Relationships between forest management and environmental and vegetation variables in the Niagara Escarpment of Hiawatha National Forest, Michigan

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Cover: Northern hardwood forest canopy in Hiawatha National Forest. Photo by D.L. Cuthrell.

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EXECUTIVE SUMMARY

Hiawatha National Forest (HNF) contains a portion of the Niagara Escarpment, a limestone geologic formation that provides habitat for several rare fern and snail species. Several of these species are considered regional forester sensitive species (RFSS) by the HNF. In 2009, HNF prepared an Environmental Impact Statement (EIS) to evaluate alternatives for managing the 64,000-acre Niagara Project area. The selected management alternative included a monitoring plan to understand the changes that may occur within karst features following three management options: Option 1 – full karst protection, Option 2 – high shade retention, and Option 3 – normal shade retention. The hypothesis was there would be no significant difference in light intensity, ground temperature, relative humidity, and moss cover between treated and untreated sites. Michigan Natural Features Inventory (MNFI) was contracted by the HNF to implement the monitoring plan, analyze the results, and present our findings in this report.

We designed the monitoring to compare microclimate and vegetation variables between managed and reference stands. In addition to using nearby mature managed forest stands as a control for treated sites, we also added reference sites containing occurrences of the rare fern and snail species of concern. The monitoring plan called for sampling treated sites during the first, second, and fifth years after winter harvest. Because the Option 3 areas were not harvested in time for sampling, we only were able to evaluate Options 1 and 2 after treatment. We installed two data loggers at each site: one data logger was placed at the top of the cliff or boulder and recorded temperature and light intensity, and the second data logger was placed at the ground surface and recorded temperature and relative humidity. Data loggers recorded hourly measurements from mid-July to mid-August. We used circular, 11.3-m radius plots (0.1-acre) to measure tree and subcanopy density for dominant species, percent canopy closure, basal area, and coarse woody debris. Three 1-m^2 quadrats were sampled within each circular plot along the cliff/boulder face where rare ferns/snails were most likely to occur to estimate percent cover of bare soil, bedrock, moss, and ferns by species. We conducted univariate analyses using mixed models to compare among treatment categories and multivariate analyses using nonmetric multidimensional scaling and multiple permutation procedures.

This project gathered microclimate and vegetation structure data from 38 forested sites, including known locations of RFSS fern and snail occurrences, over nine years. We compiled and analyzed more than 110,000 hourly records of humidity, temperature, and light intensity, and vegetation data from 124 11.3-m radius (0.1-acre) plots and 395 1-m^2 quadrats. Environmental variables differed among our reference and treatment types; however, the patterns were inconsistent and varied over years. We found treated sites tended to have lower humidity and greater surface air temperature compared to references, but some of those differences were present both before and after treatment. Harvest appeared to increase light intensity at Option 2 sites compared to pretreatment and references, but those differences seemed to disappear by the fifth year of sampling. We consistently observed similar humidity, temperature, and light intensity between our element occurrence and mature managed references, which suggests that microclimate changes caused by forest treatments are temporary. As expected, we observed a significant reduction in canopy closure and basal area in Option 2 after harvest,

whereas there was no difference in Option 1 compared to pretreatment and reference values. These results combined with light intensity data indicate Option 1 was successful in shade retention around karst features. We did not observe consistent patterns between reference and treated sites in the canopy and subcanopy density variables. Percent cover of moss at treated sites was similar between pretreatment and reference sites.

Monitoring results indicated the two management prescriptions evaluated resulted in some changes to the microclimate and vegetation structure, though it remains unknown if the level and duration of change would be detrimental to the rare species of concern. Given the limited effects observed during post-harvest sampling, Option 1, the full karst protection management prescription, appears to be a reasonable approach to protecting these unique environments. This project provided valuable information about the habitats used by rare fern and land snails in Hiawatha National Forest. We also gathered important baseline microclimate and vegetation data that could be used to monitor the long-term effects of management and other forest changes caused by pests, disease, or climate change.

INTRODUCTION

In 2009, Hiawatha National Forest (HNF) developed an Environmental Impact Statement (EIS) to evaluate alternatives for managing the 64,000-acre Niagara Project area located in the East Unit of the Forest (HNF 2009a). The project area includes a portion of the Niagara Escarpment, a dolomitic limestone formation, and some of its characteristic features, such as fissures, cliffs, and boulder fields. These limestone features provide unique habitats for several rare plant and animal species, including two regional forester sensitive species (RFSS) of plants (*Asplenium trichomanes ramosum*, and *A*. *rhizophyllum*) and four RFSS snail species (*Euconulus alderi*, *Vallonia gracilicosta*, *Vertigo bollesiana*, and *V*. *paradoxa*). As part of Alternative 2, the selected alternative in the final Niagara EIS, the HNF developed a monitoring plan to understand the changes that may occur within karst features following forest management. Three forest treatments were incorporated into the monitoring plan. Full karst protection, or Option 1, aimed at protecting limestone cliffs, ledges, alvar, outcrops, and boulder fields by creating a 100-ft buffer from the edge of the features in all directions. Road work, logging, and earth disturbance were prohibited in this buffer area (HNF 2009b). Two treatments, high shade retention and normal shade retention, allowed for reduced karst protection. Option 2 (high shade retention) provided for selection harvest around most limestone features that emphasized reduced levels of canopy removal. If canopy gaps are created for tree regeneration, they were to be limited to about 30 ft in diameter. Stocking level after harvest would be about 70-110 ft^2 and residual trees would be evenly spaced. Option 3, or normal shade retention, called for normal levels of canopy removal (HNF 2009b). Under this treatment, gaps created for tree regeneration would be limited to 50-75 ft in diameter and the stocking level after harvest would be 50-80 ft^2, with residual trees having a patchy distribution. The stated objective of the monitoring plan was to compare microhabitat conditions of karst features among the three harvest treatments and untreated sites.

The hypothesis on the plan was there is no difference in light intensity, ground temperature, relative humidity, and moss cover between treated and untreated sites (HNF 2009b). These microhabitat conditions were selected because they are known to be important to the RFSS of concern associated with the Niagara Escarpment. Although the base of research within northern hardwood/mesic northern forests in North America is limited, several studies have documented microclimate changes associated with timber harvest and fragmentation across a range of forest types, such as increased air and soil temperatures (Barrett et al. 1962, Liechty et al. 1992, Zheng et al. 2000, Stewart and Mallik 2006, Brooks and Kyker-Snowman 2008, Kermavnar et al. 2020), reduced humidity (Stewart and Mallik 2006, Kermavnar et al. 2020), and greater light intensity/availability (Zheng et al. 2000, Scheller and Mladenoff 2002, Stewart and Mallik 2006, Batori et al. 2021).

Michigan Natural Features Inventory (MNFI) was contracted by the HNF to implement the Niagara monitoring plan, analyze the results, and present our findings in a final monitoring report. We designed the long-term monitoring project, which spanned nearly a decade, to achieve the objectives of the HNF's monitoring plan. In addition to comparing conditions of treated stands with untreated mature managed forests nearby, we added additional reference sites in mature northern hardwoods containing known element occurrences of rare ferns and snails within MNFI's Natural Heritage Database (MNFI 2022). These element occurrence (EO) references served as examples of suitable habitats for rare species associated with karst features.

METHODS

Monitoring Design

We designed the monitoring to allow comparison of variables between managed and reference stands. Two types of references were used: 1) mature mesic northern forest within HNF containing rare fern or snail element occurrences (EO sites; Table 1); and 2) mature managed mesic northern forest stands near the treatment sites. The study was designed to compare three management regimes: Option 1 – full karst protection; Option 2 – high shade retention; and Option 3 – normal shade retention. We also designed the project to compare conditions of the managed stands before and after harvest, with sampling planned to occur during the growing season before winter treatment and during the first, second, and fifth growing seasons after treatment (Table 2). Actual sampling differed from the original design due to administrative delays in completing planned harvests. Although Option 2 treatment and sampling proceeded as planned, Option 1 harvest was delayed by two years and Option 3 treatment was not completed during the project period.

Table 1. Occurrence records of RFSS fern and snail species at element occurrence (EO) reference sites sampled in Hiawatha National Forest during 2011-2018.

EO Reference	RFSS Present		Status[1]	EO ID Number	Year Last Observed
	Scientific Name	Common Name			
Sites 1 & 2	*Asplenium rhizophyllum*	Walking fern	T	9203	1994
Sites 1 & 2	*Asplenium viride*	Green spleenwort	SC	11930	2000
Sites 1 & 2	*Vertigo cristata*	Crested vertigo	SC	8773	1998
Sites 1 & 2	*Vertigo paradoxa*	Mystery vertigo	SC	8968	1998
Site 3	*Vertigo bollesiana*	Delicate vertigo	T	18884	2010
Site 4	*Asplenium viride*	Green spleenwort	SC	NA	new
Site 4	*Euconulus alderi*	Land snail	T	17551	2008
Site 5	*Vertigo paradoxa*	Mystery vertigo	SC	17553	2008
Site 6	*Asplenium viride*	Green spleenwort	SC	2656	2010
Site 7	*Asplenium rhizophyllum*	Walking fern	T	9953	2010
Site 8	*Asplenium rhizophyllum*	Walking fern	T	NA	new

[1]T = state threatened, and SC = state special concern.

Table 2. Planned study design and actual sampling completed by year and treatment within mesic northern forest of Hiawatha National Forest. Gray shaded cells indicate sampled years, with dark gray cells denoting sampling occurring after winter forest treatment.

Year	Element Occurrences		Mature Reference		Option 1		Option 2		Option 3	
	Planned	Actual	Planned	Actual	Planned	Actual	Planned	Actual	Planned	Actual
2011										
2012										
2013										
2014										
2015										
2016										
2017										
2018										
2019										

Vegetation and Environmental Sampling

With the help of HNFS staff, we selected forested sites that were scheduled for harvest within three treatment options. Then within the forested stands, we randomly traversed the landscape until locating either low limestone rock outcroppings or boulders, which are needed microhabitats for the RFSS target species. We spaced the data loggers so that no circular plots would overlap. Plots within mature managed reference sites were established in adjacent, untreated stands with similar aspect, slope, and elevation (Figure 1).

We sampled circular, 11.3-m radius plots (0.1-acre; James and Shugart 1970) for tree and subcanopy density, percent canopy closure, basal area, and coarse woody debris. Tree density and composition was measured in two categories: tree (dbh ≥ 3.5 in) and subcanopy (dbh < 3.5 in). The species and dbh (to nearest cm) were recorded for each tree within the plot. We counted the number of trees in the subcanopy by species within the plot. Percent canopy closure was estimated along the cardinal directions from the plot center. Ocular tube readings of canopy conditions were taken at paced intervals (~1 m) five times in each cardinal direction. The ratio of hits to misses in the ocular tube gave the percentage canopy cover for that plot. We estimated total basal area of each plot using a sweep of a 10x prism.

Within each 11.3-m radius plot, we sampled three 1-m² quadrats along the cliff/boulder face where rare ferns typically would be growing, or rare land snails were likely to occur (Figure 2). Percent cover of bare soil, bedrock, moss, and ferns by species were estimated for each quadrat. The amount of coarse woody debris (CWD) was assessed on a scale of 1-5, with a ranking of 1 having CWD as absent or limited to small diameter (<20 cm, 8 in) and of early successional species composition. A moderate level (3) had trees ranging from 20-50 cm (8-20 in) DBH, species including shade-intolerant, mid-tolerant, and tolerant and/or a range in stages of decay. Plots with high levels of CWD (ranking of 5) had many trees >50 cm DBH with largely late-successional species composition and a full range in stages of decay. Coarse woody debris rankings of 2 and 4 were intermediate between the major three classes.

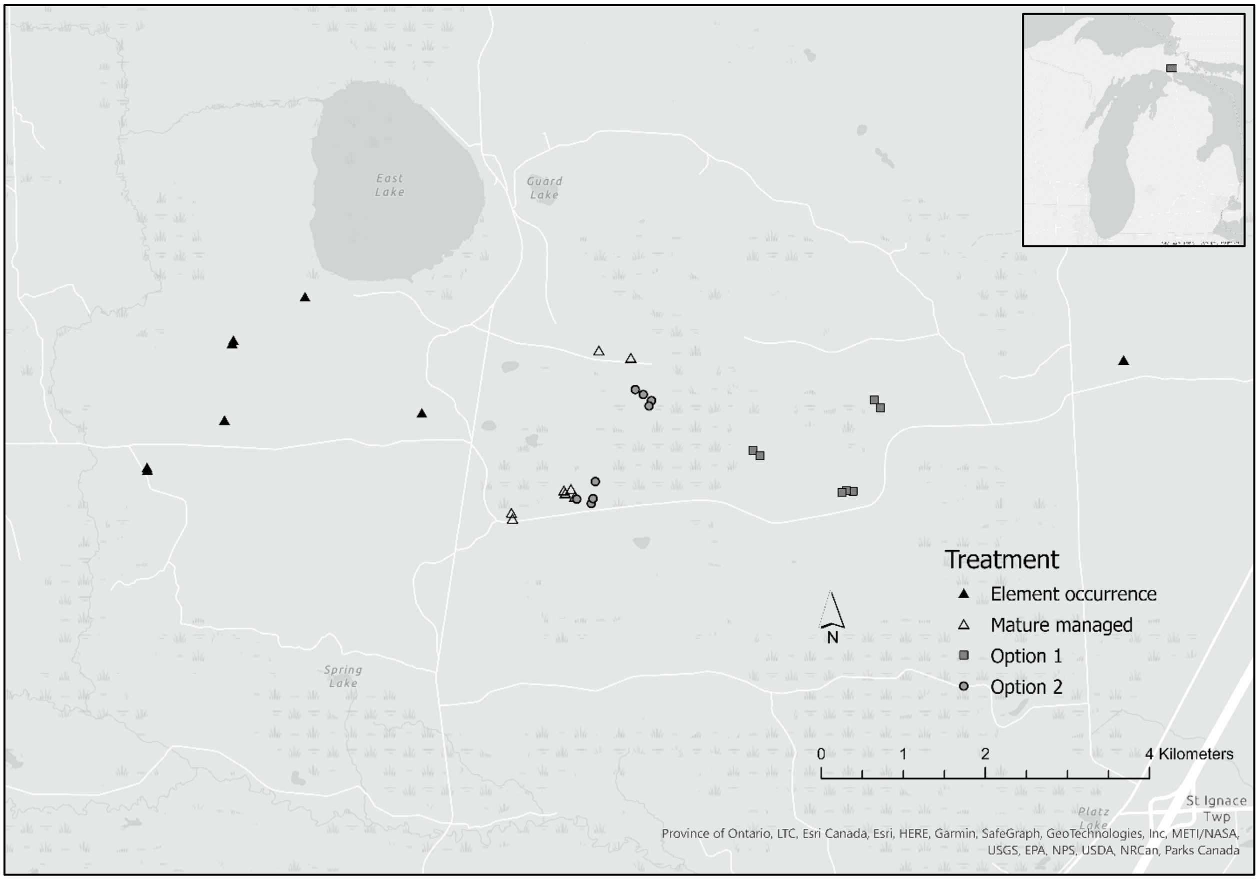


Figure 1. Location of sampling sites for Niagara monitoring within Hiawatha National Forest.

Figure 2. Example of a sample site used to gather data on microclimate and ground cover within Hiawatha National Forest.

To assess how microclimate conditions within karst features might be affected by vegetation management, we installed data loggers in each plot to measure light intensity, ground temperature, and relative humidity to facilitate comparisons among treated and untreated sites. Two data loggers were placed at each site at the plot center. One data logger placed at the top of the cliff or boulder recorded temperature and light intensity (Figure 2), whereas a second data logger placed at the base recorded both temperature and relative humidity. We set the data loggers to record hourly measurements from about mid-July to mid-August. This period was selected because it represented the peak in canopy cover (HNF 2009b).

Analysis

Environmental Variables

We compared humidity, surface temperature, elevated temperature, and mean light intensity between old-growth reference, mature managed reference, Option 1, Option 2, and Option 3 stand types to assess the potential effects of forest treatment on environmental variables sampled using data loggers. Analyses were conducted in the following ways: 1) pooled "before" comparison by treatment (element occurrence [EO], mature managed [MM], and Options 1-3 before); 2) pooled "after" comparison by treatment (EO, MM, Option 1 [O1] and Option 2 [O2] after); 3) pooled comparisons among references and treatment periods (EO, MM, O1 and O2 before, and years 1, 2, and 5 after); 4) within-year comparisons by treatment (i.e., years with multiple treatments sampled [2012-2019]). Comparisons were made using mixed models (PROC MIXED, SAS Institute, Cary, NC) consisting of treatment as a fixed effect and year as a random effect for multiyear models. We used a repeated measures component to account for hourly sampling within at the same locations in all models. We used three covariance structures to model associations among the repeated measures, variance components, autoregressive order 1, and compound symmetric (Littell et al. 1996, Kincaid 2005), and selected the best-approximating model using Akaike's Information Criterion (AIC). When residuals from analyses conducted with untransformed data were not normally distributed, we reanalyzed using transformed data. We log transformed arcsine-square root (arcsin$\sqrt{x}$) transformed relative humidity and used the box-cox transformation for light intensity data ($x^{0.2}$-1/0.2).

Vegetation

Data from vegetation sampling were compared among the following treatment categories: reference, control, pre-harvest Option 1, pre-harvest Option 2, post-harvest Option 1, and post-harvest Option 2. We compared the following variables among the treatment categories: mean basal area (ft^2/acre), percent canopy closure, canopy densities (American beech [*Fagus grandifolia*], balsam fir [*Abies balsamea*], sugar maple [*Acer saccharum*], and snags), and subcanopy densities (balsam fir, sugar maple, and snags). For canopy and subcanopy densities, we only analyzed those species/groups detected at one third (33%) or more plots. Comparisons were made using a mixed model with treatment as a fixed effect and year and site as random effects. We compared percent cover of rock and moss estimated using a mixed model consisting of treatment as a fixed effect and year, site, and plot as random effects. If residuals from analyses conducted with untransformed data were not normally distributed, we reanalyzed using transformed data. Percent canopy closure and percent cover variables were arcsine-square root (arcsin$\sqrt{x}$) transformed and densities were log transformed ($\log_e[x+1]$).

Multivariate Analyses
We used nonmetric multidimensional scaling (NMS) to explore possible patterns among our treatments in environmental and vegetation variables. Stands were assigned to the following treatment categories: old-growth reference, mature managed reference, pre-treatment (Options 1, 2, and 3 combined), post-treatment Option 1, and post-treatment Option 2. Those variables recorded on less than 20% of the sites were removed. Prior to analysis, we conducted a Pearson correlation matrix (PROC CORR, SAS Institute, Cary, NC) to examine potential collinearity among our variables. Variables were removed when $r > 0.60$, leaving a final set of 21 variables for analysis (Table 3). We performed NMS using the Bray-Curtis distance measure, 250 runs on the original data matrix, and a maximum of 500 iterations. A final solution was achieved when an instability value of 0. 0000001 was obtained or after 500 iterations. A Monte-Carlo permutation procedure (McCune and Grace 2002) was conducted with 250 randomized runs to evaluate if axes produced by NMS explained more variation than by chance alone.

Table 3. Final set of variables used in multivariate analyses.

Variable Type	**Vegetation Stratum**	**Variable Description**
Environmental	---	Elevated temperature (°C)
		Relative humidity
		Mean light intensity (lum/ft^2)
Vegetation	Canopy	Basal area (ft^2/acre)
		Percent canopy closure
		American basswood density
		American beech density
		Northern white cedar density
		Sugar maple density
		Yellow birch density
	Subcanopy	American beech density
		Balsam fir density
		Ironwood density
		Sugar maple density
		Snag density
		Shrub density
	Ground cover	Bare soil percent cover
		Bedrock percent cover
		Coarse woody debris percent cover
		Moss percent cover
		Total vegetation percent cover

We conducted multi-response permutation procedures (MRPP) to test for differences in the environmental and vegetation variables among the treatment categories. Bray-Curtis distance measures and natural weighting ($n_i/\Sigma n_i$; Mielke 1984) were used in the MRPP analysis. We tested for differences among all five categories and then completed pair-wise MRPP comparisons of all possible pairs of the treatment categories. Multivariate analyses were completed using PC-ORD v.6.22 (McCune and Mefford 2011).

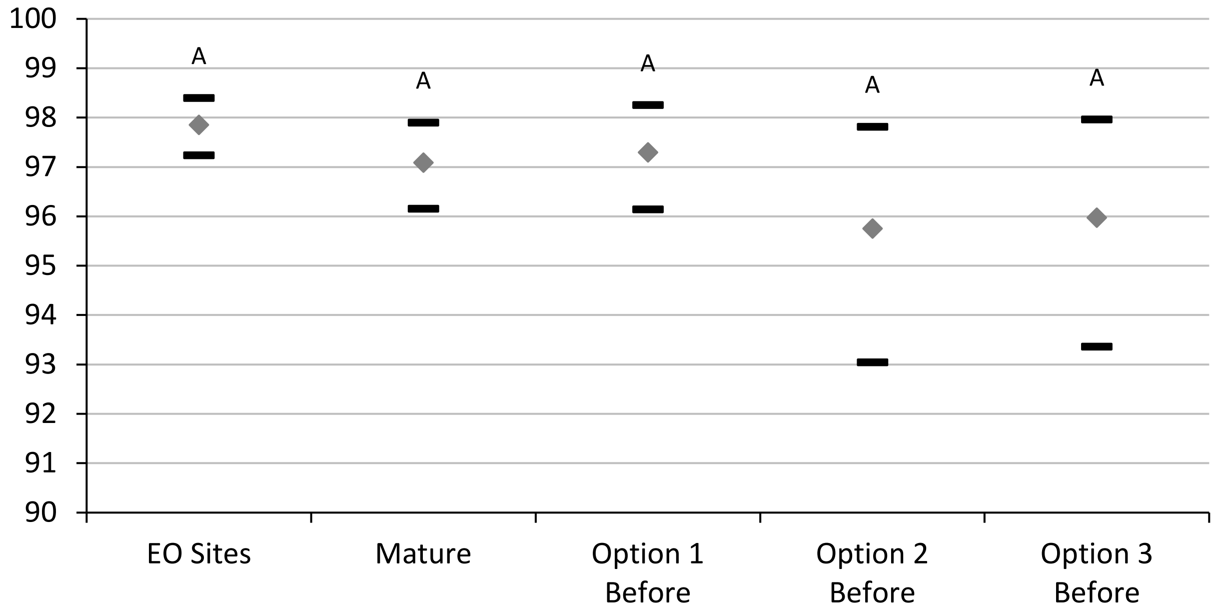
RESULTS

Environmental Variables

We analyzed over 100,000 hourly measurements of humidity, temperature, and light intensity spanning 38 sample sites, five treatment categories, and nine years. Mean relative humidity was similar between reference sites and treated stands prior to harvest, but Option 1 and 2 sites had lower average relative humidity than element occurrence references after treatment (Figures 3). For both treatments, humidity was lower than references during the second and fifth year after harvest (Figure 4). When making annual comparisons of relative humidity, there was no consistent pattern in humidity between treated and reference stands, with treated sites being lower than reference prior to harvest in some years and Option 1 stands similar in years 1 and 2 after harvest (see Appendix A, Figure A-1).

Average surface air temperature at Option 1 stands was similar to reference sites before harvest but greater after treatment (Figure 5). Conversely, surface air temperature at Option 2 sites was greater than reference stands before treatment but similar after harvest. Comparisons among treatment periods indicated Option 1 sites were similar to references during year 1 post-harvest but greater during years 2 and 5 after treatment, whereas Option 2 stands were greater than references before treatment and during year 5 post-harvest but similar during years 1 and 2. (Figure 6). In annual analyses, Option 1 sites had greater surface air temperatures than reference stands in one of three years sampled prior to treatment, had similar temperatures to references in years 1 and 2 post-harvest, and greater temperatures than the mature reference during the fifth year after treatment (Appendix A, Figure A-2). Mean surface air temperatures for Option 2 sites were greater than reference stands in all years sampled both before and after treatment.

Elevated air temperatures appeared more variable compared to air temperatures measured at the ground surface but the patterns were consistent. Prior to treatment, Option 1 and 2 sites had similar elevated air temperatures to reference stands. After treatment, Option 1 stands had greater temperatures compared to reference sites, whereas Option 2 stands had similar temperatures to references (Figure 7). When comparing by treatment period, Option 1 sites were similar to references during year 1 post-harvest but greater during years 2 and 5 after treatment (Figure 8). Option 2 sites had similar temperatures during years 1 and 2 but greater mean temperatures than references both before and the fifth year after harvest (Figure 8). In annual comparisons of elevated air temperatures, both Option 1 and 2 sites had similar temperatures compared to reference stands before harvest. Option 2 sites had greater means than reference stands during 2 and 5 years after treatment, whereas Option 1 stands only had greater temps than references during year 5 post-harvest (Appendix A, Figure A-3).



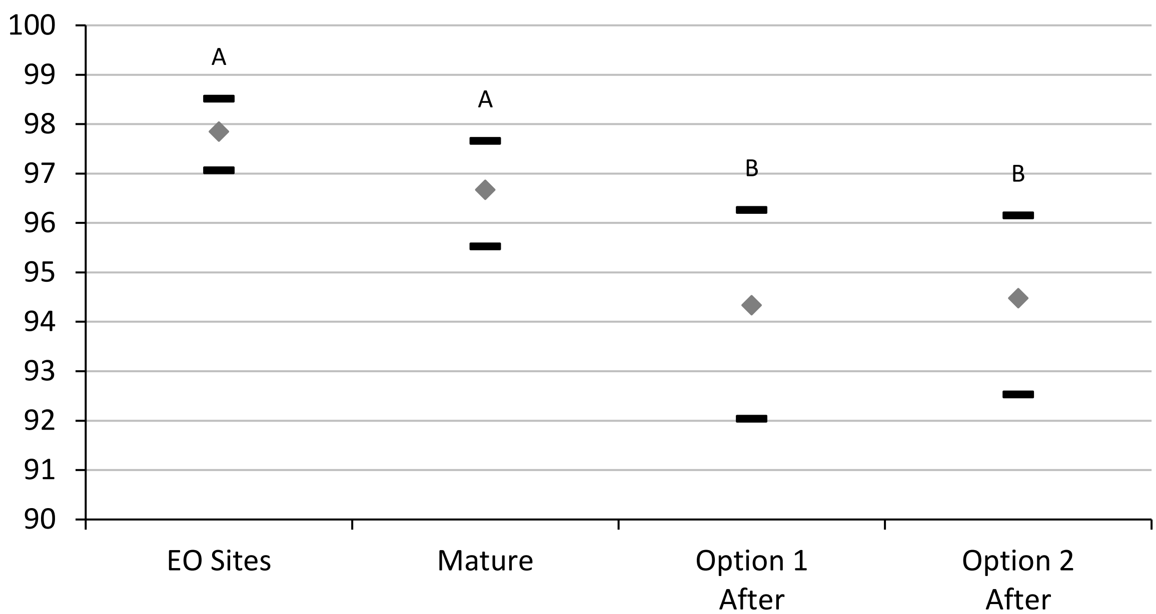
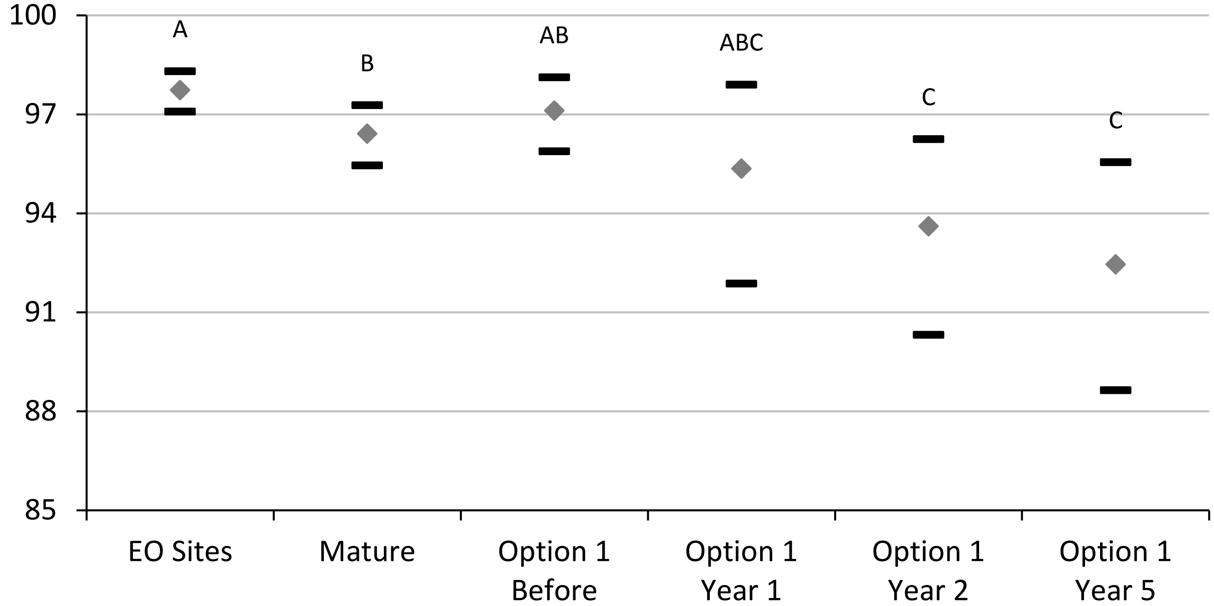


Figure 3. Comparison of mean hourly percent relative humidity between reference (element occurrence sites and mature managed stands) and treatment sites before and after harvest within Hiawatha National Forest during 2011-2019. Bars indicate upper and lower 95% confidence limits. Estimates labeled with the same letter were not significantly different (P > 0.05).



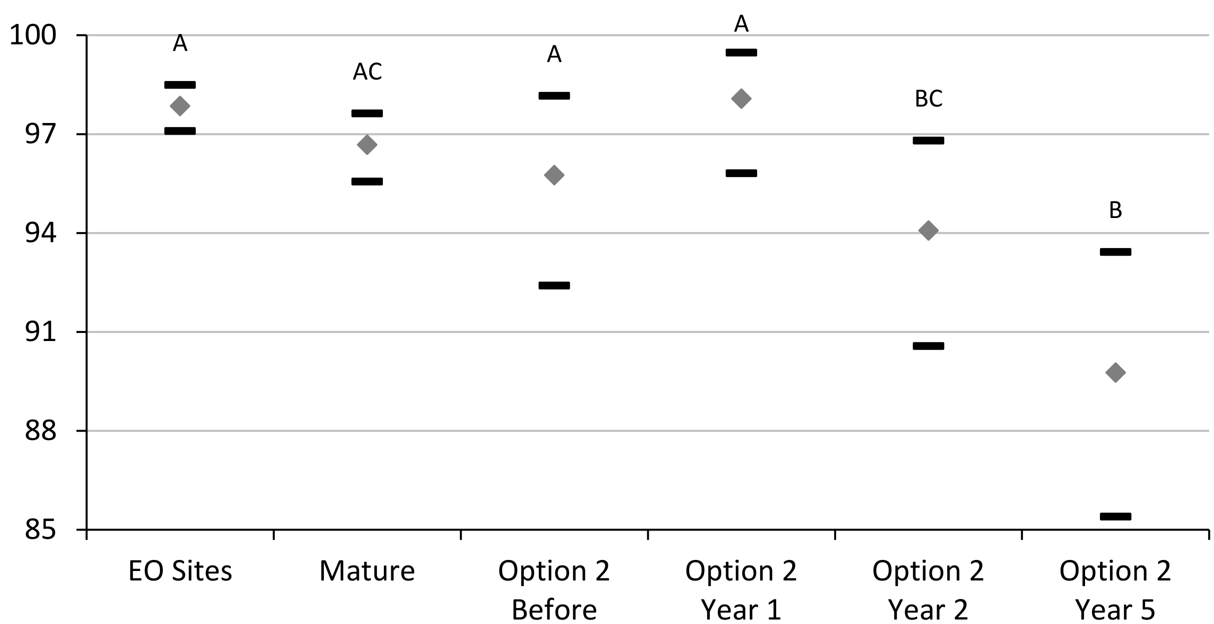
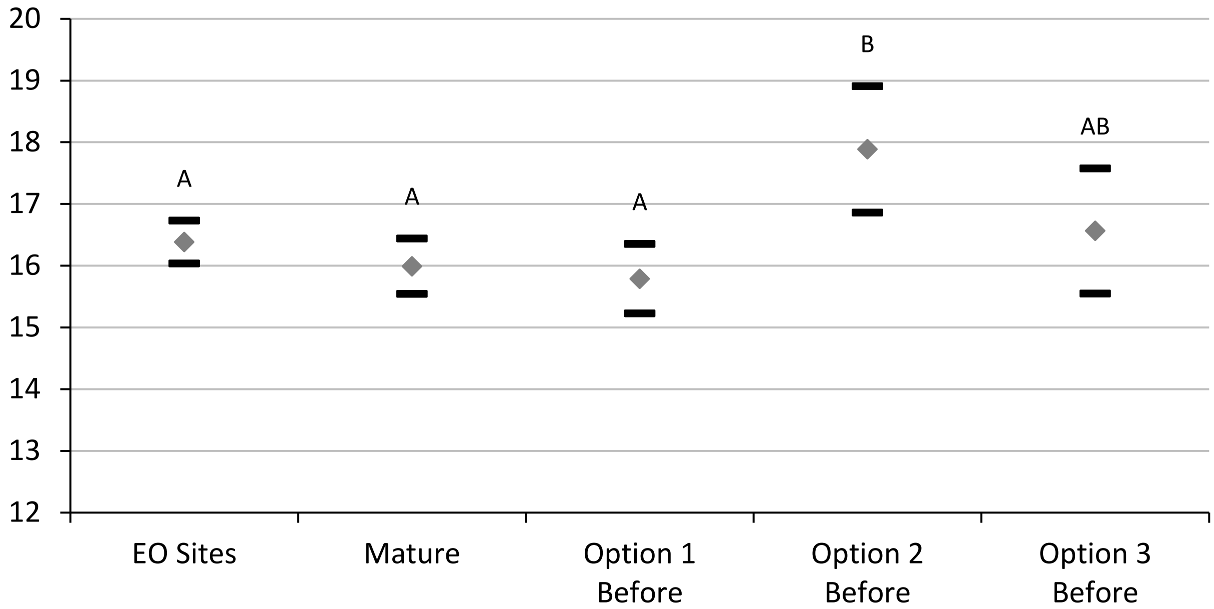


Figure 4. Comparison of mean hourly percent relative humidity between reference (element occurrence sites and mature managed stands) and Option 1 and 2 sites by treatment period within Hiawatha National Forest during 2011-2019. Bars indicate upper and lower 95% confidence limits. Estimates labeled with the same letter were not significantly different (P > 0.05).



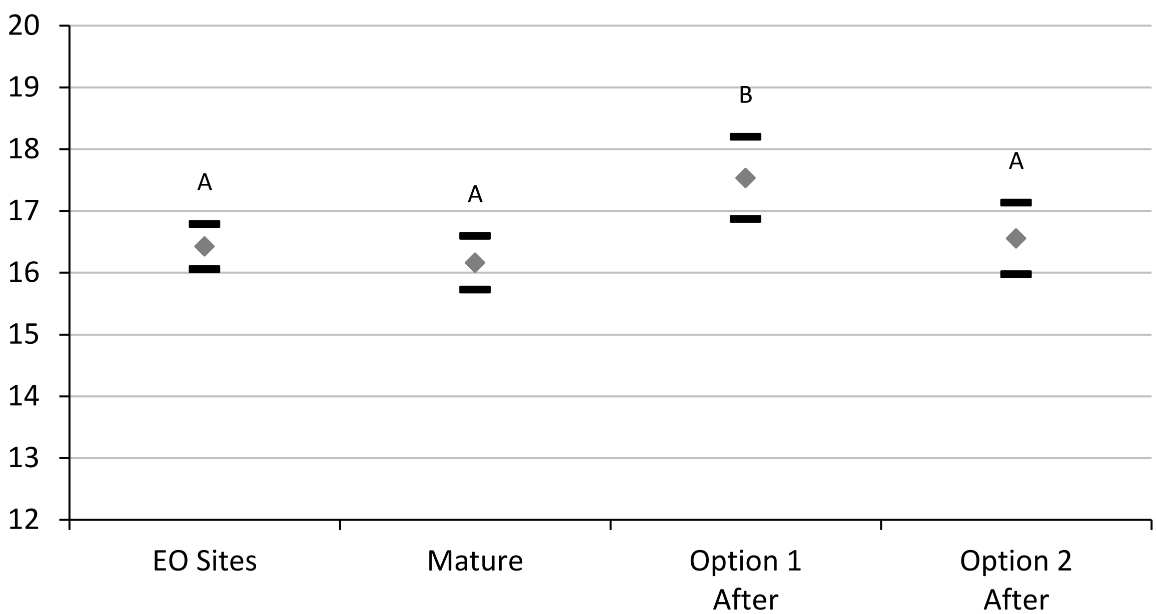
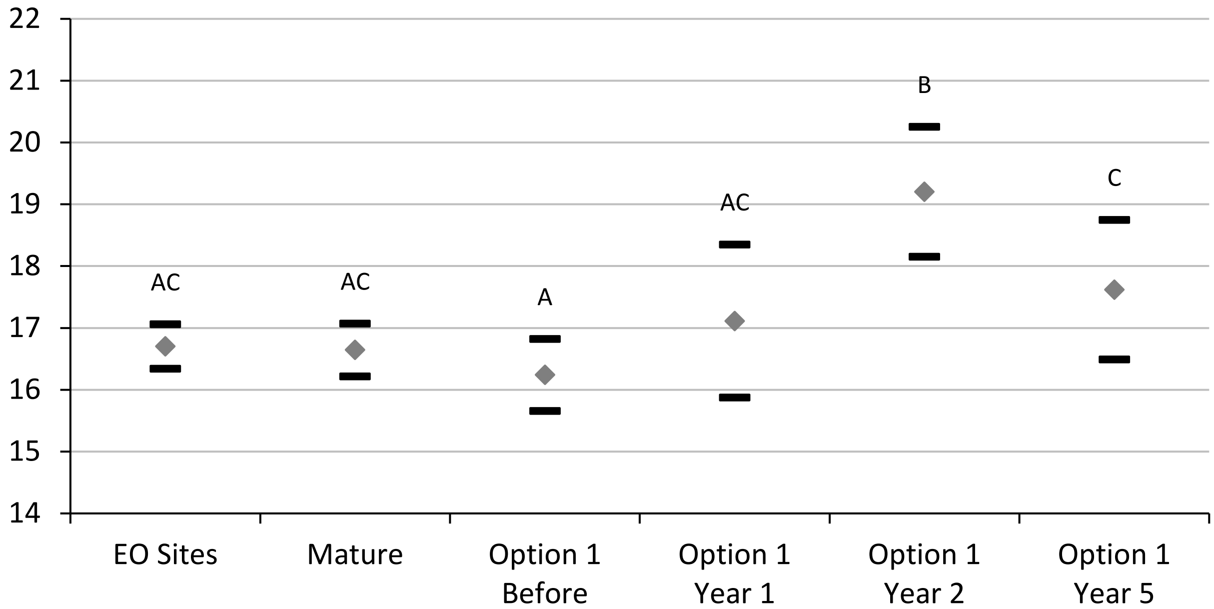


Figure 5. Comparison of mean hourly air temperature (°C) from data loggers on the ground surface between reference (element occurrence sites and mature managed stands) and treatment sites before and after harvest within Hiawatha National Forest during 2011-2019. Bars indicate upper and lower 95% confidence limits. Estimates labeled with the same letter were not significantly different (*P* > 0.05).



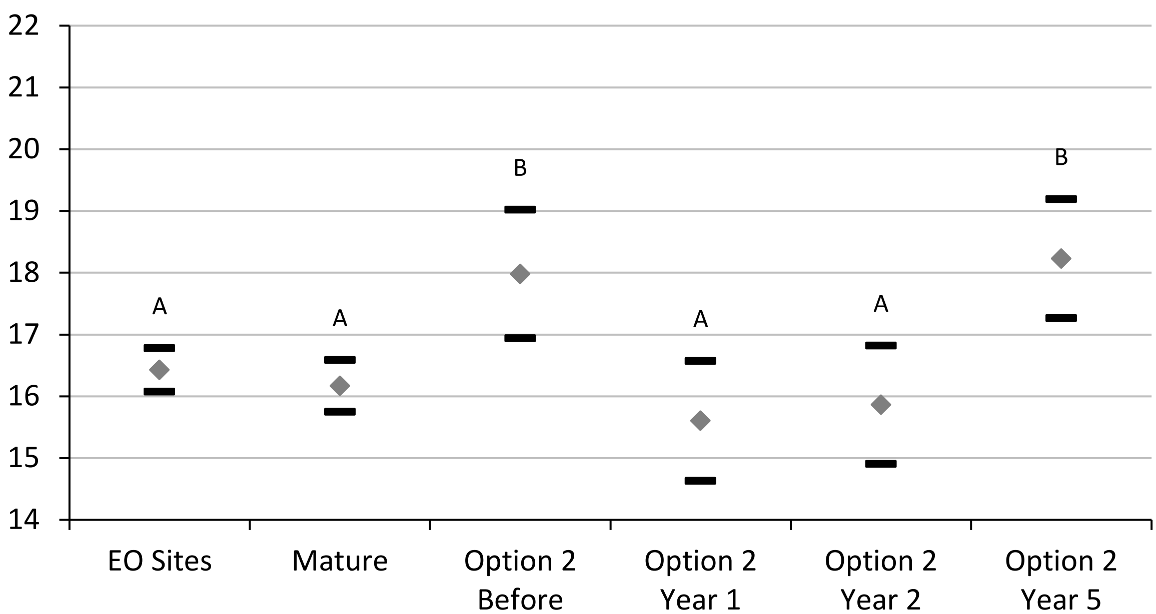
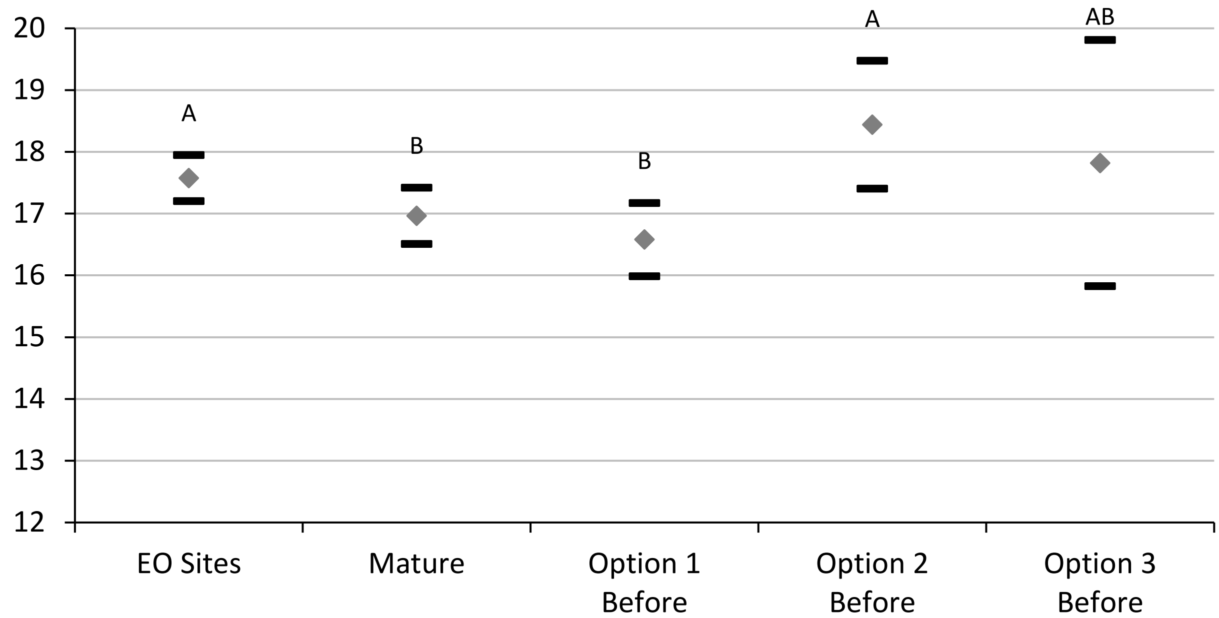


Figure 6. Comparison of mean hourly air temperature (°C) from data loggers on the ground surface between reference (element occurrence sites and mature managed stands) and Option 1 and 2 sites by treatment period within Hiawatha National Forest during 2011-2019. Bars indicate upper and lower 95% confidence limits. Estimates labeled with the same letter were not significantly different ($P > 0.05$).



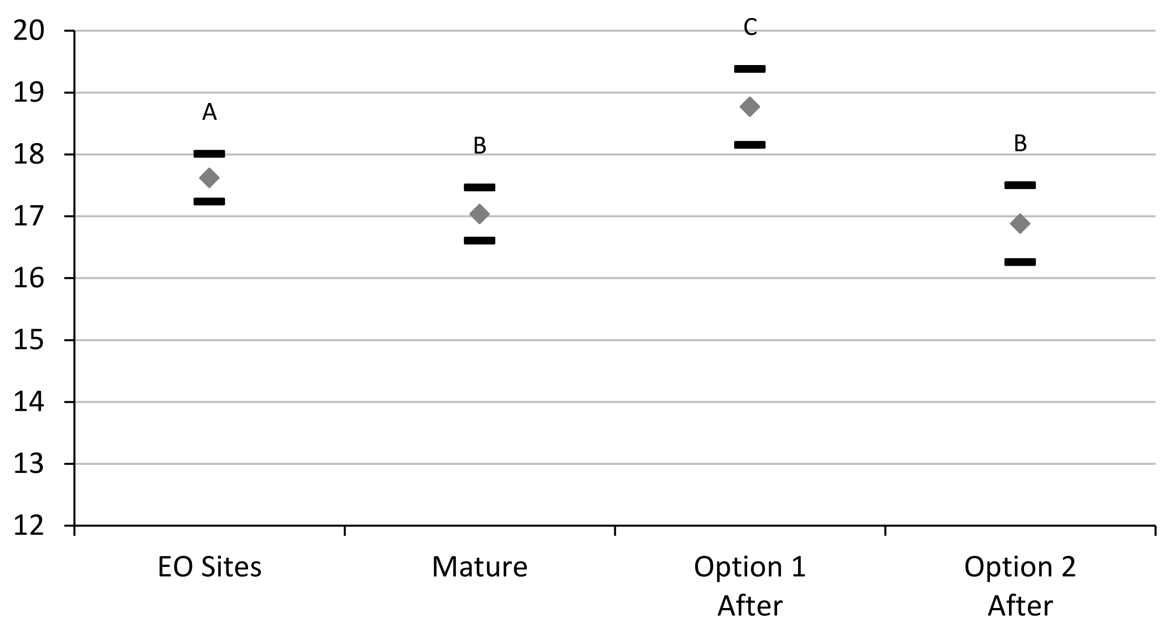
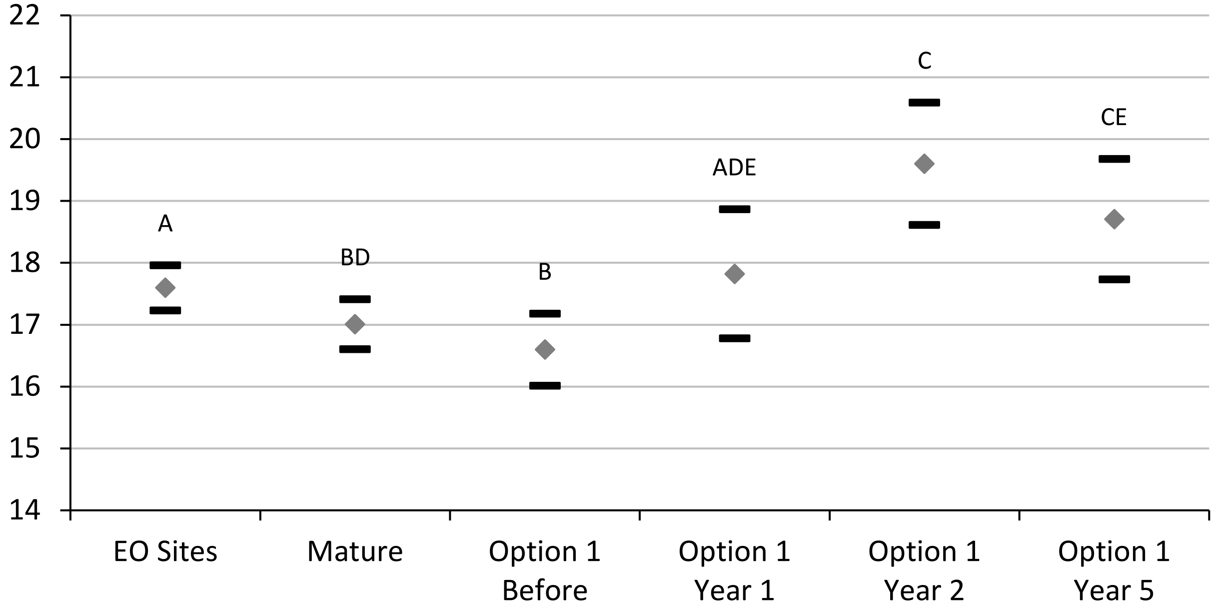


Figure 7. Comparison of mean hourly air temperature (°C) from data loggers elevated off the ground surface on bedrock features between reference (element occurrence sites and mature managed stands) and treatment sites before and after harvest within Hiawatha National Forest during 2011-2019. Bars indicate upper and lower 95% confidence limits. Estimates labeled with the same letter were not significantly different ($P > 0.05$).



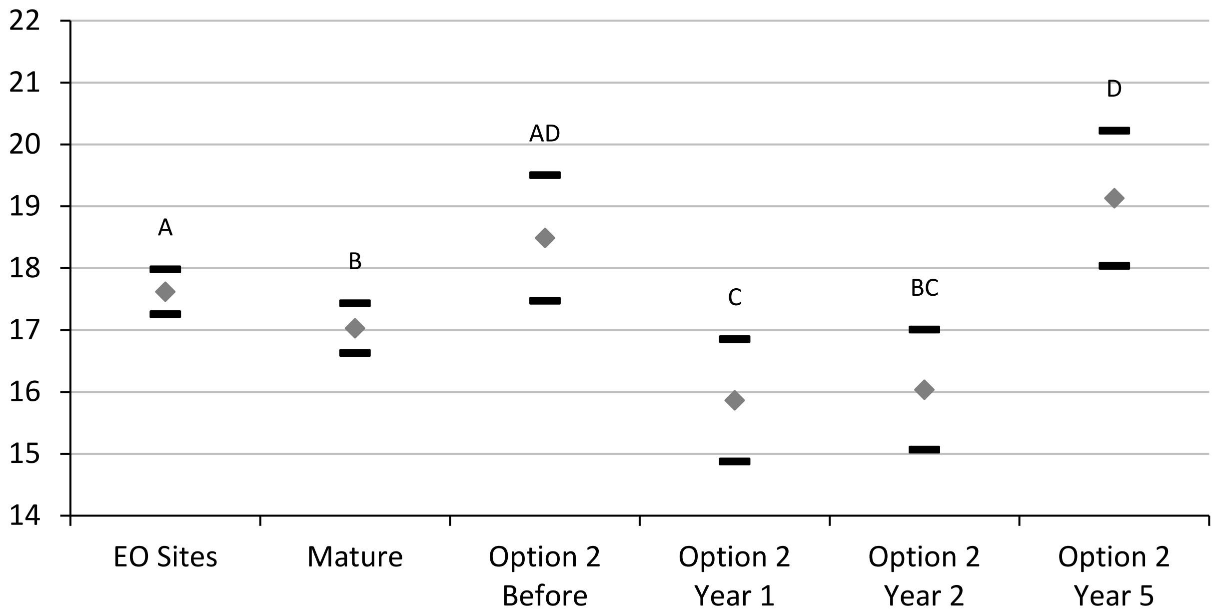
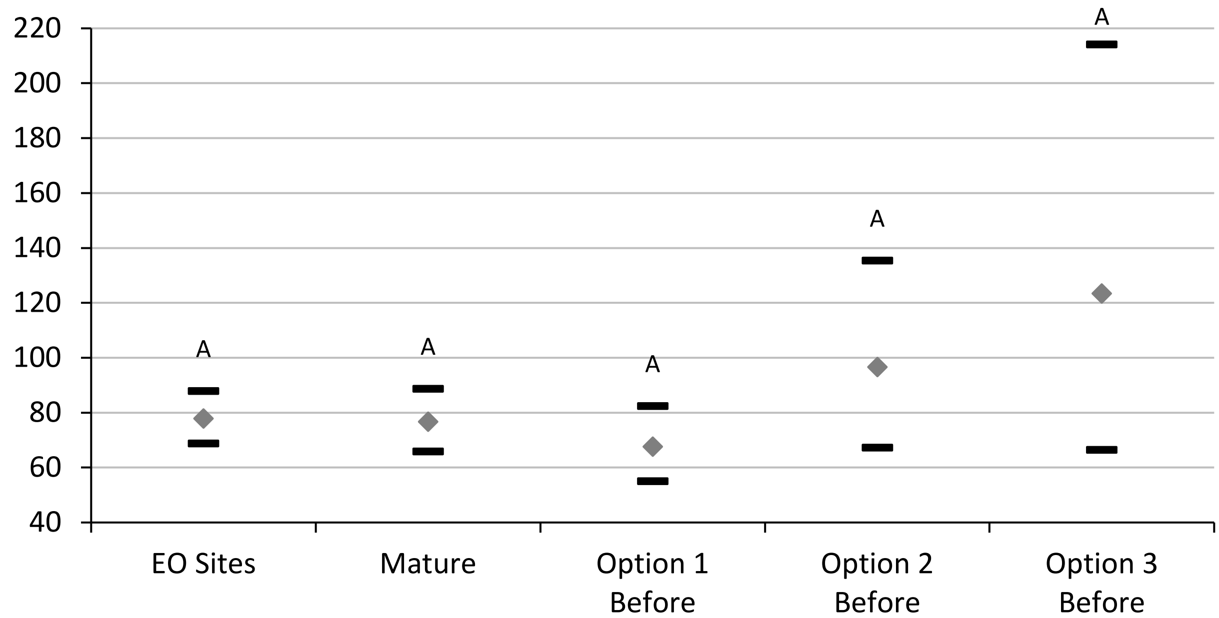


Figure 8. Comparison of mean hourly air temperature (°C) from data loggers elevated off the ground surface on bedrock features between reference (element occurrence sites and mature managed stands) and Option 1 and 2 sites by treatment period within Hiawatha National Forest during 2011-2019. Bars indicate upper and lower 95% confidence limits. Estimates labeled with the same letter were not significantly different (P > 0.05).

Mean hourly light intensity was similar between reference and treated sites prior to harvest, whereas Option 2 stands showed greater light intensities than references after treatment (Figure 9). When comparing treatment periods to references, Option 1 sites consistently had similar light intensities to references (Figure 10). Conversely, Option 2 stands had significantly greater light intensity than references during the first and second years after harvest. In annual analyses, we found Option 1 stands had similar or lower levels than reference sites in all years except 2015, when levels were greater than element occurrence stands during the first year following harvest (Appendix A, Figure A-4). Option 2 sites had similar mean light intensities to reference stands before and five years after treatment, but greater levels in the first and second years after harvest.

Vegetation

Across the nine years of sampling, we completed vegetation surveys at 124 11.3-m radius plots and 395 1-m^2 quadrats. We found significantly lower percent canopy closure and basal area in post-harvest Option 2 sites compared to references, whereas Option 1 estimates were similar to reference stands both before and after treatment (Table 4). American beech density in the canopy was similar between Option 1 and reference sites both before and after harvest. Beech canopy density at Option 2 stands was greater than reference sites before harvest but similar after treatment (Table 4). Sugar maple canopy density differed among treatments, but there was no clear pattern between treated and reference sites or before and after harvest. Snag canopy density decreased after harvest in Option 2 stands, but snag subcanopy density increased after treatment at both Option 1 and Option 2 sites (Table 4). When comparing percent cover of bedrock and moss, we did not observe significant differences within treatment (i.e., Option 1 or 2) between before and after harvest samples. Estimates of moss percent cover gathered after treatments were also similar to our element occurrence and mature managed reference stands (Table 4).



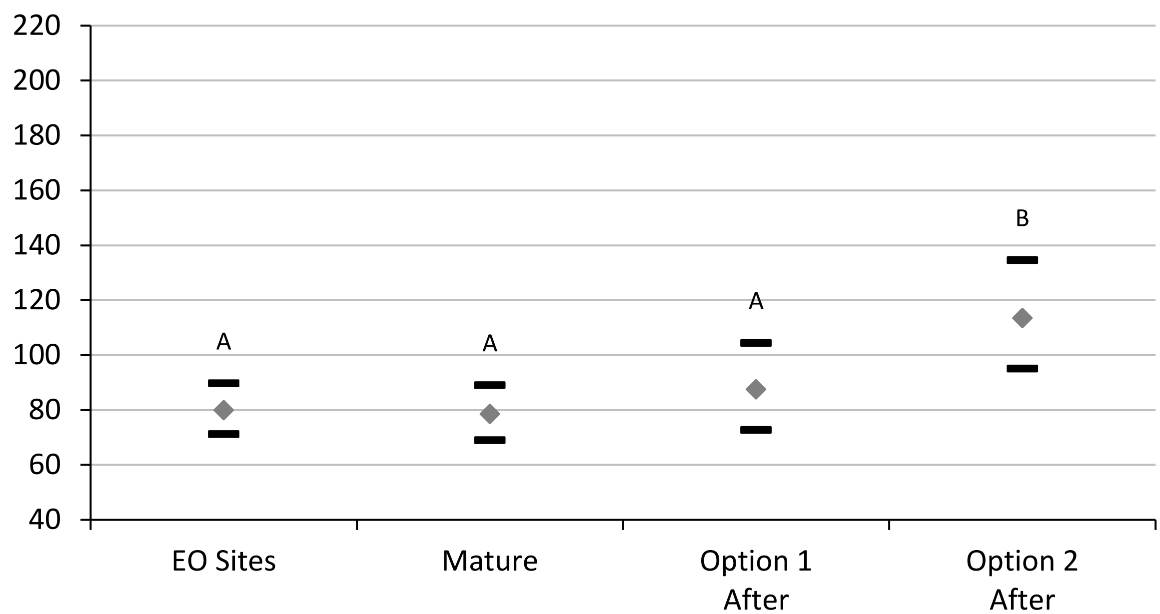
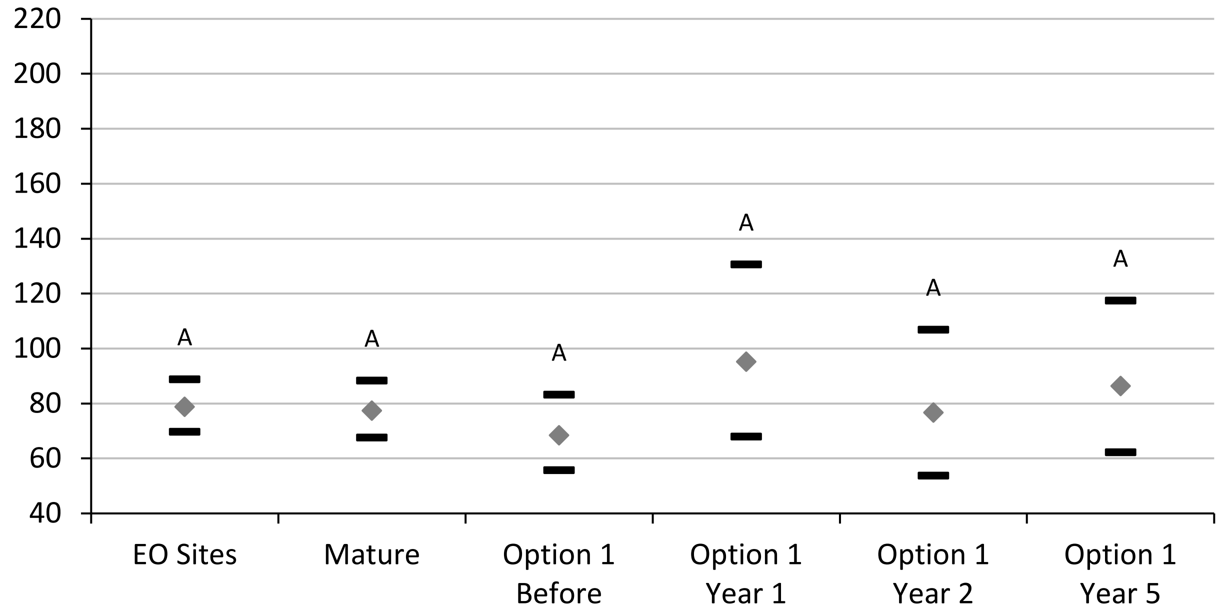


Figure 9. Comparison of mean hourly light intensity (lum/ft^2) from data loggers elevated off the ground surface on bedrock features between reference (element occurrence sites and mature managed) and treatment sites before and after harvest within Hiawatha National Forest during 2011-2019. Bars indicate upper and lower 95% confidence limits. Estimates labeled with the same letter were not significantly different ($P > 0.05$).



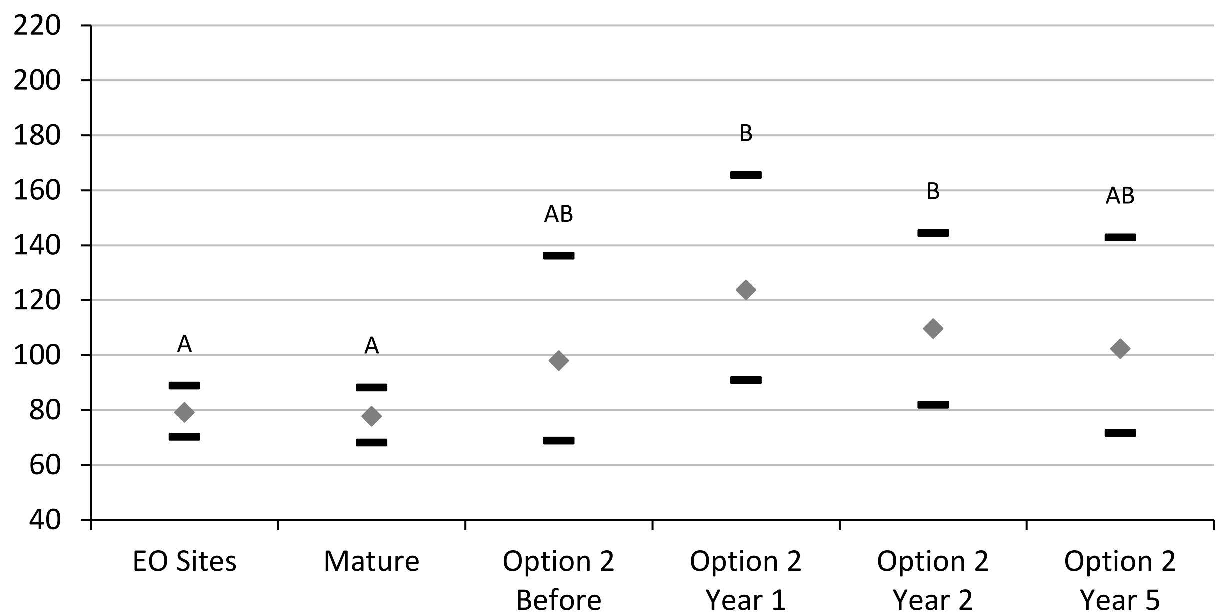


Figure 10. Comparison of mean hourly light intensity (lum/ft^2) from data loggers elevated off the ground surface on bedrock features between reference (element occurrence sites and mature managed stands) and treatment sites by treatment period within Hiawatha National Forest. Bars indicate upper and lower 95% confidence limits. Estimates labeled with the same letter were not significantly different ($P > 0.05$).

Table 4. Comparison of mean vegetative variables (standard error in parentheses) between reference (element occurrence sites and mature managed stands) and treatment sites before and after harvest within Hiawatha National Forest during 2011-2018. Estimates labeled with the same letter were not significantly different ($P > 0.05$).

Variable	EO Sites	Mature Reference	Option 1 Before	Option 2 Before	Option 1 After	Option 2 After	*P*-value
Canopy Closure (%)	**A** 78.5 (2.5)	**A** 80.2 (2.4)	**A** 86.9 (4.6)	**A** 85.0 (4.6)	**A** 81.9 (2.6)	**B** 63.7 (2.6)	**<0.0001**
Basal Area (ft^2/acre)	**A** 109.6 (6.2)	**A** 115.2 (6.1)	**A** 107.5 (9.3)	**AB** 117.5 (9.3)	**AB** 102.4 (6.2)	**B** 87.2 (6.8)	**0.0052**
Canopy Density (per 11.3-m radius plot)							
American beech	**AC** 0.9 (0.6)	**AC** 1.8 (0.7)	**AC** 1.6 (0.8)	**B** 4.3 (0.8)	**C** 0.6 (0.7)	**A** 2.8 (0.8)	**0.0098**
Balsam fir	0.7 (0.4)	1.6 (0.3)	0.6 (0.6)	1.5 (0.6)	0.3 (0.3)	1.1 (0.4)	0.5832
Sugar maple	**A** 14.9 (4.5)	**B** 29.3 (4.5)	**AB** 28.1 (9.6)	**AB** 22.1 (9.6)	**A** 16.0 (4.5)	**B** 26.5 (5.1)	**0.0003**
Snag	**A** 2.6 (0.2)	**AC** 1.4 (0.2)	**B** 3.9 (0.2)	**AB** 2.0 (0.2)	**B** 4.1 (0.2)	**C** 0.8 (0.2)	**0.0032**
Subcanopy Density (per 11.3-m radius plot)							
Balsam fir	1.3 (0.4)	4.0 (0.4)	4.5 (0.6)	2.6 (0.6)	2.3 (0.4)	3.5 (0.5)	0.2933
Sugar maple	2.0 (0.3)	3.8 (0.3)	1.5 (0.6)	1.5 (0.6)	3.4 (0.3)	4.8 (0.4)	0.5411
Snag	**A** 0.1 (0.1)	**A** 0.5 (0.1)	**A** <0.1 (0.2)	**A** <0.1 (0.2)	**B** 0.7 (0.1)	**B** 0.9 (0.2)	**0.0025**
Percent Cover (1-m^2 plot)							
Bedrock	**AC** 3.7 (0.2)	**A** 2.3 (0.2)	**B** 16.3 (0.3)	**B** 10.3 (0.3)	**BC** 13.8 (0.2)	**BC** 9.5 (0.2)	**0.0029**
Moss	**A** 79.7 (0.2)	**B** 63.2 (0.2)	**A** 76.5 (0.3)	**A** 76.0 (0.3)	**AB** 75.0 (0.2)	**AB** 69.7 (0.2)	**0.0284**

Multivariate Analyses

Initial NMS analysis suggested the data were best represented by three dimensions and a solution with equal or less stress was not likely to occur by chance alone (P = 0.004). After rerunning NMS with only three dimensions, 79.0% of the variation in the original distance matrix was explained (final stress of 16.66). The first axis was positively correlated with northern white cedar (*Thuja occidentalis*) canopy density (r = 0.525) and negatively associated with American basswood (*Tilia americana*) canopy density (r = -0.520), American beech subcanopy density (r = -0.562), and ironwood (*Ostrya virginiana*) subcanopy density (r = -0.626). Axis 2 was negatively associated with sugar maple canopy density (r = -0.699), balsam fir subcanopy density (r = -0.532), and shrub density (r = -0.525) canopy density and positively related to yellow birch (*Betula alleghaniensis*) canopy density (r = 0.630), whereas Axis 3 was positively correlated with bare soil percent cover (r = 0.563), sugar maple subcanopy density (r = 0.489), and northern white cedar canopy density (r = 0.403), and negatively associated with American beech canopy density (r = -0.430) and rock percent cover (r = -0.402). We did not observe substantial separation of the sites by treatment type across the first or second dimensions; however, there was some clustering of Option 1 and 2 sites along the third axis by treatment status, with harvested samples tending to have greater scores than pre-treatment samples (Figure 11). This shift was likely associated with changes to the canopy and subcanopy structure and composition due to selective harvest.

Although we did not see discernable clustering by treament in NMS analysis, our MRPP analysis did indicate significant differences in the positions of treatment categories in multidimensional space (T = -8.44, A = 0.10, P < 0.001). Pair-wise MRPP comparisons indicated that reference and control sites were similar (T = 0.61, A < 0.01, P = 0.711), as were Option 1 and Option 2 prior to harvest (T = -0.57, A = 0.01, P = 0.249) and mature reference and Option 1 after treatment (T = -0.84, A = 0.01, P = 0.187), but all other treatment combinations differed ($P \leq 0.013$). These results suggest that when considering multiple vegetation and environmental measures at the same time, the treated stands differed from the reference sites both before and after harvest. We also found significant differences within treatment when comparing sites before and after harvest.

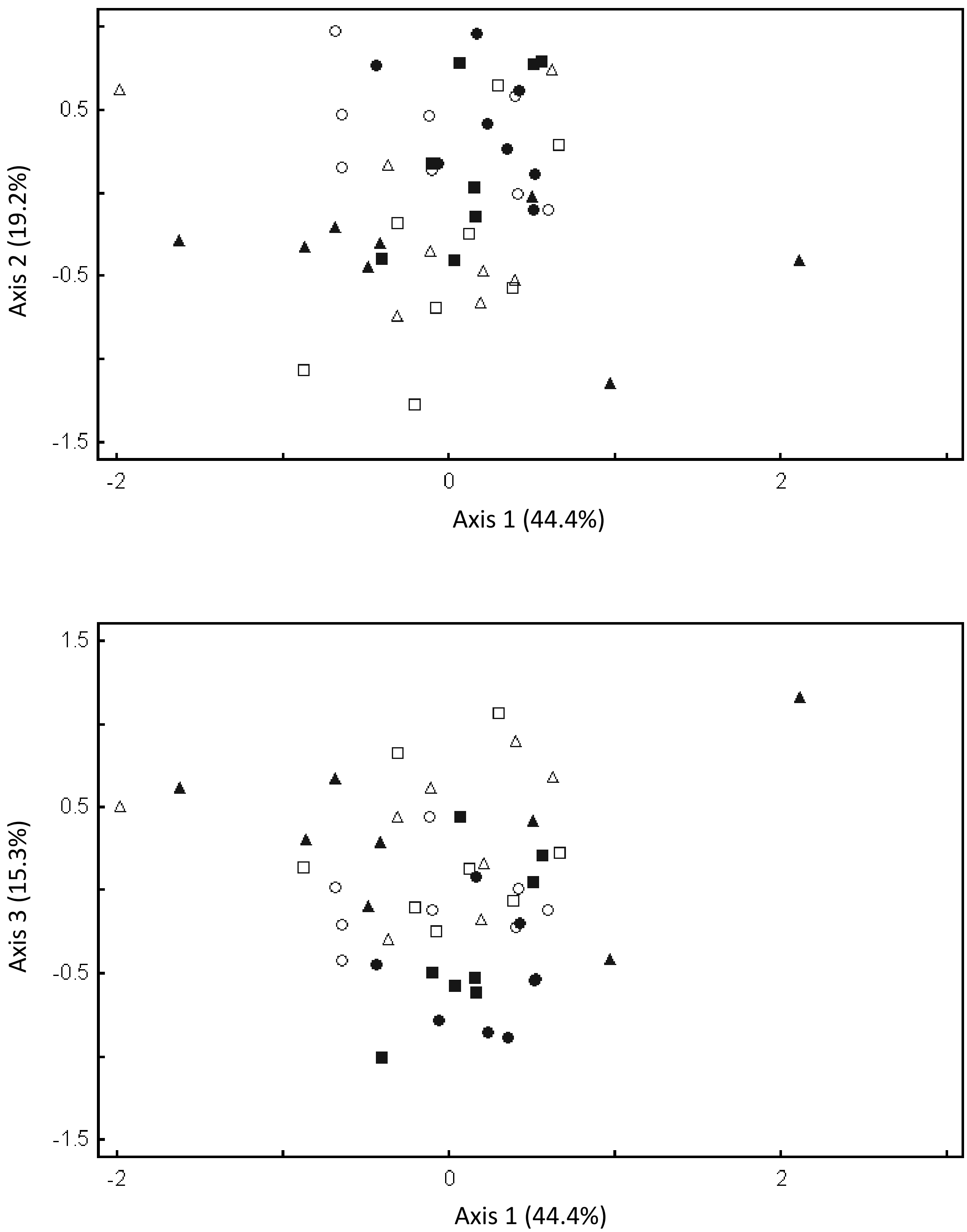


Figure 11. Nonmetric multidimensional scaling plot of vegetation and environmental variables at stands in Hiawatha National Forest during 2011-2019. Treatments are coded as follows: shaded triangle = element occurrence sites; open triangle = mature managed stands; Option 1 pre-harvest = shaded square; Option 1 post-harvest = open square; Option 2 pre-harvest = shaded circle; and Option 2 post-harvest = open circle.

DISCUSSION

Bedrock features within the Niagara escarpment support unique species, including rare fern and land snail species. Hiawatha National Forest supports several RFSS and its policies are to maintain populations of these species and develop and implement management practices to ensure they do not become threatened or endangered. The intent of the Niagara monitoring plan was to evaluate three options for managing forests containing rare species requiring the cool, moist microclimates offered by limestone boulders, fissures, and cliff faces. Rare ferns and land snails are vulnerable to changes in light intensity, temperature, and humidity that could result from timber management (Penskar and Higman 1997, Lee 2007, Badra 2008).

We found significant differences in environmental variables among our reference and treatment types, but the patterns were inconsistent and varied over years. Treated sites tended to have lower humidity and greater surface air temperature compared to references; however, some of those differences were present both before and after treatment occurred and could be related to preexisting conditions rather than a result of management. Harvest treatment for Option 2 stands increased light intensity compared to pretreatment and references, but those differences seemed to disappear by the fifth year of sampling. In northern hardwood forests of Michigan and Wisconsin, Scheller and Mladenoff (2002) found greater mean photosynthetically active radiation (PAR) in uneven-aged stands compared to even-aged and old growth forests, which had similar PAR levels. Our element occurrence and mature managed references had consistently similar humidity, temperature, and light intensity. This similarity suggests that microclimate changes caused by forest treatments are temporary.

Our vegetation sampling revealed significant differences in some variables among our forest categories, but we did not find consistent patterns between reference and treated sites in densities of common species in the canopy or subcanopy. Harvest treatments appeared to alter snag densities, with densities in the canopy decreasing and densities in the subcanopy increasing. We observed a significant reduction in canopy closure and basal area in Option 2 after harvest, whereas Option 1 was similar to pretreatment and reference values. These results combined with light intensity data indicate Option 1 was successful in shade retention. Forest managers were concerned about potential impacts to moss cover on boulders and cliff faces caused by harvest, but we did not detect significant changes after treatment when compared to pretreatment and reference conditions.

Considering all our analyses together, it appears both management prescriptions resulted in some changes to the microclimate and vegetation structure, though it remains unknown if the amounts and duration of change would be detrimental to the rare species of concern. In their study of a New England forest dominated by oaks and white pine (P*inus strobus*), Brooks and Kyker-Snowman (2008) suggested the small differences they found in forest floor temperatures and moisture between cut and uncut forest would likely have minor effects on climatic conditions for forest amphibian and other forest floor biota. The Option 1 treatment produced fewer changes compared to Option 2 and appeared to maintain shade as intended. If limiting forest treatment completely is not an option, Option 1 would seem to be a reasonable approach to protecting the karst environments, given the limited effects observed during the first two years post-harvest sampling.

This project provides methods and baseline data for continued monitoring of sites with rare fern and snail occurrences within the HNF and other parts of northern Michigan. We developed methods that could be used as a standard for monitoring changes to rare fern and snail habitats in relation to forest management or other environmental modifications. This project can serve as the first steps toward better characterizing the microhabitats of these RFSS in the HNF. Finally, we have gathered valuable baseline temperature, humidity, and light intensity data at existing rare land snail and fern sites, as well as several other forest stands, that could be valuable in addressing future research questions.

This project revealed several areas for additional research, such as determining if the level of change observed would be detrimental to rare species associated with karst environments. We also need to assess how long apparent changes to humidity, temperature, and light intensity remain after harvest, and if the duration is long enough to cause harm to rare species. Although most studies examining microclimate in relation to forest management have focused on the growing season, full-year microclimate monitoring at known RFSS fern/snail sites would be valuable to determine if early spring or "false spring" heating associated with climate change is having an impact on these species. Other changes to forests, such as extreme eastern tent caterpillar (*Malacosoma americanum*) outbreaks, should be examined to evaluate possible effects to the microclimates required by these rare species. Previous studies indicated that openings adjacent to forests can alter the microclimate and vegetation within the forests (Gehlhausen et al. 2000, Dovciak and Brown 2014), so additional research to understand how far from the edge changes occur within mesic northern forests would help inform the buffer width and allowable gap sizes within buffers surrounding RFSS. More surveys of RFSS fern and snail sites are needed to determine if the occurrences are extant, along with an examination of past forest management to assess if current population status is related to management history.

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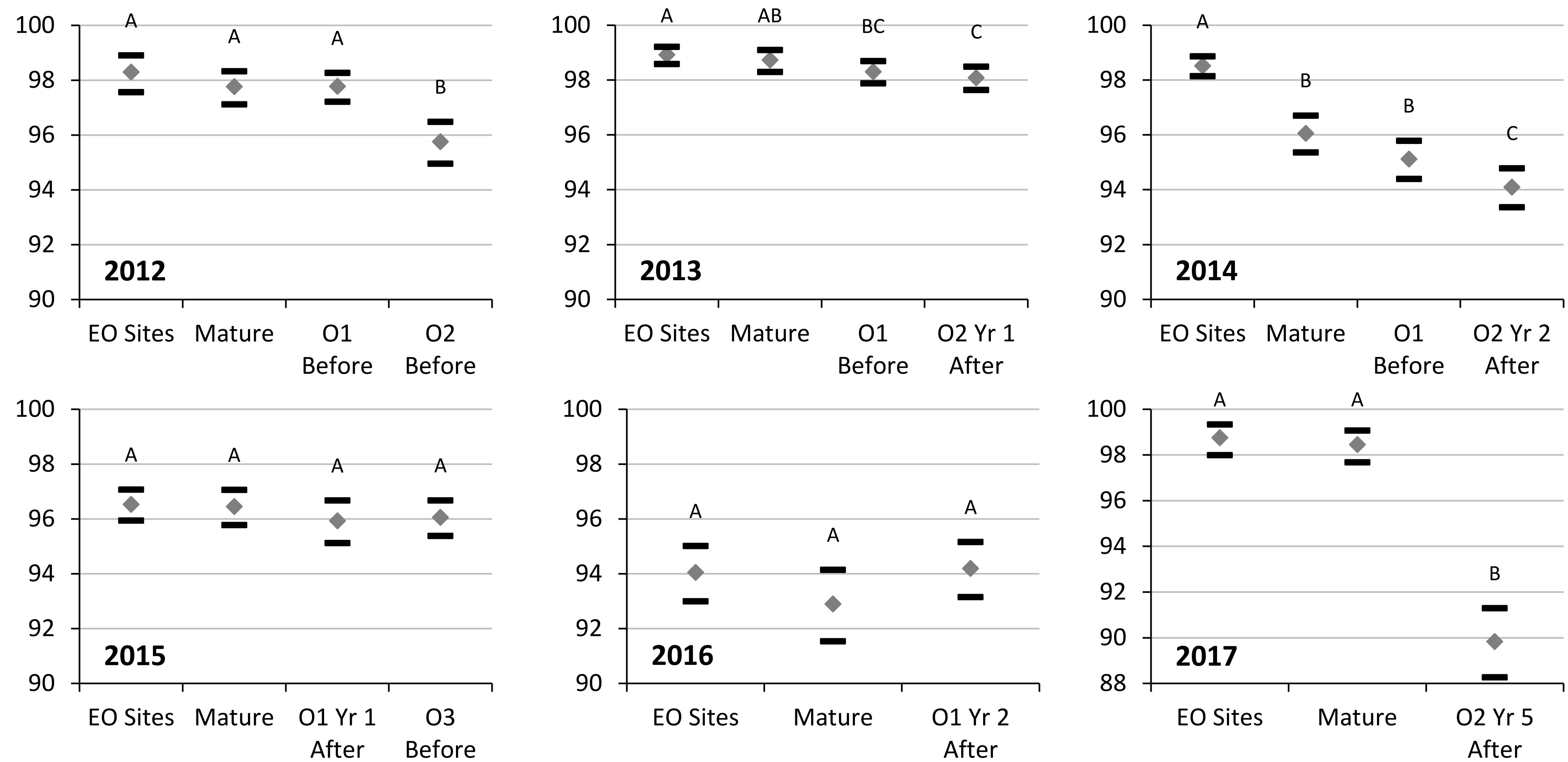
APPENDIX A

ANNUAL COMPARISONS OF ENVIRONMENTAL VARIABLES



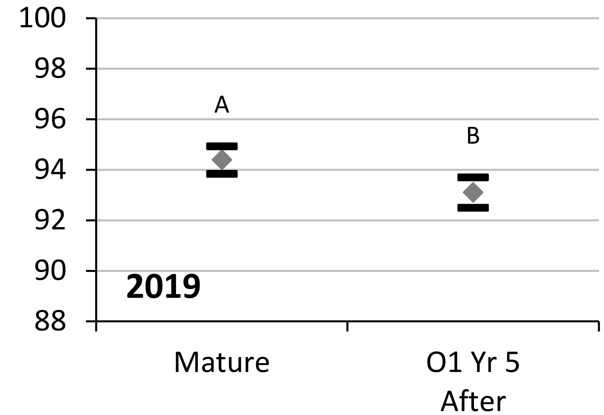
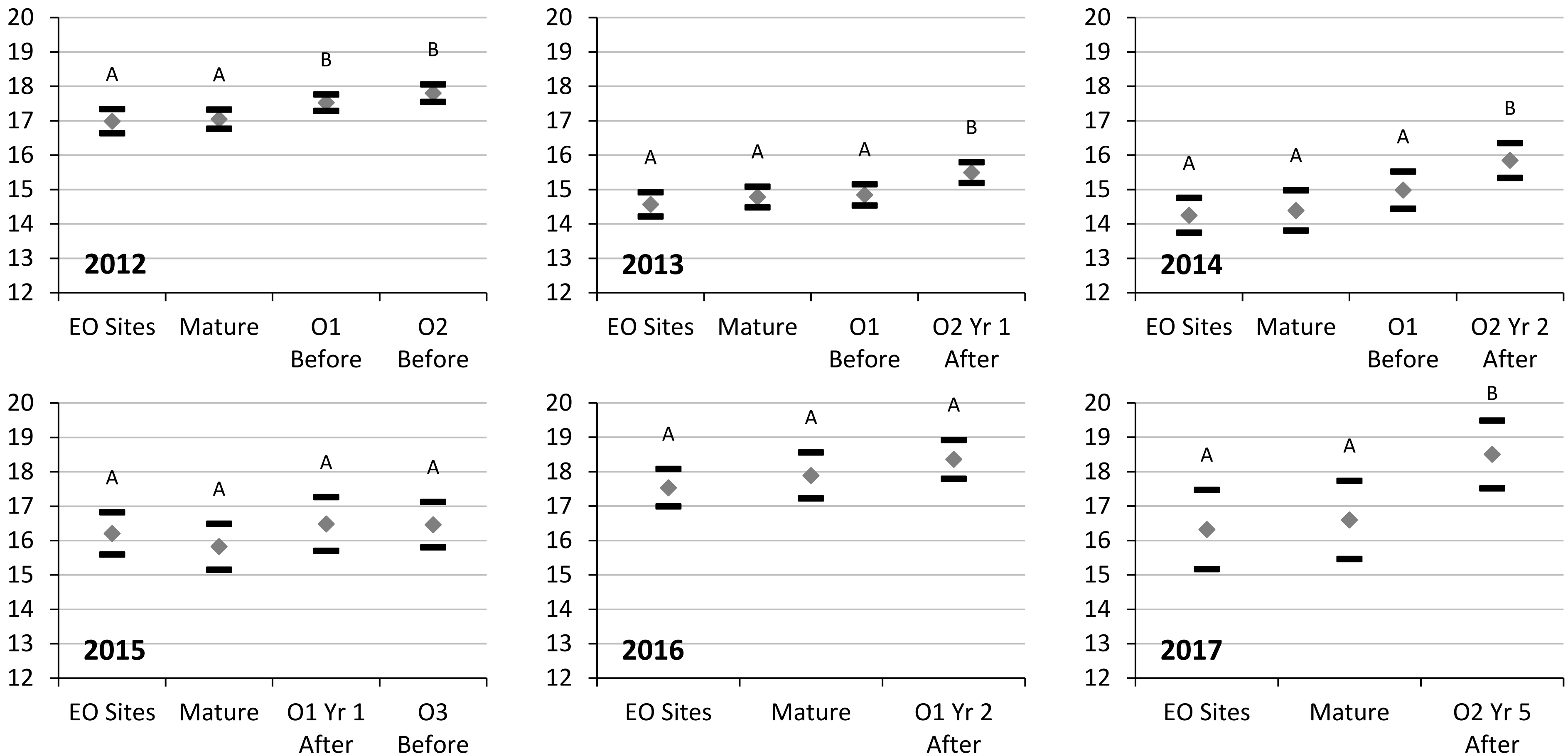


Figure A-1. Comparison of mean hourly percent relative humidity between reference (element occurrence sites and mature managed stands) and treatment sites by year within Hiawatha National Forest during 2012-2019. Bars indicate upper and lower 95% confidence limits. Estimates labeled with the same letter were not significantly different ($P > 0.05$).



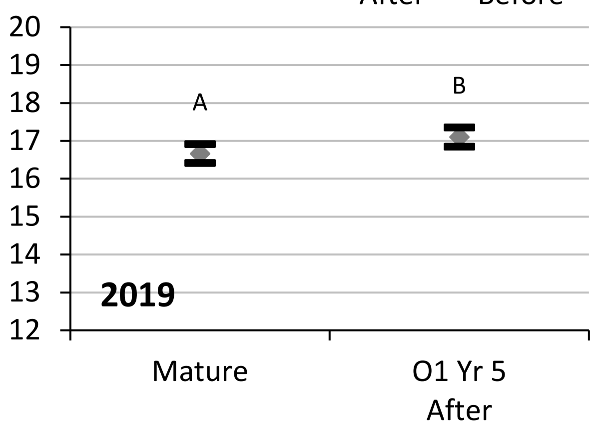
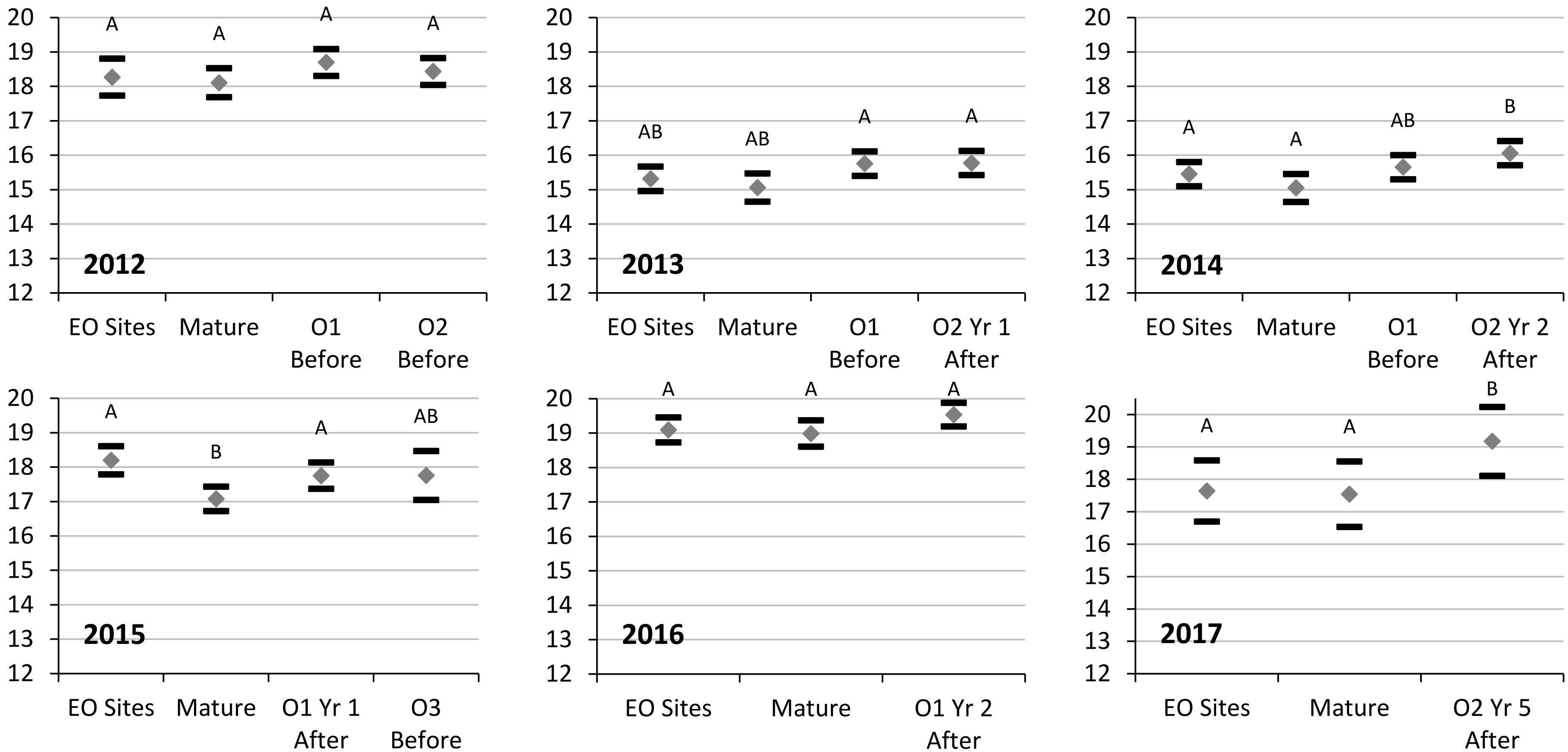


Figure A-2. Comparison of mean hourly air temperature (°C) from data loggers on the ground surface between reference (element occurrence sites and mature managed stands) and treatment sites by year within Hiawatha National Forest during 2012-2019. Bars indicate upper and lower 95% confidence limits. Estimates labeled with the same letter were not significantly different (P > 0.05).



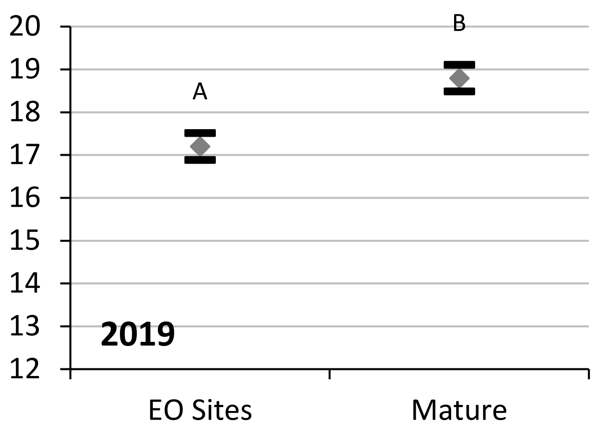


Figure A-3. Comparison of mean hourly air temperature (°C) from data loggers elevated off the ground surface on bedrock features between reference (element occurrence sites and mature managed stands) and treatment sites by year within Hiawatha National Forest during 2012-2019. Bars indicate upper and lower 95% confidence limits. Estimates labeled with the same letter were not significantly different (P > 0.05).

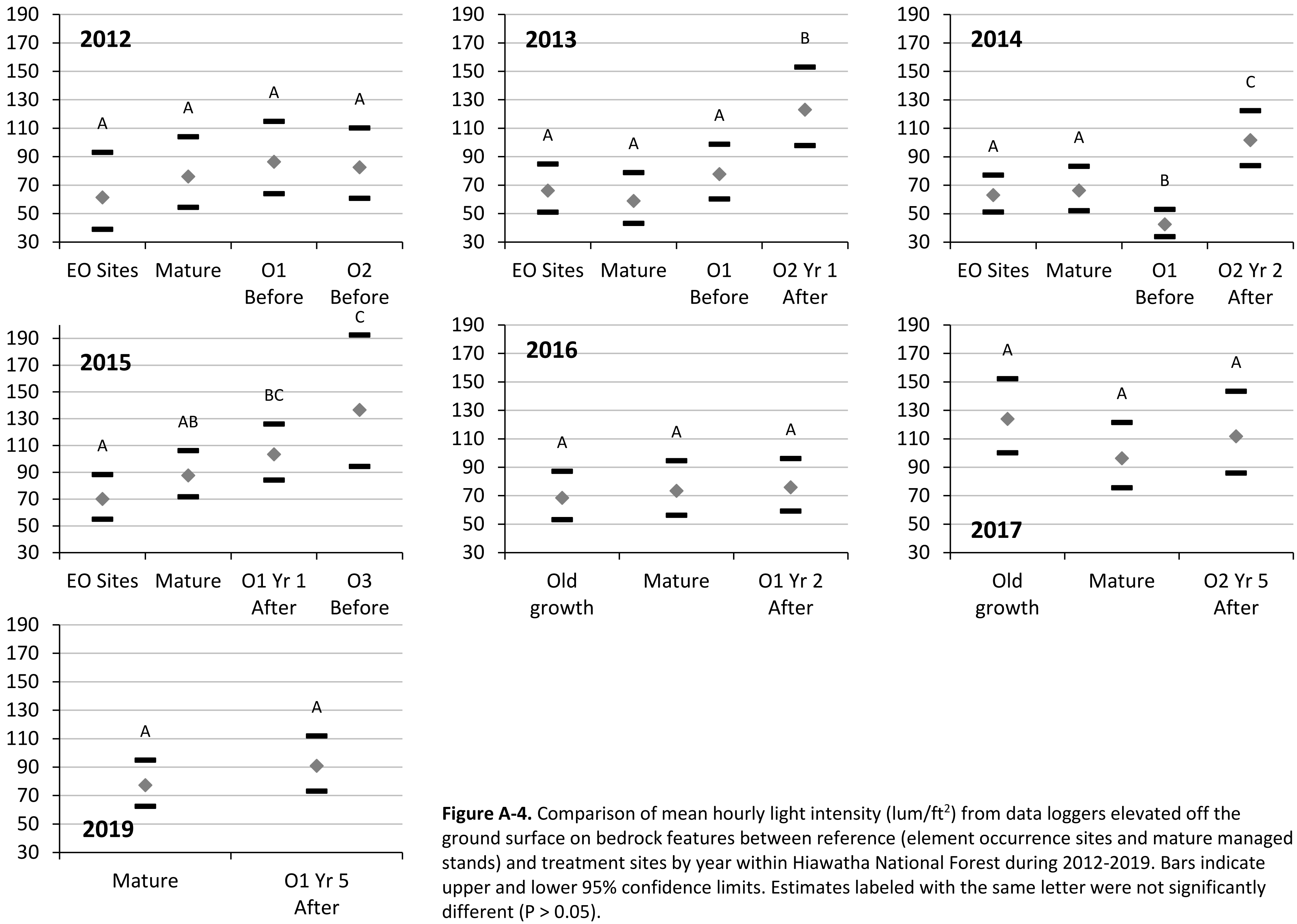


Figure A-4. Comparison of mean hourly light intensity (lum/ft^2) from data loggers elevated off the ground surface on bedrock features between reference (element occurrence sites and mature managed stands) and treatment sites by year within Hiawatha National Forest during 2012-2019. Bars indicate upper and lower 95% confidence limits. Estimates labeled with the same letter were not significantly different (P > 0.05).