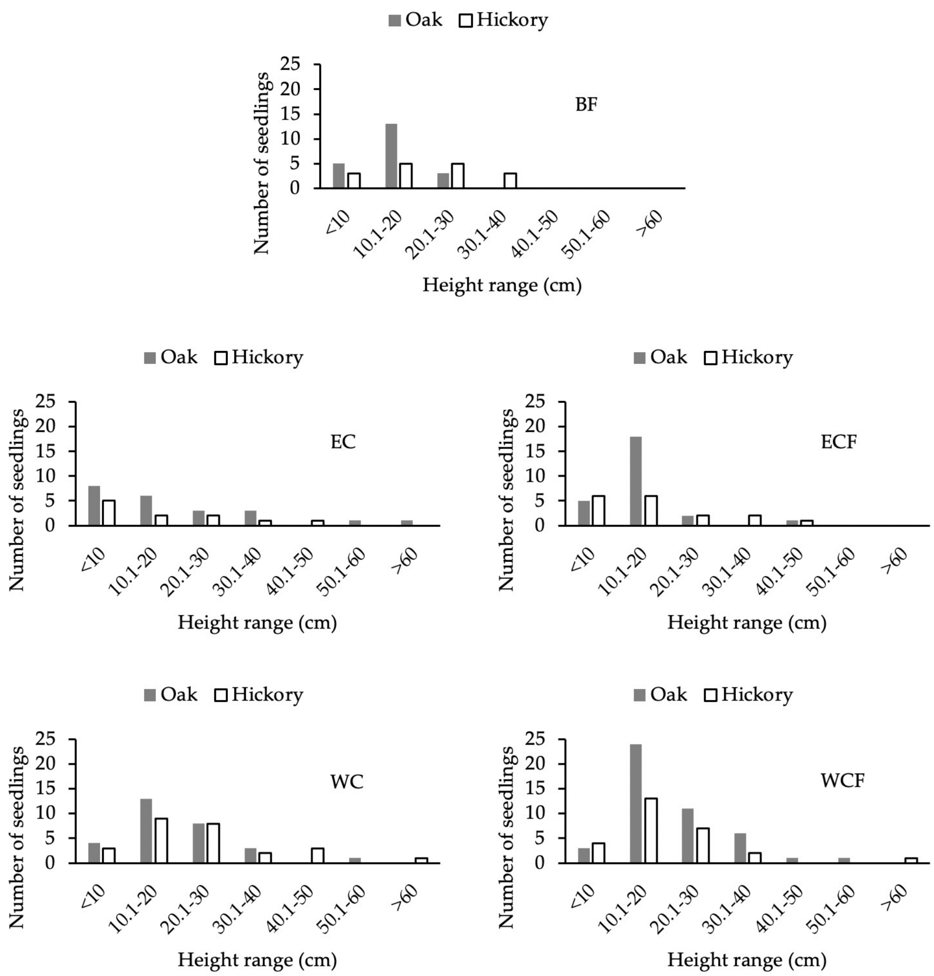

Figure 8. Height distribution of oak and hickory seedlings present by treatment (BF=burn first, EC=east control, ECF= ast cut first, WC=west control, and WCF=west cut first) in August 2016 in a central hardwood forest in southern Illinois.

DISCUSSION

After only 1 year of study, oak regeneration and other herbaceous species responded slightly to deer exclusion and silvicultural treatments, which was somewhat surprising given that many studies examining seedling response to deer removal or silvicultural treatment do so after >5 years (Asnami et al., 2006; Schweitzer, 2007; Iverson et al., 2008; Holm et al., 2013; Holzmueller et al., 2014). A decline of both presence and number of oak seedlings in all treatment units and plot types was observed during the study period, however, this was not the case for hickory seedlings. Survival of seedlings over several years is known to be extremely low, but the number of oak and hickory seedlings on the ground should be replenished occasionally by plentiful seed crops (Sork and Boucher, 1977; Lorimer et al., 1994; Abrams and Scheibel, 2013). We had no data on past seed crops in our research area, but it is possible that a large crop of hickory nuts dropped more recently than a large crop of acorns, resulting in the discrepancy between seedling numbers over time. It could also be that hickory seedling numbers are more stable through time because the shells of their seeds are more difficult for nucivores to penetrate, thus decreasing use of hickory nuts compared to acorns (Sork and Boucher, 1977; Moore and Swihart, 2006).

White oak seedlings responded positively to exclosures, whereas red oak seedlings did not. It is unclear whether this discrepancy was indicative of deer preference for white oak over red or if red oak seedlings were able to cope with the browse pressure better than white oaks. Our results agree with others who have suggested that deer have likely facilitated the decline of white oak recruitment in Central Hardwood forests during the last century (Stromayer and Warren, 1997; Abrams, 2003; Holm et al., 2013). Alternatively, red oak seedlings responded positively to thinning in the ECF unit. Red oak seedlings generally grow faster than white oak seedlings (Abrams, 2003), so it is possible that white oak seedlings were merely slower to demonstrate a response to the increased resources.

Species richness, measured by number of individual woody species, was higher within exclosure plots than reference plots, while competition, measured by individual hickory seedlings, remained consistent between plot types. As in other parts of the U.S., deer are negatively affecting species richness through their preferential feeding (Russell et al., 2001; Horsley et al., 2003; Holm et al., 2013). There was a varied response of species richness, competition, and percent coverage of miscellaneous herbaceous vegetation to silvicultural treatments. The ECF unit was the only unit where we recorded an increase in species richness. The thinning treatment in that unit may have increased competition; more than doubling the number of non-oak/hickory seedlings/plot. Continued measurements and comparisons to control units will be needed to evaluate this relationship. Cover by miscellaneous herbaceous plants did not increase in the ECF unit compared to other units, which we expected due to the reduction of competition and the increase of resources such as light and moisture (Small and McCarthy, 2002). Plants in this unit may not have had enough time to capitalize on these resources or may have been outcompeted by woody species (Horsley et al., 2003; Côté et al., 2004). Burning in the BF unit did not lead to any significant differences in understory vegetation over the course of a year, which also may have been due to the lack of time for effects to become apparent. The effects of burning become more pronounced when sampling occurs following multiple burns performed over several years rather than following a single burn, so the single burn performed in the BF unit may not have been sufficient to produce lasting changes in vegetation (Arthur et al., 1998).

Management Implications. The discovery of a positive effect of exclosures on oak regeneration after merely 1 year of study emphasizes the need for land managers to strongly consider the effects of deer on regeneration when creating forest management plans. In conjunction with silvicultural treatments meant to encourage oak and hickory regeneration, managers may wish to consider fencing and deer harvest to improve regeneration (Waller, 2002; Latham et al., 2005; Steckel and Harper, 2014). When properly installed and maintained, fencing eliminates all browsing of regeneration by deer, but costs may deter many managers from their use (Urbanek et al., 2011). Reducing deer numbers would lower browse levels rather than eliminating them, but would be far less expensive.

Deer removal through hunter harvest would be the most economically efficient way to reduce deer density (VerCauteren et al., 2011). Such programs can (1) increase hunter effort via longer seasons or larger bag limits and (2) increase female harvests via earn-a-buck programs (Reive and Stephenson, 2002; Waller, 2002; Van Deelen et al., 2010; VerCauteren et al., 2011; Boulanger et al., 2012). The limitation to such programs may be having adequate hunter effort. For example, hunters on our research area harvested only 37 deer/year during the last 5 years on 1,936 ha open to hunting (Nawojski, 2016). For any removal program to be successful, managers must find ways of attracting hunters to this area, which may be problematic. Hunters generally have particular areas they prefer to hunt because of a number of factors including ease of access, an abundance of deer, and the presence of large bucks (Cornicelli et al., 2011). Our research area is particularly hilly in comparison with much of Illinois, which deters many hunters who are unable or unwilling to move a carcass through such terrain. Managers do have a service whereby they will assist successful hunters in removing a carcass, but it is not well known and is limited by employee availability (Nawojski, 2016). Outreach is necessary to educate hunters on this service and the need for their assistance in removing deer in this area.

If managers are unable to attract more hunters to the area to harvest a larger proportion of the population, they may consider implementing a sharpshooting program performed by managers (Reive and Stephenson, 2002; Miller et al., 2010; VerCauteren et al., 2011). This method would require monetary investment and would need to be repeated every few years (Nielsen et al., 1997), but would allow managers to meet their deer reduction goals and ensure that deer removals are spread evenly through space rather than grouped around trails and roads which provide easier access for hunters.

Summary. The research presented here represents the first year of a long-term study, where our goals were to provide baseline information for future comparisons. By measuring these plots annually, responses of oak and hickory regeneration to silvicultural treatments and deer exclusion will be documented over time rather than compared to a single snapshot in the future. We expect the positive responses of white oak seedlings to deer exclusion and of red oak seedlings to thinning that we found after only 1 year to become more exaggerated over time. We found no response of oak and hickory regeneration to the single burn performed before in November 2014, but expect future measurements to show responses to multiple burns over time. Oak and hickory seedlings in our study area may grow and be divided into height categories that will allow researchers to more directly measure browse impacts and compare more comprehensively to other studies.

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