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Influence of Strip Clearcuts, Deer Exclusion and Herbicide on Initial Sapling Recruitment in Northern Hardwood Forests

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Abstract: Sapling recruitment in hardwood forests is often suppressed by overstory shade, interspecific competition, and browsing pressure from white-tailed deer (*Odocoileus virginianus* Zimmerman). In some northern hardwood stands, these three interacting factors may cause persistent recruitment failure of the dominant canopy species, sugar maple (*Acer saccharum* Marsh.), into the sapling size class. In this study, we compared initial (two-year) sugar maple and hophornbeam (*Ostrya virginiana* ((Mill.) K. Koch) seedling and sapling recruitment in strip clearcuts to strip selection cuts, with combinations of herbicide and deer exclosures, in a northern hardwood forest with limited sugar maple sapling recruitment. We found that sugar maple sapling recruitment was higher in exclosures, particularly in strip clearcuts. Moreover, mixed models predicted that exclosures in strip clearcuts with herbicide tended to benefit sugar maple sapling recruitment, especially when the pre-treatment density was less than ~1500 stems ha^{-1}. Sapling density of hophornbeam was also promoted in exclosure plots but was negatively affected by herbicide. Graminoid and *Rubus* spp. cover was also limited by herbicide following harvest, potentially alleviating constraints on future sugar maple sapling recruitment. Our findings indicate that sugar maple sapling recruitment in strip clearcuts is similar to strip selection cuts unless browsing pressure and interspecific competition are also alleviated.

Keywords: silviculture; northern hardwoods; *Acer saccharum*; *Ostrya virginiana*; deer browsing; herbicide; strip clearcuts

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1. Introduction

Conventional management has tended to promote shade-tolerant regeneration in mesic hardwood forests [1,2]. However, deer browsing [3,4], competition from other plant species [5], and exotic earthworms [6], among other factors, may interact with management techniques and instead cause regeneration failure of desired shade-tolerant species. For example, declining shade-tolerant sugar maple (*Acer saccharum* Marsh.) sapling recruitment has been observed in northern hardwood regions with high white-tailed deer (*Odocoileus virginianus* Zimmerman) populations [7], while heightened competition from shrubs and Pennsylvania sedge (*Carex pensylvanica* Lam.) may further inhibit seedling survival or recruitment of sugar maple into the sapling size class [6,8]. Applying alternative silvicultural techniques to alleviate contemporary threats may therefore curtail regeneration failure of economically desirable species, including sugar maple. However, since the early twentieth century, conventional management systems in the northern hardwoods of the United States and Canada have been largely based on the widespread use of single-tree selection [9,10]. In a single-tree selection system, individual trees across a range of diameter classes are harvested singly throughout a stand to reach a residual basal area and structural goal at the whole-stand level, and the stand is then harvested in a similar way every 10–20 years. This system tends to promote shade-tolerant sugar maple regeneration [11], which can survive decades in shaded understories until released by gaps created by harvesting or natural disturbance [12].

Recruitment into the sapling size class, however, can be constrained by ungulate browsing, as documented by numerous studies across various forest types [13–15]. For example, intense browsing due to elevated white-tailed deer populations may compromise the recruitment of palatable species such as sugar maple, therefore favoring unpalatable and economically undesirable species like hophornbeam (*Ostrya virginiana* (Mill.) K. Koch) [4], the seedlings and saplings of which often compete with sugar maple regeneration [16]. Moreover, competition from shrubs (e.g., *Rubus* spp.) and graminoids can further suppress regeneration and alter plant community taxonomic and functional composition [17,18]. Canopy and soil disturbances often promote the colonization of *Rubus* spp. owing to long-lived (~60 years), animal-dispersed seeds [19]. Graminoids such as Pennsylvania sedge are another strong competitor in mesic hardwood forests [20], and reproduce vegetatively, which allows this functional group to spread rapidly without depending on seed germination [21]. Reduced competition from browsed seedlings and saplings further promotes the spread of Pennsylvania sedge. Consequently, failure to recruit sugar maple saplings in some northern hardwood regions may be driven by the interacting effects of heightened browsing pressure and increased competition from shrubs or graminoids.

Silvicultural systems beyond single-tree selection have recently been explored throughout eastern mesic forests in Canada and the United States [22–25]. Among other systems, strip clearcutting may be a viable option to alleviate regeneration failure by opening the canopy more than conventional single-tree selection yet still receive seed and shade from the adjacent uncut strip [26], and evidence suggests that additional treatments, such as herbicide, may further promote the regeneration of desirable species [27,28]. In one study, strip clearcuts in New England northern hardwood forests exhibited an initial dominance of pin cherry (*Prunus pensylvanica* L.f.) and early successional shrubs, succeeding to a canopy with a similar composition to the original overstory [26,29]. In eastern Canadian northern hardwood stands, strip clearcutting near ample seed sources promoted the regeneration of economically desirable species while also overcoming competitive effects from graminoids by increasing light availability and allowing seedlings to rapidly grow above the sedge layer into the sapling size class [30]. In a Great Lakes northern hardwoods study, advanced regeneration present prior to strip harvesting was the main predictor of tree growth six and seven years following harvesting and herbicide application, and species composition was similar to the original overstory [31]. Taken together, this evidence suggests that concurrent herbicide application may help to limit shrub and graminoid competition, but the interacting effects with strip harvesting and browsing reduction are not well known. Consequently, there is an opportunity to quantify the interacting effects of conventional management and present-day biological challenges on regeneration.

In this study we assessed initial (i.e., within two years) seedling and sapling recruitment following the application of strip clearcuts and adjacent strip selection cuts, along with herbicide and deer exclosures, to promote the regeneration of sugar maple in Great Lakes northern hardwood stands exhibiting recruitment failure. Knapp et al. (2021) [32] found that northern hardwood seedling and sapling density two years after gap creation was correlated with regeneration 21 years later, suggesting that early regeneration dynamics might predict longer-term trends. We hypothesized that (1) strip clearcuts combined with exclosures and herbicide would promote rapid sugar maple seedling growth into the sapling size class, but exclosures would have little effect on the more unpalatable hophornbeam, and (2) herbicide application would decrease the cover of competing plants and change the plot-level composition of forbs, ferns, graminoids, and *Rubus* spp., especially in strip clearcuts. To test our hypotheses, we applied an operational-scale experiment testing the use of strip clearcuts vs. strip selection cuts, herbicide, and deer exclosures on regeneration in the Upper Peninsula of Michigan, USA. Seedlings, saplings, and plant functional groups were surveyed before and two growing seasons following treatment application.

2. Materials and Methods

2.1. Site Description

Three study sites were established in Dickinson and Menominee counties of the Upper Peninsula of Michigan, USA (Figure 1). The sites were within the Northern Lake Michigan Till Plain [33] where soils are rocky, sandy loam, with limestone bedrock approximately 9.1 to 15.2 m below the surface. The average yearly temperature (2000–2014) is 5.6 °C, with an average of −9.4 °C in January and 19.7 °C in July [34]. The growing season typically lasts about 100 days, with 49.2 cm of average annual precipitation (2000–2014) [33]. Prior to harvest, the average (±standard error) basal area across the three study sites was 19.7 (±0.7) m^2 ha^{-1}, with sugar maple comprising an average of 83.7% (±0.02) of the total basal area (Table 1). Quadratic mean diameter averaged 30.4 (±0.5) cm. Average *Rubus* spp. cover ranged from 12.7 (±0.2)% in selection plots to 13.2 (±0.4)% in clearcut plots prior to treatment application, while graminoid cover was 17.0 (±1.9)% in selection plots and 18.8 (±1.3)% in clearcut plots prior to treatment application (Table 1).

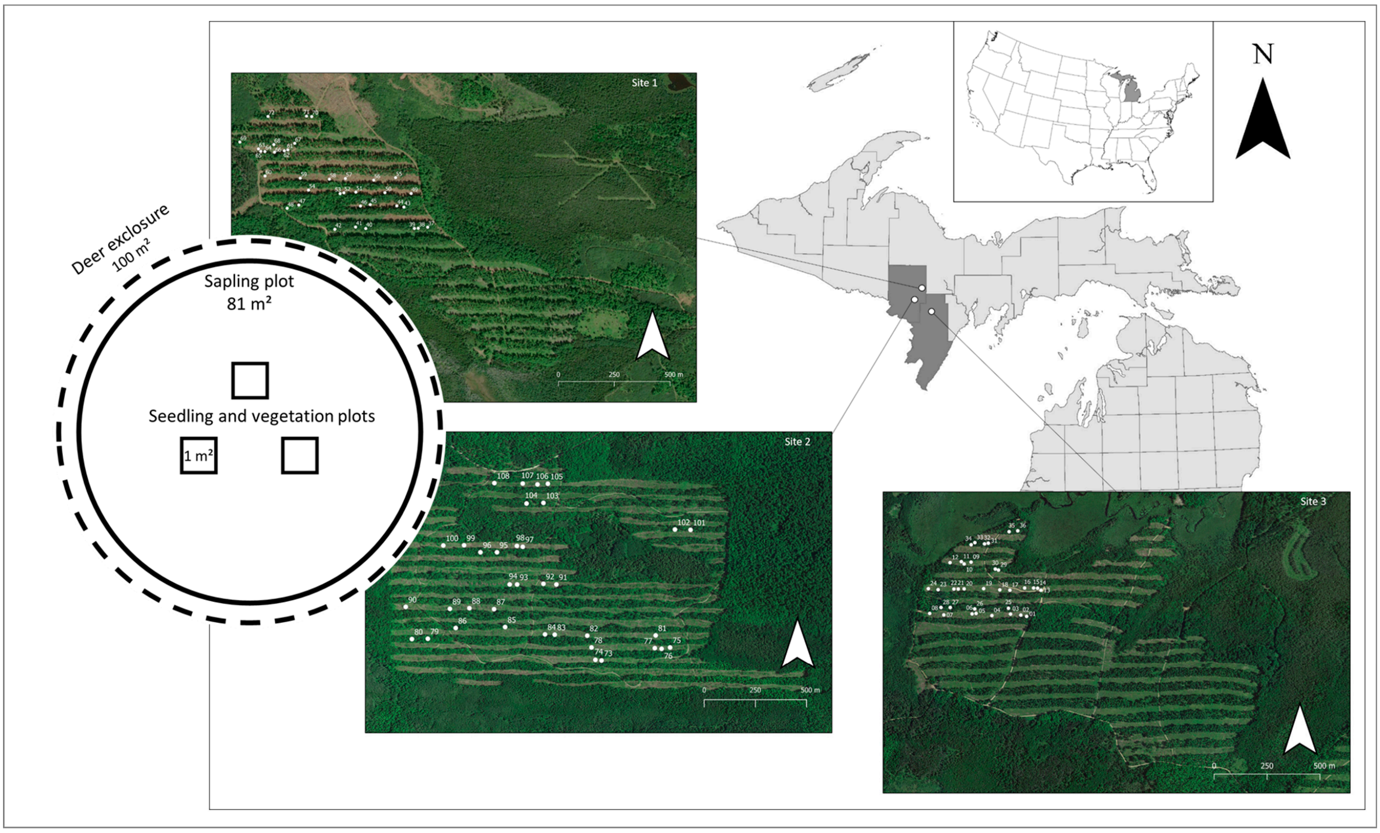


Figure 1. Experimental plot design and site locations in the Dickinson and Menominee counties in the Upper Peninsula of Michigan, USA. Numbers within each site denote plot numbers. Plot sizes are not to scale. Sites are managed by American Forest Management, Inc. (Charlotte, NC, USA). Satellite imagery retrieved from Google.

Table 1. Average (±SE) stand characteristics pre- and post-harvest in a managed northern hardwood forest in the Upper Peninsula of Michigan, USA. Saplings were defined as ≥45.7 cm (18 inches) tall but <15.4 cm (6 inches) diameter at breast height. Seedlings were defined as <45.7 cm tall. Trees were counted for basal area if the diameter at breast height was >15.4 cm. BA, basal area; QMD, quadratic mean diameter; BA, basal area; SM, sugar maple; HB, hophornbeam.

Year	**Harvest**	**Ferns (% Cover)**	**Forbs (% Cover)**	***Rubus* spp. (% Cover)**	**Graminoids (% Cover)**	**BA (m^2 ha^{-1})**	**QMD (cm)**	**SM BA (m^2 ha^{-1})**
2015	Strip clearcut (*n* = 72)	14.7 (0.9)	13.6 (0.9)	13.2 (0.4)	18.8 (1.3)	20.0 (1.0)	30.3 (0.7)	16.5 (1.0)
2015	Strip selection (*n* = 35)	13.9 (0.9)	13.2 (0.4)	12.7 (0.2)	17.0 (1.9)	19.0 (0.9)	30.8 (0.8)	16.5 (1.0)
2017	Strip clearcut (*n* = 72)	12.8 (0.2)	16.2 (0.9)	21.3 (2.0)	36.2 (2.4)	1.3 (0.3)	13.0 (2.2)	1.0 (0.2)
2017	Strip selection (*n* = 35)	16.3 (1.4)	18.2 (2.1)	14.4 (0.8)	32.3 (3.2)	15.6 (1.0)	30.6 (0.7)	14.0 (1.1)

Year	**Harvest**	**Seedlings ha^{-1}**	**Saplings ha^{-1}**	**SM Seedlings ha^{-1}**	**HB Seedlings ha^{-1}**	**SM Saplings ha^{-1}**	**HB Saplings ha^{-1}**
2015	Strip clearcut (*n* = 72)	61,573 (9197)	3296 (429)	48,055 (9193)	2005 (398)	235 (49)	1031 (159)
2015	Strip selection (*n* = 35)	42,856 (7249)	3276 (641)	35,618 (7299)	848 (260)	593 (205)	752 (164)
2017	Strip clearcut (*n* = 72)	15,555 (2735)	2644 (362)	8055 (2471)	768 (179)	446 (127)	637 (131)
2017	Strip selection (*n* = 35)	27,047 (3712)	3029 (458)	19,523 (3745)	655 (237)	452 (154)	890 (195)

There was a documented paucity of saplings at the three study sites. Average (±SE) pre-treatment sapling (≥45.7 cm tall and <15.4 cm dbh) density was between 3276 (±641) stems ha^{-1} and 3296 (±429) stems ha^{-1} (Table 1), lower than the recommended minimum stocking levels of 4942 to 9884 stems ha^{-1} for regeneration that is 30.5 to 121.9 cm tall in northern hardwoods [35]. Moreover, the pre-treatment sapling density of sugar maple, which is the dominant commercial species in Great Lakes northern hardwood forests [36], was only between 235 (±49) stems ha^{-1} and 593 (±205) stems ha^{-1} (Table 1).

Regeneration failure may be compounded by white-tailed deer browsing pressure, as demonstrated by studies that have found strong effects of deer exclosures on tree regeneration or plant community dynamics in areas of high deer populations [13,37–39]. White-tailed deer harvest data, which can be used as an indicator of local deer population size [40,41], suggest that deer populations in the study region were elevated compared to the surrounding regions in the Upper Peninsula of Michigan. There were an average (±SE) of 21 (±2, *n* = 2) cumulative deer harvested km^{-2} from 2006–2015 in the deer management units in which our study sites were located, compared to 11 (±2, *n* = 20) deer km^{-2} in the remaining Upper Peninsula deer management units, pooled (Table S1) [42].

2.2. Experimental Design

The main purpose of this study was to compare seedling regeneration and sapling recruitment in strip clearcuts with strip selection cuts, along with the interacting effects of herbicide and deer exclosures. Consequently, strip selection cuts without herbicide or exclosures were used as the control in this study, but edge effects are an inherent feature of any strip-harvesting system and should be considered when making any inferences or applying these results to block or conventional harvesting. Strip clearcut and selection harvesting was applied in alternating ~20–30 m wide strips of varying length in an east-west orientation (Figure 1). The sites were harvested during the summer and fall of 2015, following pre-treatment measurements, using a wheeled- or tracked-processor and an 8-wheeled forwarder.

In the strip clearcuts, basal area was reduced from 20.0 (±1.0) m^2 ha^{-1} to 1.3 (±0.3) m^2 ha^{-1} (Table 1). In the strip selection cuts, basal area was reduced from 19.0 (±0.9) m^2 ha^{-1} to 15.6 (±1.0) m^2 ha^{-1}, with sugar maple comprising 92.2% of removed basal area and 89.7% of remaining basal area (Table 1). Quadratic mean diameter remained unchanged (30.6 ± 0.7 cm, Table 1).

Circular 80.9 m^2 measurement plots were established in 2015 prior to treatment application. Overall, 34 plots were established in strip selection cuts and 73 plots were established in strip clearcuts (Table 2). Specifically, in Site 1, 12 plots were distributed among three strip selection cuts and 24 plots were distributed among five strip clearcuts. In Site 2, 10 plots were distributed among five strip selection cuts and 26 plots were distributed among seven strip clearcuts. In Site 3, 12 plots were distributed among four strip selection cuts and 23 plots were distributed among three strip clearcuts (Figure 1). Plot locations were randomly assigned with ArcGIS (Esri, Redlands, CA, USA) and permanently marked with rebar posts. Circular 100 m^2 × 1.83 m tall deer exclosures were constructed at Sites 1 and 3 in fall 2015 (shortly after harvest) and at Site 2 in May 2016. For each site, three exclosures, each containing one plot, were constructed in strip clearcuts, while one exclosure was constructed in strip selection cuts for a total of nine clearcut × exclosure plots and three selection × exclosure plots (Table 2). Herbicide was applied to 19 out of 73 clearcut plots and 4 out of 34 strip selection plots by helicopter using a mixture of 0.67 L glyphosate and 0.02 L sulfometuron per hectare. Application was in fall 2016 during leaf senescence, as recommended by other silvicultural studies [43]; however, we recognize that the time lag between establishing deer exclosures and later herbicide application may have reduced statistical power and limited our ability to detect treatment effects.

Table 2. Plot distribution among harvest, herbicide, and exclosure treatments in managed northern hardwood forests in the Upper Peninsula of Michigan, USA.

	Treatment		Plot Count
Strip selection			25
Strip selection	+herbicide		4
Strip selection	+exclosure		3
Strip selection	+herbicide	+exclosure	2
Strip clearcut			43
Strip clearcut	+herbicide		19
Strip clearcut	+exclosure		9
Strip clearcut	+herbicide	+exclosure	2

2.3. Measurements

Pre-treatment data were collected during the 2015 field season and post-treatment data collected during the 2017 field season. Sapling (≥45.7 cm [i.e., 18 inches] tall, <15.4 cm [i.e., 6 inches] dbh) density was measured in each plot and tree seedling (<45.7 cm tall) density was measured in three square 1 m^2 fixed area subplots nested within each plot. All seedlings and saplings originated from natural regeneration (i.e., were not planted). The cover of broad functional groups including graminoids, ferns, forbs, and *Rubus* spp. was visually estimated in each subplot using four cover classes: 0%–25%, 26%–50%, 51%–75%, and 76%–100%. The large cover class sizes were a consequence of time and cost constraints, which are typical of operational-scale experiments. Cover classes were converted to respective midpoints prior to all analyses.

2.4. Data Analysis

To test the first and second hypotheses, the effects of harvest, herbicide, and exclosure on seedling densities were explored using linear mixed-effects statistical models, with dummy coding [44] (i.e., "treatment contrasts") for treatment factors [45,46]. This approach, using a regression framework rather than effect coding in classical ANOVA, readily accommodates unbalanced designs [47–49]. The statistical significance of treatment effects and interactions was determined by first fitting the full model (including all treatments and interactions) and then testing against a reduced model; if the explained variance was statistically significant then the group of terms was retained [47]. To account for subsampling and reduce the occurrence of zeros, seedling density was averaged among the three 1 m^2 subplots (n = 107) and site was included as a random effect to account for the nested design (i.e., blocked by site). We included pre-treatment stem density as a covariate to account for possible pre-treatment differences and test whether treatments actually changed stem densities. The same approach was used to test for treatment effects on sapling densities

(n = 107). Seedling and sapling densities were fourth-root transformed to meet normality and homoskedasticity assumptions. The tests were conducted using the lme function in the 'nlme' package of R 3.5.0 software [50] and fitted by the Satterthwaite test. Pairwise multiple comparisons were conducted with the 'emmeans' package [51] using Tukey's HSD correction.

To test the second hypothesis, the treatment effects on post-treatment *Rubus* spp. and graminoid cover were assessed in a mixed-effects regression framework as described above. Further, to examine the treatment effects on changing the composition of competing plant groups, the effects of harvest, herbicide, and exclosure on the change in plot (average of three 1 m^2 subplots) composition (2017 cover minus 2015 cover) of forbs, ferns, graminoids, and *Rubus* spp., were assessed with a permutational multivariate analysis of variance (PERMANOVA, adonis function in 'vegan' package of R 3.5.0 [52]), using Bray–Curtis distance matrices constrained within the sites (n = 107). Pairwise multiple comparisons were conducted with the pairwise.perm.manova function in the 'RVAideMemoire' package [53] using Holm's multiple comparison adjustment. Changes in composition from 2015 to 2017 were visualized with nonmetric multidimensional scaling (NMDS) ordination using Bray–Curtis distances. Three-axis ordinations were constructed with the *metaMDS* function in the 'vegan' package of R 3.5.0, with 999 iterations [52]. Variables were then fitted as vectors onto the ordination using the envfit function, and treatment groupings overlaid as ellipses using the standard deviation of point scores.

3. Results

3.1. Seedlings and Saplings

Sugar maple and hophornbeam were the two most frequently occurring species in the seedling size class (<45.7 cm tall), found in 69.2% and 42.1% of plots, respectively, prior to treatment and found in 44.9% and 29.0% of plots, respectively, post-treatment. Trembling aspen (*Populus tremuloides* Michx.) was found in 40.2% and 24.3% of pre- and post-treatment plots, respectively, while big-tooth aspen (*Populus grandidentata* Michx.) was found in 11.2% and 15.0% of pre- and post-treatment plots, respectively. Other species found in smaller frequencies included balsam fir (*Abies balsamea* (L.) Mill.) and red maple (*Acer rubrum* L.).

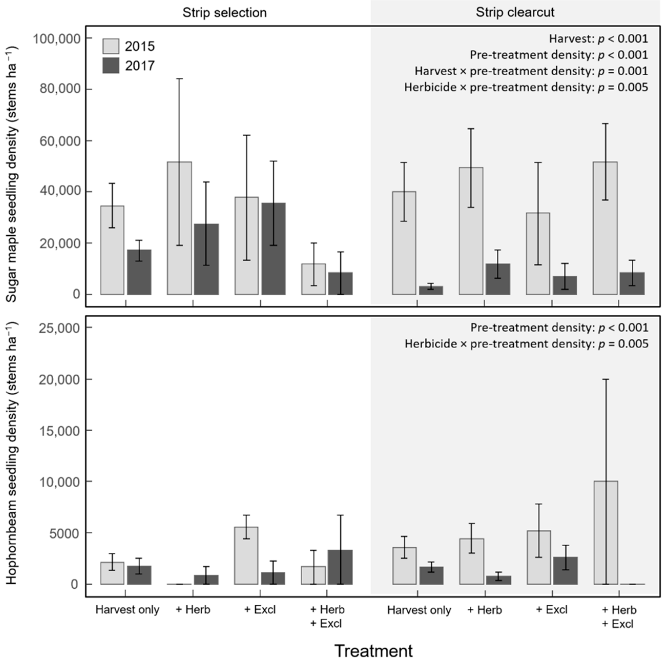
Sugar maple seedling density was negatively affected by strip clearcutting, especially in plots with higher pre-treatment seedling density ($F_{1,96}$ = 11.6, p = 0.001, Table 3, Figures 2 and 3). Herbicide generally favored sugar maple seedling density, but the effect was stronger in plots with higher pre-treatment seedling density ($F_{1,96}$ = 8.4, p = 0.005, Table 3, Figures 2 and 3). Herbicide negatively affected hophornbeam seedling density in plots with higher pre-treatment density ($F_{1,97}$ = 4.1, p = 0.045, Table 3, Figures 2 and 3). Mixed models also indicate that site differences introduced small random effects on seedling density (see marginal R^2 vs. conditional R^2, Table 3).

Sugar maple and hophornbeam were the two most frequently occurring species in the pre-treatment sapling size class (>45.7 cm tall, <15.2 cm dbh), found in 56.1% and 79.4% of plots, respectively. Post-treatment, sugar maple and hophornbeam saplings were found in 38.3% and 66.4% of plots, respectively, but trembling aspen saplings were found in 43.9% of plots. We continued our focus on sugar maple and hophornbeam, however, due to their contrasting commercial and browse values. Other species found in smaller frequencies included big-tooth aspen, balsam fir, and red maple.

Sugar maple sapling density was positively related to exclosure treatment ($F_{1,93}$ = 14.1, p < 0.001, Table 4, Figures 2 and 3), and a marginally significant harvest × herbicide × exclosure interaction effect ($F_{1,93}$ = 2.9, p = 0.090, Table 4) indicated that sugar maple sapling density was highest in herbicide strip clearcut plots within exclosures (Figure 2). However, herbicide had little effect in strip selection plots within exclosures (Figure 2). Mixed model regressions suggested that when pre-treatment sugar maple sapling density was lower than ~1500 stems ha^{-1}, such as the present study, the largest positive response of sugar maple sapling density was in strip clearcut exclosures receiving herbicide (Figure 3). Mixed models indicated that site differences introduced small random effects on sugar maple sapling density (see marginal R^2 vs. conditional R^2, Table 4).

Hophornbeam sapling density was related to all main treatments. Strip clearcut harvesting had a negative effect on hophornbeam sapling density ($F_{1,99} = 5.5$, $p = 0.021$, Table 4, Figures 2 and 3), as did herbicide ($F_{1,99} = 12.9$, $p < 0.001$, Table 4, Figures 2 and 3). In contrast, exclosures had a positive effect on hophornbeam sapling density ($F_{1,99} = 7.0$, $p = 0.009$, Table 4, Figures 2 and 3). No treatment interactions related to hophornbeam sapling density were detected.

a) Seedlings



b) Saplings

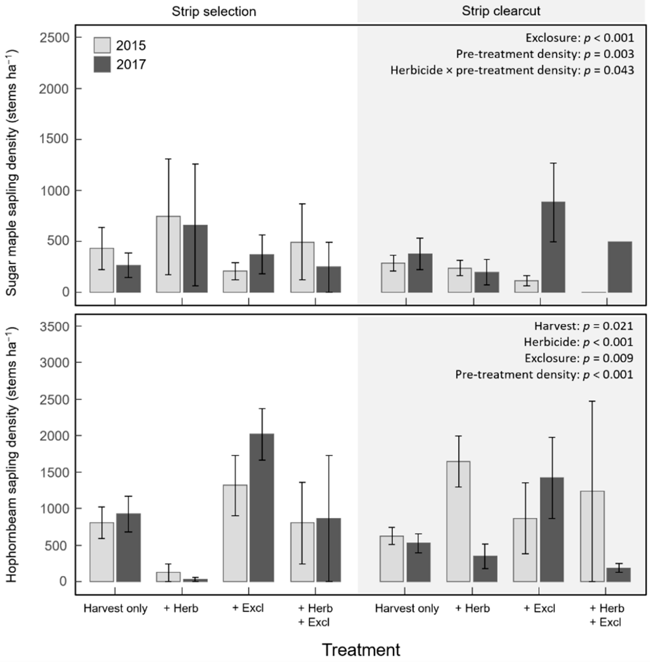


Figure 2. Sugar maple (*Acer saccharum* Marsh.) and hophornbeam (*Ostrya virginiana* ((Mill.) K. Koch) seedling (<45.7 cm tall) and sapling (>45.7 cm tall, <15.2 cm dbh) density among harvest, herbicide (Herb), and exclosure (Excl) treatments in a managed northern hardwood forest in the Upper Peninsula of Michigan, USA. Note the different *y*-axis ranges.

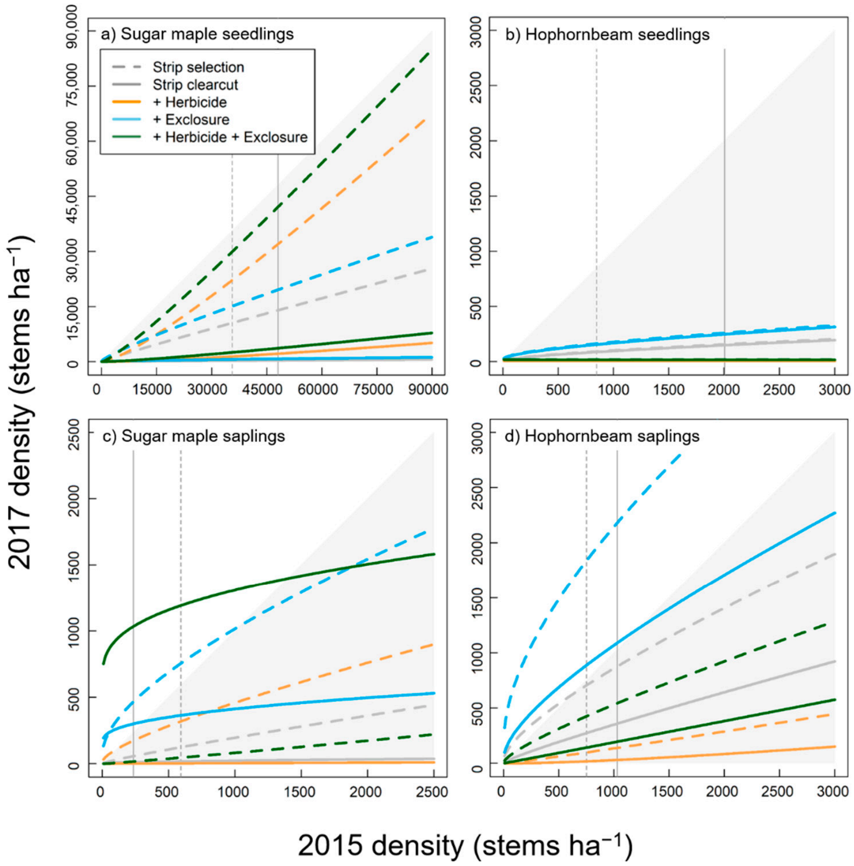


Figure 3. Mixed model regressions illustrating predicted sugar maple (*Acer saccharum* Marsh.) and hophornbeam (*Ostrya virginiana* ((Mill.) K. Koch) seedling (<45.7 cm tall) and sapling (>45.7 cm tall, <15.2 cm dbh) density among harvest, herbicide, and exclosure treatments in a managed northern hardwood forest in the Upper Peninsula of Michigan, USA. Regression lines falling within the gray area indicate lower 2017 density compared to 2015 density. Vertical lines indicate average measured pre-harvest density in selection (dashed) and clearcut (solid) strips. Note the different axis ranges.

Table 3. Mixed model effects of harvest, herbicide, exclosure, and pre-treatment density on sugar maple and hophornbeam seedling (<45.7 cm tall) density in managed northern hardwood forests in the Upper Peninsula of Michigan, USA. Density among three 1 m^2 subplots was averaged prior to analysis. The site was included as a random effect. Models first included all treatment interactions and were then simplified if no interaction effect was detected. Lower order interactions were retained if higher order interactions were statistically significant. * Asterisks indicate statistical significance ($p < 0.05$), italicized values indicate marginal significance ($0.05 < p < 0.10$). R^2_M, marginal R^2 (fixed effects only); R^2_C, conditional R^2 (fixed and random effects); Df_{num}, numerator degrees of freedom; Df_{den}, denominator degrees of freedom.

	Sugar Maple (*n* = 105)				**Hophornbeam (*n* = 105)**			
	R^2_M		R^2_C		R^2_M		R^2_C	
	0.544		**0.573**		**0.145**		**0.154**	
Predictor	**Df_{num}**	**Df_{den}**	**F-Value**	***p* Value**	**Df_{num}**	**Df_{den}**	**F-Value**	***p* Value**
Intercept	1	96	49.745	<0.001	1	97	32.576	<0.001
Harvest	1	96	34.658	<0.001 *	1	97	0.006	0.939
Herbicide	1	96	3.152	*0.079*	1	97	1.185	0.279
Exclosure	1	96	1.029	0.313	1	97	1.057	0.307
Pre-treatment (trt) density	1	96	57.132	<0.001 *	1	97	10.125	0.002 *
Harvest × Pre-trt density	1	96	11.606	0.001 *				
Herbicide × Pre-trt density	1	96	8.405	0.005 *	1	97	4.135	0.045 *

Table 4. Mixed model effects of harvest, herbicide, exclosure, and pre-treatment density on sugar maple and hophornbeam sapling (>45.7 cm tall, <15.2 cm dbh) density in 80.94 m^2 plots of managed northern hardwood forests in the Upper Peninsula of Michigan, USA. The site was included as a random effect. Models first included all treatment interactions and were then simplified if no interaction effect was detected (i.e., $p > 0.10$). Lower order interactions were retained if higher order interactions were statistically significant. * Asterisks indicate statistical significance ($p < 0.05$), italicized values indicate marginal significance ($0.05 < p < 0.10$). R^2_M, marginal R^2 (fixed effects only); R^2_C, conditional R^2 (fixed and random effects); Df_{num}, numerator degrees of freedom; Df_{den}, denominator degrees of freedom.

	Sugar Maple (n = 105)				**Hophornbeam (n = 106)**			
	R^2_M		**R^2_C**		**R^2_M**		**R^2_C**	
	0.262		**0.342**		**0.498**		**0.498**	
Predictor	**Df_{num}**	**Df_{den}**	**F-Value**	**p Value**	**Df_{num}**	**Df_{den}**	**F-Value**	**p Value**
Intercept	1	93	15.174	<0.001	1	99	318.380	<0.001
Harvest	1	93	1.924	0.169	1	99	5.527	0.021 *
Herbicide	1	93	1.119	0.293	1	99	12.876	<0.001 *
Exclosure	1	93	14.057	<0.001 *	1	99	7.045	0.009 *
Pre-treatment (trt) density	1	93	9.029	0.003 *	1	99	73.681	<0.001 *
Harvest × Herbicide	1	93	0.125	0.725				
Harvest × Exclosure	1	93	1.457	0.230				
Herbicide × Exclosure	1	93	0.125	0.724				
Harvest × Pre-trt density	1	93	4.195	0.043 *				
Harvest × Herbicide × Exclosure	1	93	2.945	*0.090*				

3.2. *Rubus* spp. and Graminoid Cover

Rubus spp. cover was higher in strip clearcut plots ($F_{1,100}$ = 5.3, p = 0.023, Table 5, Figure 4), but lower in plots which received herbicide ($F_{1,100}$ = 6.5, p = 0.013, Table 5, Figure 4), highlighting the ability of herbicide to dampen the spread of potential sugar maple competitors. Graminoid cover was influenced by the combined effect of harvest and exclosure treatments ($F_{1,99}$ = 5.6, p = 0.020, Table 5, Figure 4); exclosures had a positive effect on graminoid cover in strip selection plots.

Table 5. Mixed model effects of harvest, herbicide, and exclosure on post-treatment *Rubus* spp. and graminoid cover in managed northern hardwood forests in the Upper Peninsula of Michigan, USA. Cover among three 1 m^2 subplots was averaged prior to analysis. The site was included as a random effect. Models first included all treatment interactions and were then simplified if no interaction effect was detected. * Asterisks indicate statistical significance ($p < 0.05$). R^2_M, marginal R^2 (fixed effects only); R^2_C, conditional R^2 (fixed and random effects); Df_{num}, numerator degrees of freedom; Df_{den}, denominator degrees of freedom.

	***Rubus* spp. Cover (n = 107)**				**Graminoid Cover (n = 107)**			
	R^2_M		**R^2_C**		**R^2_M**		**R^2_C**	
	0.098		**0.179**		**0.257**		**0.328**	
Predictor	**Df_{num}**	**Df_{den}**	**F-Value**	**p Value**	**Df_{num}**	**Df_{den}**	**F-Value**	**p Value**
Intercept	1	100	420.080	<0.001	1	99	132.513	<0.001
Harvest	1	100	5.318	0.023 *	1	99	1.107	0.295
Herbicide	1	100	6.469	0.013 *	1	99	27.809	<0.001 *
Exclosure	1	100	0.057	0.812	1	99	2.096	0.151
Harvest × Exclosure					1	99	5.605	0.020 *

3.3. Composition

An exclosure × harvest interaction effect ($F_{1,106}$ = 3.120, p = 0.011, Table 6, Figure 5) indicated that the effect of exclosures on compositional change depended on harvest. Post-hoc tests, however, failed to detect pairwise differences, perhaps suggesting that the interaction effects may have been an artifact of small sample sizes. Changing composition was also marginally affected by a harvest × herbicide interaction ($F_{1,106}$ = 2.008, p = 0.077,

Table 6, Figure 5), highlighting the combined potential effects of canopy cover and herbicide on plant composition. Nonmetric multidimensional scaling ordination suggested that the change in composition of non-herbicide plots was driven more by changes in graminoid and *Rubus* spp. cover than ferns or forbs (Figure 5).

Table 6. Permutational multivariate analysis of variance (PERMANOVA) effects of silvicultural treatment on the change in composition (absolute value of 2017 minus 2015 cover) of ground-layer vegetation (forbs, ferns, graminoids, and *Rubus* spp.) in managed northern hardwood forests in the Upper Peninsula of Michigan, USA (n = 107). Response variables among three 1 m^2 subplots were averaged prior to analysis. * Asterisks indicate statistical significance (p < 0.05), italicized values indicate marginal significance (0.05 < p < 0.10). df, degrees of freedom; Sum. sq., sum of squares; Mean sq., mean square.

	df	**Sum. Sq**	**Mean Sq**	**F-Value**	R^2	p **Value**
Harvest	1	0.365	0.365	1.513	0.013	0.166
Herbicide	1	1.286	1.286	5.330	0.047	0.001 *
Exclosure	1	0.124	0.124	0.512	0.005	0.730
Harvest × Herbicide	1	0.485	0.485	2.008	0.018	*0.077*
Harvest × Exclosure	1	0.753	0.753	3.120	0.027	0.011 *
Residuals	101	24.377	0.241		0.890	
Total	106	27.389			1.000	

df, degrees of freedom; Sum. sq., sum of squares; Mean sq., mean square.

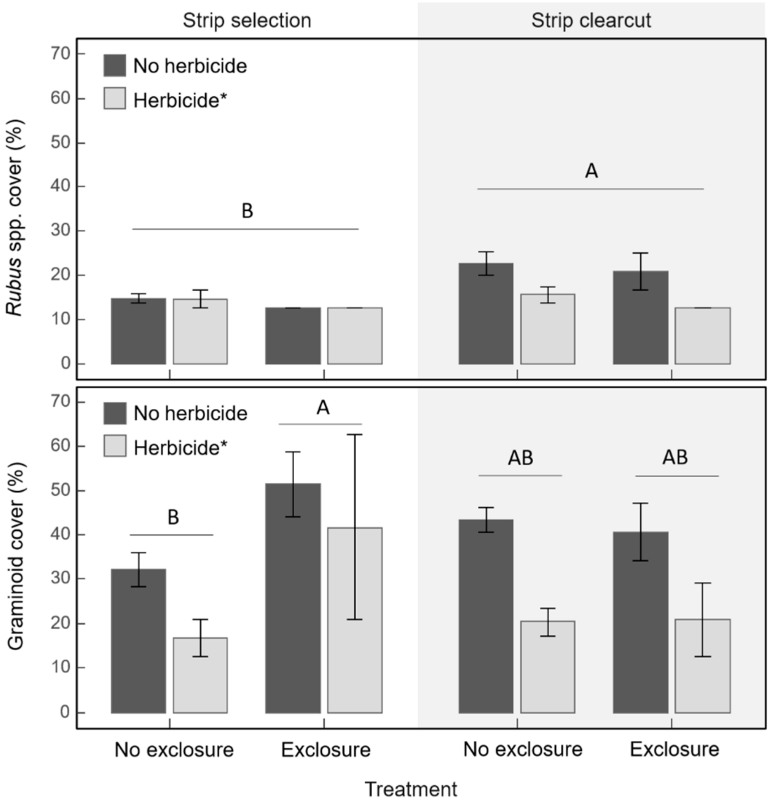


Figure 4. Average (±1 SE) *Rubus* spp. and graminoid cover among harvest, herbicide, and exclosure treatments in a managed northern hardwood forest in the Upper Peninsula of Michigan, USA. Cover among three 1 m^2 subplots was averaged prior to analysis (n = 107). Letters indicate significant differences among harvest or exclosure treatments within each cover type. * Asterisk indicates a significant herbicide effect.

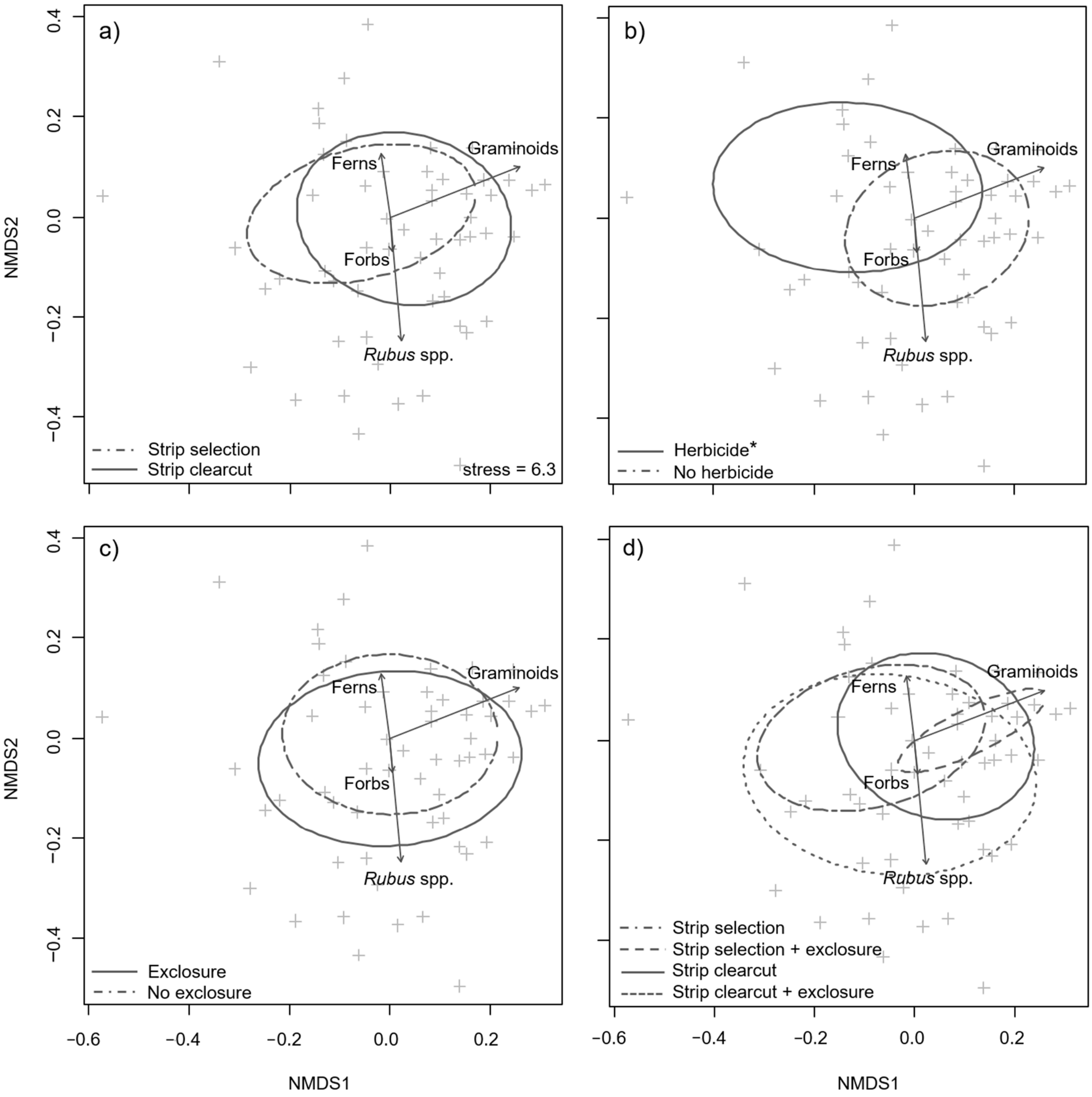


Figure 5. Nonmetric multidimensional scaling ordinations illustrating the relationships among treatments and changes in average cover (2017 cover minus 2015 cover) of ferns, forbs, graminoids, and *Rubus* spp. in 1 m^2 plots ($n = 107$ plots), depicting two axes of a three-axis ordination. Ellipses indicate (**a**) harvest, (**b**) herbicide, (**c**) exclosure, and (**d**) harvest × exclosure treatments, based on the standard deviation of point scores for each plot. Points represent individual plots, and distances between points represent the similarity among plots (i.e., points closer together are more similar in composition). Cover among three 1 m^2 subplots was averaged prior to analysis. The direction and length of each vector indicate the relative treatment influence on the response variables. One ordination model was constructed, and ellipses highlighted separately for each treatment. * Asterisk indicates a significant difference between herbicide and no herbicide plots ($p < 0.05$).

4. Discussion

In this study, we predicted that strip clearcuts along with herbicide and deer exclosures would promote sugar maple sapling recruitment more than strip selection harvesting in forests experiencing sugar maple sapling recruitment failure. Though sugar maple sapling densities were not related to harvest treatment alone, the addition of deer exclosures had a positive effect on sugar maple sapling density, while herbicide limited the cover of graminoids and *Rubus* spp. These results suggest that relief from browsing pressure is necessary for increasing sugar maple sapling recruitment after overstory removal, and further suggest that herbicide may help to dampen the spread of competing species.

4.1. Recruitment

Our first hypothesis was partially supported. We predicted that strip clearcuts, herbicide, and exclosures would promote seedling recruitment into the sapling size class but our findings suggest a more complex relationship among harvest, herbicide, exclosures, and recruitment. Sugar maple seedling densities declined overall following harvest, but seedlings in strip selection cuts coupled with exclosure treatments tended to remain unchanged, while seedlings in strip clearcuts declined regardless of exclosure or herbicide treatment. Seedlings in selection strips may have been buffered against mechanical damage from machinery, and harsh environmental conditions (e.g., compacted soil, wide temperature fluctuations, and high solar radiation) typically found in recent clearcuts [54], and consequently had higher survival rates. The decline in seedling density may also be partially explained by recruitment into the sapling size class following harvest.

Sugar maple sapling density was promoted in exclosures regardless of harvest treatment, though the large sapling size class used in this study may have masked the impacts of harvesting. Mixed model predictions suggested that exclosures in strip clearcuts combined with herbicide tended to benefit sugar maple sapling recruitment when density was less than ~1500 stems ha^{-1}, which is roughly two- to six-fold more than the pre-treatment sugar maple sapling density in this study (235 (±49) to 593 (±205) stems ha^{-1}). Though we did not differentiate saplings that derived from stump sprouting, the positive effect of exclosures remains an informative and relevant finding, and is widely supported by previous work in various forest types. For example, four decades of exclosure treatments in New Zealand *Nothofagus* (Blume)-conifer forests resulted in higher sapling recruitment compared to non-exclosure controls [14]. Moreover, Matonis et al. (2011) [4] concluded that deer browsing overrides the benefits of increased light availability on northern hardwood seedling and sapling densities in harvested gaps. Similarly, strip clearcutting in boreal Québec had little benefit to the growth of palatable species unless accompanied by deer exclosures [55]. Our present study corroborates these findings and indicates that strip harvesting must be accompanied by browsing reductions if forest managers aim to quickly increase the recruitment of desired species. However, despite the positive effect of exclosures in strip clearcuts, the average sugar maple sapling density in this study remained well below the minimum acceptable stocking levels.

In addition to deer browsing, the limited positive response of sugar maple sapling recruitment within strip clearcuts but outside exclosures was likely partially driven by inadequate advance regeneration in our stands prior to harvest. For example, approximately 32.7% of pre-harvest plots (i.e., average of three subplots) were completely devoid of sugar maple seedlings (though seedlings of other species may have been present), highlighting the many complications in recruiting sugar maple saplings in these stands. In contrast to species which maintain robust seedbanks for capturing resources following disturbances, sugar maple typically maintains abundant seedling banks (i.e., advance regeneration) [12], and previous work has demonstrated that adequate advance regeneration can out-compete mid-tolerant and intolerant species following a severe canopy disturbance. For example, Metzger [31] found that regeneration six and seven years following strip harvesting and herbicide application in northern hardwoods was driven by advance regeneration, and several group harvesting studies have found that sugar maple continues to dominate seedling and sapling layers in silvicultural systems designed to instead promote mid-tolerant species [56,57]. Lastly, our findings corroborate previous work demonstrating that canopy removal cannot single-handedly improve recruitment unless other factors, such as advance regeneration, are favorable [15,20,32]. Taken together, the present study suggests that inadequate advance regeneration contributes toward myriad obstacles to recruit sugar maple saplings in these stands.

In contrast to our hypothesis, hophornbeam sapling density was higher in exclosure plots when compared to plots outside exclosures. Given its reputation as an undesirable browsing species [37–39], we anticipated little effect of exclosures on hophornbeam sapling density. Our contradictory findings could suggest that deer have exhausted their preferred browsing sources and are consequently browsing species that are typically considered undesirable (i.e., hophornbeam). Significantly lower hophornbeam sapling densities in herbicide clearcut plots also indicate that hophornbeam may be more sensitive to herbicide and the harsh environmental conditions of clearcuts when compared to sugar maple. Lastly, the absence of interaction effects on hophornbeam sapling density suggests that its sensitivity to the treatments was not context-dependent in this study.

4.2. Graminoid and Rubus spp. *Cover*

Competition from graminoids or *Rubus* spp. can negatively affect seedling and sapling regeneration, and we anticipated similar interactions in our study. We further hypothesized that herbicide application would suppress *Rubus* spp. and graminoid cover and positively affect sugar maple recruitment into the sapling size class. Our hypotheses were partially supported; strip clearcuts tended to increase cover of *Rubus* spp., but herbicide dampened further spread of graminoids and *Rubus* spp. Though we found limited support for the positive effects of herbicide on sugar maple seedling and sapling density, the reduced cover of graminoids and *Rubus* spp. in strip clearcuts suggests that sugar maple seedlings may benefit from alleviated competition in subsequent growing seasons. Shields and Webster [58] similarly found that *Rubus* spp. cover increased with increasing light availability in harvest-created gaps, and northern hardwood studies have documented the persistence of *Rubus* spp. for over a decade following the creation of harvest gaps [17,59]. Long-lived and animal-dispersed seeds of *Rubus* spp., along with rhizomatous growth, may contribute to its ability to quickly colonize a recently disturbed site [19], and the rhizomatous growth strategy of Pennsylvania sedge (a major component of our 'graminoid' functional group) similarly promotes rapid colonization [21]. Dominant understory layers following a canopy disturbance can have detrimental effects on regeneration in forests worldwide [5], but our findings suggest that one-time herbicide application may temporarily alleviate competition from graminoids in northern hardwoods. However, Randall et al. (2019) [20] found that reduced sedge cover after herbicide application increased the vulnerability of maple seedlings to browsing, suggesting that herbicide may need to be combined with treatments that reduce browsing in areas with high browsing pressure. Further assessments at our study site will help determine if one-time herbicide application has long-term benefits.

We found no relation between exclosures and *Rubus* spp. or graminoid competition in the two-year time frame of this study, but previous work has shown differing results. For example, Trumball et al. [60] found that deer browsing caused a decline in *Rubus* spp. and concurrent increase in graminoid competition 13 years following the creation of 1-acre (~0.41 ha) exclosures. Moreover, Powers and Nagel [6] found that Pennsylvania sedge cover was generally related to higher deer densities in northern hardwood forests, though it varied with management history.

4.3. Composition

We anticipated that potential changes in composition of broad functional groups would be more related to herbicide treatment when compared to harvest or exclosure treatments, and our results support this hypothesis. Though unaffected by harvest treatment, diverging plot composition from 2015 to 2017 was strongly affected by herbicide treatment and largely driven by the changing cover of graminoids and *Rubus* spp. However, we found an interaction effect between harvest and exclosure treatment, indicating that exclosures within strip selection cuts tended to favor compositional change driven by increasing graminoid cover, while exclosures within strip clearcuts tended to favor compositional change driven by increasing *Rubus* spp. cover. It should be noted, however, that the coarse resolution we used to survey plant communities in the present study likely overlooked more nuanced changes in composition that others have found. For example, Kraft et al. [61] found that plant species cover was more related to harvest than deer exclosures, likely owing to changing light environments. Moreover, in another Upper Peninsula northern hardwood forest, Hupperts et al. [62] found that changing plant species composition was linked to harvest treatment, and was largely driven by diverging composition between patch clearcut and selection harvesting after only two years.

5. Study Limitations

Several limitations of our study design are characteristic of operational-scale experiments, and are the consequence of cost and time constraints. First, time lags among treatment applications along with limited replication for some treatments may have restricted our ability to detect the real effects of treatment combinations, especially harvesting combined with herbicide and exclosure, which may hinder overgeneralizations. Our findings, however, are reinforced by similar studies in northern hardwoods [4,17], which lends support to our conclusions. Further, our statistical approach readily accommodates unbalanced designs, meaning that our inferences are supported by sound statistical techniques. Second, the short-term nature of this study may not reflect outcomes at longer time scales that are relevant to forest managers. Nevertheless, in a similar northern hardwood forest, [32] found that seedling and sapling density two years after silvicultural gap creation was correlated with densities 21 years later, suggesting that early regeneration trends may influence long-term stand dynamics. However, longer-term monitoring will be necessary to fully evaluate the effectiveness of these silvicultural treatments. Third, the primary objective of this study was to compare strip clearcuts to strip selection harvests, for which edge effects are an inherent feature. Consequently, our results must be interpreted with caution when applied to block or stand-scale harvesting.

6. Conclusions

In this study, we tested the use of strip clearcuts, herbicide, and deer exclosures to quantify the effects of overstory, competition, and browsing pressure, respectively, on sugar maple sapling recruitment in a sugar maple-dominated northern hardwood forest with a history of recruitment failure. We found that exclosures promoted sugar maple sapling recruitment, but exclosures in strip clearcuts combined with herbicide may be beneficial when sugar maple sapling density is less than ~1500 stems ha^{-1}. Taken together with other work in northern hardwoods, this study reinforces the hypothesis that harvesting must be combined with additional techniques to promote recruitment of desired species in areas with high deer abundance. Though our findings show promise for addressing sugar maple sapling recruitment failure due to browsing pressure and competing vegetation, continued observation will be necessary for a more comprehensive assessment of recruitment dynamics in this novel silvicultural experiment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13071149/s1, Table S1: White-tailed deer (*Odocoileus virginianus* Zimmerman) harvested in the Upper Peninsula of Michigan from 2006–2015.

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