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Microclimatic Variation Between Managed and Unmanaged Northern Hardwood Forests in Upper Michigan, USA

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Cover Caption:
Microclimate monitoring equipment mounted on a 70-foot steel tower reaching into the forest canopy.

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Abstract

Managing forests for timber production generally involves manipulating the composition and structure of forests to improve growing conditions for selected trees and to improve the chances for regenerating trees. Altering forest structure changes the microclimate within the forest. Temperature, light, wind, and precipitation were measured in the understory of managed and unmanaged northern hardwood forests in the Upper Peninsula of Michigan from 1995 through 2001. These measurements provide a baseline of information to compare microclimatic conditions during the study to long-term averages and to compare the microclimate under managed and unmanaged conditions. Under management, partial removals of the overstory reduced tree density, resulting in increased light beneath the forest canopy. Regrowth following thinning mitigated some of the differences in understory microclimate between managed and unmanaged forests. Mean aboveground and belowground temperatures in managed and unmanaged forests were either not significantly different or the differences were not consistent. Extreme events, however, are likely to be more meaningful to forest development than mean conditions. More attention should be given to extreme climatic events (high and low temperatures, abundant precipitation, severe droughts, and high winds) as factors influencing the growth and development of forests and other ecosystems. In addition to the summaries presented here, the data are made available to the readers.

Acknowledgments

The authors thank Warren Heilman, Jiquan Chen, and Kim Brosofske for their valuable review comments and suggestions. We thank Bob Evans, Ottawa National Forest, for logistical support. We also thank David Buckley, Adam Weise, and Ed Gritt for their professional and technical support, as well as Michael Worland and Chris Hense for their physical effort during tower construction. This research was funded with a USDA Forest Service Ecosystem Management Grant received by the North Central Research Station.

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Introduction

The impact of management on the diversity of forests is a fundamental question facing forest managers (Probst and Crow 1991, Franklin 1993). There is concern that many management activities simplify forest composition and structure and that these changes may affect forest health and long-term ecosystem productivity (Crow *et al*. 1994). Because of this concern, a study was initiated to compare the structural and compositional diversity of northern hardwood forests under even- and uneven-aged management to the diversity found in unmanaged old-growth and second-growth forests as well as forests being managed for old-growth characteristics (Nauertz 1999; Hura 2001; Crow *et al*. 2002; Fisk *et al*. 2002; Szabo 2002; Buckley *et al*. 2003; Kent *et al*., in press).

The microclimate encompasses the suite of climatic conditions that exist in a localized area near the Earth's surface (Chen *et al*. 1999). The variables that define the microclimate (e.g., temperature, solar radiation, wind speed and direction, and moisture) influence ecological processes such as the establishment, growth, and mortality of plants (Geiger *et al*. 1995). When forests are managed, changes in microclimate with forest structure changes are expected. Such changes occur at many spatial scales, including the forest stand (Reifsnyder *et al*. 1971) and landscape (Brosofske *et al*. 1997).

The first objective of our study was to characterize the variation that occurred in microclimatic variables throughout the study period (1995-2001). For this temporal aspect, measurements taken in unmanaged forests served as the baseline. A second objective was to compare the microclimatic variables in managed forests to those in unmanaged forests. In addition, our intention was to make the microclimatic database available to others.

Methods

Study Area

Measurements were taken on five study sites located on the Watersmeet and the Iron River Districts of the Ottawa National Forest in Michigan's Upper Peninsula. Sugar maple (*Acer saccharum* Marsh.), the most dominant species at all study sites, typically accounted for 70 to 80 percent of the stand basal area (Crow *et al*. 2002). Other common species in order of their relative abundance included eastern hemlock (*Tsuga canadensis* (L.) Carr), yellow birch (*Betula alleghaniensis* Britton), American basswood (*Tilia americana* L.), eastern hophornbeam (*Ostrya virginiana* (Mill.) K. Koch), and red maple (*Acer rubrum* L.).

Study areas were also restricted to a single ecological unit—Ecological Landtype Phase (ELTP) 38—within Albert's (1995) Sub-subsection IX.3.2. The sub-subsection can be considered a regional ecosystem, while the ELTP is a local ecosystem. The Winegar Moraine, a

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prominent physiographic feature in western upper Michigan and extending into northern Wisconsin, largely defines Sub-subsection IX.3.2. ELTP 38 has moderately well drained, sandy loam and loamy sand soils. A fragipan is common at 45 to 90 cm below the surface in ELTP 38.

Three management treatments [even-aged, uneven-aged, and managed for old-growth characteristics (MOGC)] and two unmanaged baselines (old growth and second growth) were included in the study. The uneven-aged and MOGC stands were of old-growth origin; the even-aged stand was of second-growth origin. All managed forests were last entered for harvesting from 1 to 3 years before our study was established in 1994. The management treatments consisted of thinning the overstory to enhance tree growth and promote regeneration; none involved complete canopy removal. The MOGC is a variation of uneven-aged management where old-growth structural features have been retained where possible. Individual tree selection was conducted to create some old-growth characteristics in a managed forest. The prescription for this treatment included no maximum diameter, the retention of cull trees as possible sources of coarse woody debris, the creation of multi-tree gaps in the canopy, and the retention of noncommercial tree species when present (Robert Evans, Ottawa National Forest, personal communication).

The treatments and baselines provide a contrast in forest structures. Basal areas in the unmanaged forests generally ranged from 30 to 35 m^2 ha^{-1} as compared to 20 to 25 m^2 ha^{-1} in the managed forests (Crow *et al*. 2002). The old-growth, uneven-aged, and MOGC forests were multi-aged and multi-sized forests represented by a reversed J-shape distribution of stem diameters; the even-aged and unmanaged second-growth forests had stem diameters that approximated a normal distribution. The old-growth stand was dominated by trees >200 years old, and the median tree age at diameter at breast height for the three treatments and the unmanaged second growth ranged from 60 to 80 years (Crow *et al*. 2002). The three treatments and the unmanaged second growth, however, all had residual trees >150 years, so these forests could be considered two or more aged.

Microclimate Measurements

Instrumentation: A Rohn 25 gauge galvanized steel tower was erected in each of the three treatment and two baseline study areas. The towers, 18 to 22 m in height and extending to midcanopy, were located to avoid large canopy gaps. The 22-m towers were located in the stands of old-growth origin (unmanaged old growth, uneven-aged, and MOGC), and the 18-m towers were located in stands of second-growth origin (unmanaged second growth and even-aged). The stands of old-growth origin had a higher canopy height than did the stands of second-growth origin. The goal was to align the tower instrumentation within the same general area of the canopy regardless of treatment.

At each tower, a Campbell Scientific CR10 XT datalogger with an AM 32 multiplexer was installed within an ENC 30 x 36 cm fiberglass enclosure (Campbell Scientific, Inc., Logan, Utah). A Campbell Scientific extended temperature storage module (SM716) was connected to each datalogger. A 12-volt deep cycle marine battery was used to power each system. Vaisala HMP 35C relative humidity and temperature probes were enclosed within radiation shields and mounted on each tower at 2, 10, and 20 m. A R.M. Young Wind Sentry Set was mounted on each tower at 10 m to measure wind speed and direction. Near each tower, a single vertical temperature profile was established using thermocouples (ANSI Type T, copper-constantan) referenced to a Campbell T 107 air temperature probe (thermister with error range of ± 0.1% from –20 to 40º C). The thermocouples were mounted on a wooden stake at 0.05, 0.25, 0.5, and 1.0 m heights. In addition, a single temperature profile was established at 1.0, 0.5, 0.2, 0.1, 0.05 m below the surface and at the surface of the forest floor. Thermocouples placed at the surface and belowground were enclosed in brass tubing and sealed with shrink-wrap.

Two LI-COR LI190SB quantum sensors were mounted on 1-m high tripods at approximately 6 m from each tower. The first quantum sensor was located along the same azimuth as a tower guide wire, and the second sensor was located 120° from the first sensor. A single Texas Instrument 525 tipping bucket (rain gauge) was installed at each tower site. Each tipping bucket was placed in an area that best represented the forest management, that is, to avoid large or multiple canopy gaps. Finally, three wooden measuring stakes were located near each tower (three stakes per treatment), where snow depths were monitored.

Measurement increments: Data collection began in 1995 and continued through 2001. Relative humidity (%), temperature measurements (º C), and rainfall totals (mm) were recorded every 60 seconds. The 60-second readings were used to compute the hourly and the daily averages, recording of the maximum and minimum measurements, and hourly and daily rainfall totals. The 10-second readings were used to compute hourly and daily averages for wind speed (m s^{-1}), wind direction (azimuth º), and photosynthetically active radiation (PAR) measurements (μmol m^{-2} s^{-1}). Computed average wind speed, average wind direction and standard deviation, and maximum wind speed were based on the 10-second readings. Research staff recorded snow depth measurements (cm) at each site visit during the winter.

Data Summaries

Hourly and daily summaries were computed for each microclimatic variable from 1995 until 2001. Regression analysis was used to predict missing values when sufficient data were available to make reliable estimates. Predicted values were used only when the R^2 for the regression model exceeded 0.80. Further summaries were compiled based on either the hourly or the daily computed data. The old-growth baseline summaries were then compared to long-term averages from a nearby weather station (Marenisco, MI, elevation = 379 m, latitude 46º 31'N, longitude 90º 08'W) to help us explain annual variation in measurements.

Parameters compared among years included mean monthly temperature, mean monthly maximum and minimum temperatures, monthly maximum wind speed, monthly precipitation, effective accumulative temperature (EAT), snow depth, and length of growing season. Effective accumulative temperature (EAT) was calculated for each month (sum of daily average temperature (T_d) minus 5° C). Similar to degree-days, EAT is correlated with forest productivity and other growth measurements (Chen *et al.* 1997).

Aboveground and belowground temperature profiles were compared among treatments and baselines. These comparisons were based on hourly measurements taken over short periods (e.g., 1 day) under different conditions (clear day, cloudy day) during the growing and dormant seasons or based on averages of monthly measurements. Comparisons were generally but not exclusively reported for 1999 due to the completeness of the record for that year.

PAR was compared among treatments and baselines. Again, comparisons were made over both short and long periods under varied weather conditions and different seasons.

Snow depths were compared among treatments and baselines during the 1996 and 1997 season—the period with the most complete measurements and above average snowfall. Snow depths were measured on October 31, November 13, and December 3 of 1996 and on January 23, March 8, and April 5 of 1997 at three locations within each study area. We used the General Linear Model (GLM) procedure (SAS Institute, Inc. 1999) to conduct repeated measures Analysis of Variance (ANOVAs) for comparing snow depths among measurement dates, study areas, and measurement stakes.

Results

Comparisons Among Years

Mean monthly temperatures, monthly maximum and minimum temperatures, and monthly precipitation were compared among years in one baseline area, the old-growth forest, and mean monthly temperatures and monthly precipitation were compared to long-term averages recorded at a nearby weather station located in open conditions (Marenisco, MI, elevation = 379 m, latitude 46º 31'N, longitude 90º 08'W). Temperature measurements at long-term weather stations are typically made in shelters 2 m above the surface whereas the study site measurements used for comparison beneath the forest canopy are taken 2 m above the forest floor.

Mean monthly temperatures were much above the long-term average in February of 1997, 1998, 1999, and 2000 and in November of 1999 and 2001 (fig. 1). These extremes can be attributed to high minimum temperatures in February for all 4 years (fig. 2) and high maximum temperatures in February for 1998, 1999, and 2000 (fig. 3), as well as high minimum and maximum temperatures in November 1999 (figs. 2 and 3). Mean monthly temperatures during 1996 were lower than average in at least 8 of the 12 months (fig. 1). The year-to-year variation in mean monthly temperatures, mean monthly minimum temperatures, and mean monthly maximum temperatures was greater during November through April than during May through October (figs. 1-3).

The areas under the curves for effective accumulative temperatures (EAT, >5˚ C) provide a means for comparing heat sums recorded

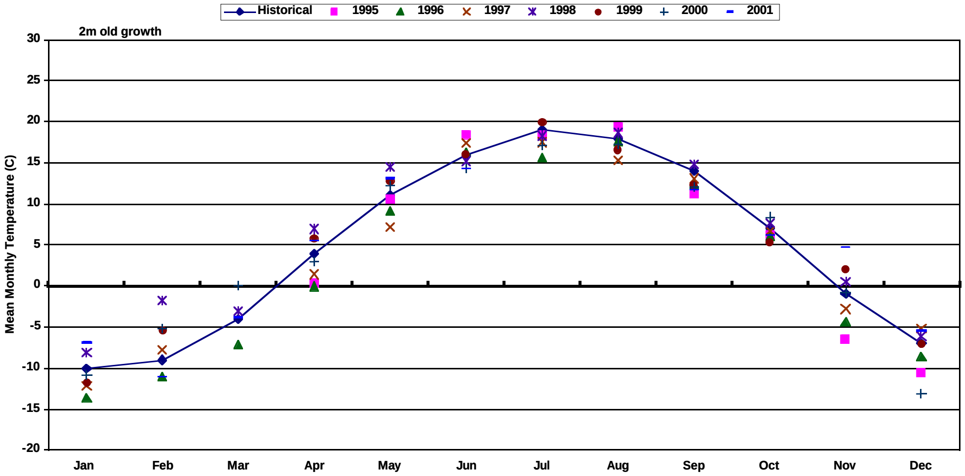


Figure 1. — *Mean monthly temperatures (˚ C) by year for the old-growth forest. Two-meter mean monthly temperatures are compared to the historical record (58 years) at 2 m for Marenisco, MI (source: www.weatherbase.com).*

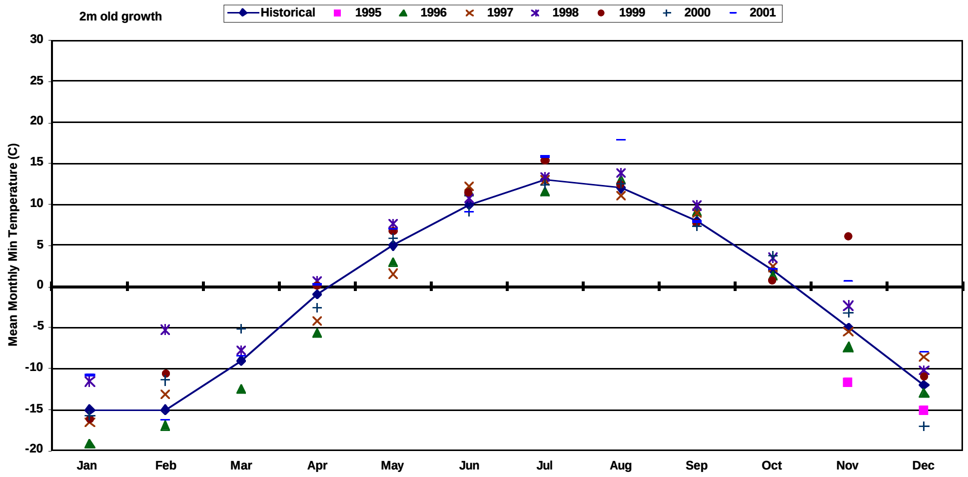


Figure 2. — *Mean monthly minimum temperatures (˚ C) by year for the old-growth forest. Two-meter mean monthly minimum temperatures are compared to the historical record (58 years) at 2 m for Marenisco, MI (source: www.weatherbase.com).*

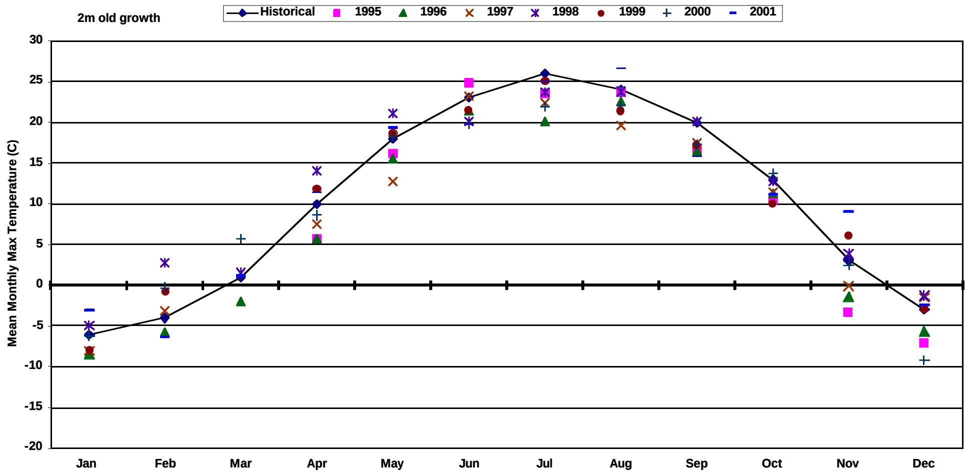
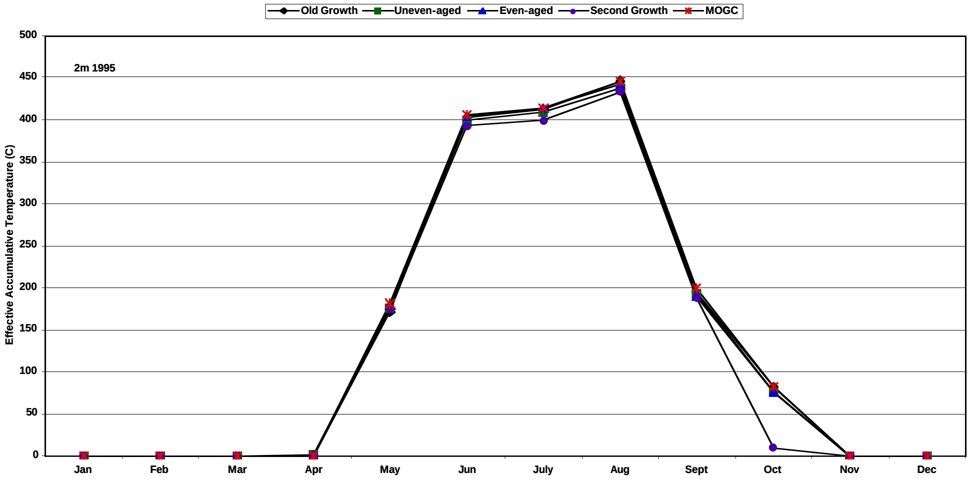


Figure 3. — *Mean monthly maximum temperatures (˚ C) by year for the old-growth forest. Two-meter mean monthly maximum temperatures are compared to the historical record (58 years) at 2 m for Marenisco, MI (source: www.weatherbase.com).*

among years (fig. 4a-f). When compared to other years, less accumulation of EAT in May and June is evident for 1996 and 1997. There was an abundance of snowfall in both years, and a snow pack was present well into May.

4a



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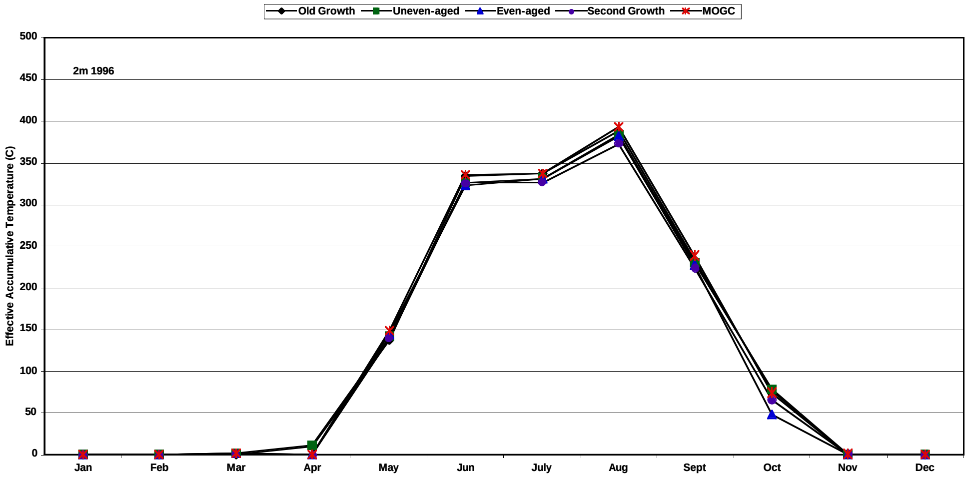

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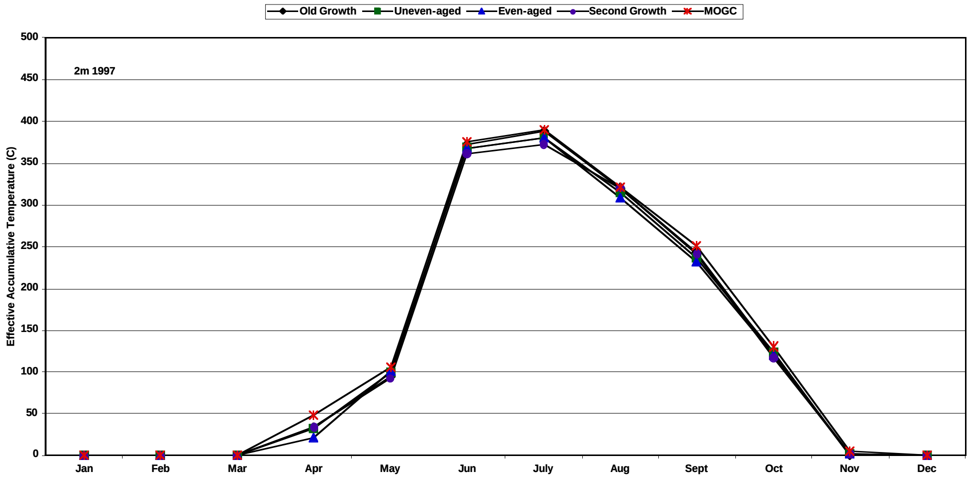

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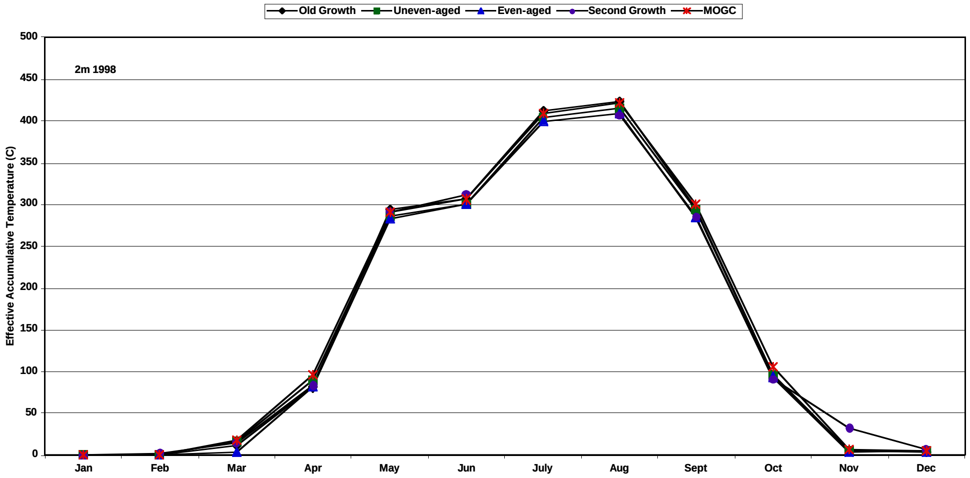

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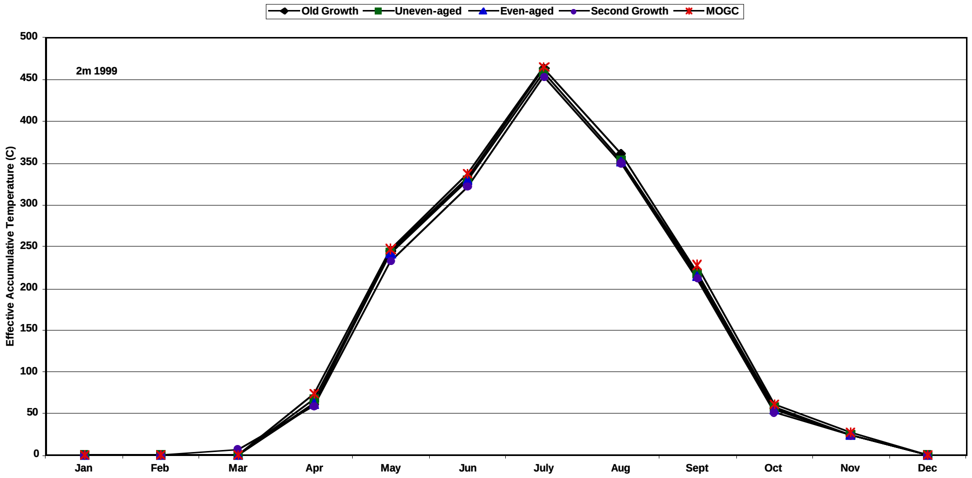

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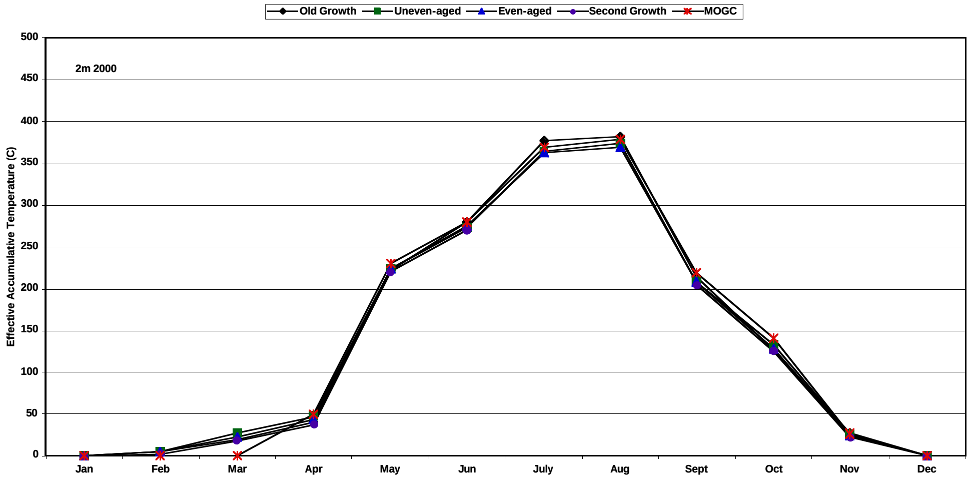

Figure 4a-f. — *Effective accumulative temperature (° C) calculated as the sum of the daily average temperature minus 5° C for each study year and site.*

Temperatures measured in a shelter under open conditions are likely to differ somewhat from those measured beneath a forest canopy. When we compared mean monthly minimum temperature (fig. 2) and mean monthly maximum temperature (fig. 3) between a weather station located under open conditions in Marenisco, MI, and our study sites, for example, the mean monthly minimum temperature beneath the canopy was consistently higher and the mean monthly maximum temperature beneath the canopy was consistently lower for the forest measurements compared to those recorded in the open during June, July, and August.

The highest average growing season precipitation (April through October) among the five study areas (485 mm) occurred in 1995, and the lowest average precipitation (275 mm) occurred in 1996. Most monthly precipitation totals measured during April through October in the old-growth forest fell below the 58-year average recorded for nearby Marenisco, MI (fig. 5). Precipitation measurments for Marenisco, however, were taken in the open, and the individual measurement at each study site was taken beneath the forest canopy. Obviously, interception of rain by the canopy accounts for some of the differences between our study site and the 58-year average.

The monthly precipitation during the growing season, the number of days in which rain was recorded, and the maximum rainfall per day for each site and each year are provided in table 1. On average, 65 percent of the mean total annual precipitation at the study sites occurred during the April through October growing season. Localized convective storms during the summer created large variations in monthly precipitation among study sites. The maximum rainfall for a single 24-hr period was 58.6 mm, recorded in the unmanaged second-growth forest in July 2000 (table 1). In comparison, the maximum recorded in the even-aged forest during the same month and year was 15.9 mm. Such differences were related more to spatial variation in rainfall than to differences in forest structure (e.g., canopy density) among the treatments.

A prevailing wind from the southwest (210-250°) was recorded in both summer (May – October) and winter (November – April) when all sites and years were averaged (fig. 6). Seasonal differences in wind direction did exist and were consistent from year to year

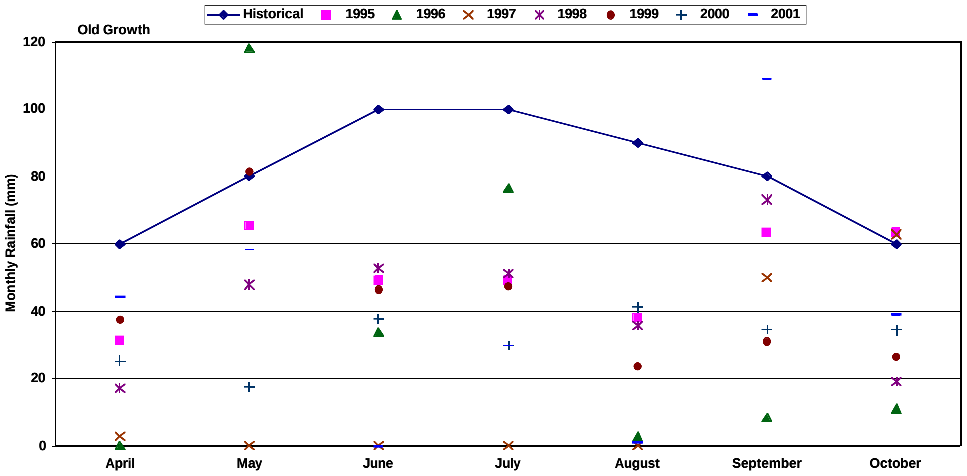

Figure 5. — *A comparison of monthly rainfall (mm) by year for the old-growth forest to the historical average (58 years) for Marenisco, MI (source: www.weatherbase.com).*

Table 1.—*Monthly rain (mm) during the growing season, number of days per month for which precipitation was measured, and the maximum daily precipitation (mm/day) recorded during the month by study site and year*

1995 Old Growth	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	31.5	98.1	59.1	98.4	65.0	94.9	95.0
# Rainy Days	10	15	12	20	17	15	15
Max Rainfall (mm/day)	9.0	21.2	14.6	41.8	11.1	34.0	36.3

1995 Uneven-aged	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	23.5	87.7	45.0	79.9	77.2	49.6	107.2
# Rainy Days	8	11	10	16	16	14	16
Max Rainfall (mm/day)	8.7	19.8	15.3	15.3	22.5	11.7	43.4

1995 Even-aged	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	28.7	104.6	27.9	101.0	59.5	53.3	93.3
# Rainy Days	8	12	12	20	15	14	18
Max Rainfall (mm/day)	11.8	22.2	11.0	22.9	10.1	13.4	28.1

1995 Unmanaged Second	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	22.5	84.2	49.1	95.0	68.4	56.2	96.9
# Rainy Days	9	13	11	23	15	13	17
Max Rainfall (mm/day)	9.1	16.8	25.1	19.1	14.3	13.5	32.2

1995 MOGC	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	26.0	99.6	43.6	83.7	73.5	50.4	96.9
# Rainy Days	9	15	9	19	14	13	17
Max Rainfall (mm/day)	10.0	20.4	14.9	20.3	16.0	14.0	32.2

1996 Old Growth	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	0.0	35.5	47.3	99.6	0.8	2.5	1.1
# Rainy Days	0	3	14	13	3	3	1
Max Rainfall (mm/day)	0.0	31.3	6.3	42.3	0.4	1.2	1.1

1996 Uneven-aged	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	0.0	44.3	67.0	108.5	48.7	28.3	6.5
# Rainy Days	0	4	19	18	10	16	3
Max Rainfall (mm/day)	0.0	42.2	24.2	21.2	23.1	5.7	3.7

1996 Even-aged	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	0.0	47.4	41.6	72.8	56.8	24.0	26.2
# Rainy Days	0	3	20	19	14	20	8
Max Rainfall (mm/day)	0.0	47.0	13.6	12.6	26.6	6.0	9.1

1996 Unmanaged Second	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	0.0	37.2	61.4	92.1	43.6	42.3	58.5
# Rainy Days	0	3	18	16	9	14	13
Max Rainfall (mm/day)	0.0	36.8	23.1	20.3	21.0	12.1	19.4

1996 MOGC	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	0.0	46.6	94.1	67.1	17.8	0.0	54.4
# Rainy Days	0	2	15	12	5	0	14
Max Rainfall (mm/day)	0.0	46.1	27.9	13.5	13.5	0.0	19.4

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(table 1 continued)

1997 Old Growth	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	0.6	0.0	0.0	0.0	0.0	60.2	75.5
# Rainy Days	2	0	0	0	0	12	12
Max Rainfall (mm/day)	0.4	0.0	0.0	0.0	0.0	28.8	26.7

1997 Uneven-aged	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	0.0	46.0	52.9	31.3	66.5	14.4	32.7
# Rainy Days	0	16	12	17	13	17	16
Max Rainfall (mm/day)	0.0	11.9	15.0	5.1	26.6	4.8	15.5

1997 Even-aged	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	0.0	62.8	25.6	39.8	25.8	36.8	55.3
# Rainy Days	0	17	19	16	12	17	14
Max Rainfall (mm/day)	0.0	15.2	9.3	24.2	16.6	31.0	19.4

1997 Unmanaged Second	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	0.0	62.3	44.4	59.4	61.4	39.9	87.5
# Rainy Days	0	18	17	12	21	17	17
Max Rainfall (mm/day)	0.0	16.2	13.0	25.2	39.4	24.5	26.2

1997 MOGC	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	0.0	64.5	48.1	14.7	129.9	49.9	78.3
# Rainy Days	0	19	10	10	14	11	15
Max Rainfall (mm/day)	0.0	14.1	12.5	5.2	52.2	18.0	22.3

1998 Old Growth	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	17.2	43.1	95.3	51.1	46.6	117.1	26.6
# Rainy Days	10	9	18	10	13	16	14
Max Rainfall (mm/day)	6.8	13.9	15.7	14.6	14.7	47.2	7.9

1998 Uneven-aged	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	9.3	13.2	59.5	39.1	19.0	78.6	14.8
# Rainy Days	10	8	12	13	11	20	11
Max Rainfall (mm/day)	4.6	7.1	22.8	8.4	6.4	40.2	3.7

1998 Even-aged	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	26.3	21.5	35.9	22.8	56.6	80.7	27.6
# Rainy Days	11	7	19	12	17	14	12
Max Rainfall (mm/day)	18.3	8.9	12.6	16.9	14.9	35.7	5.7

1998 Unmanaged Second	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	16.6	5.3	31.5	48.0	41.6	75.5	22.2
# Rainy Days	8	8	14	11	12	17	15
Max Rainfall (mm/day)	9.1	1.5	19.6	16.6	9.8	21.4	6.4

1998 MOGC	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	25.7	18.7	66.7	68.8	35.5	9.0	0.0
# Rainy Days	8	8	14	11	9	3	0
Max Rainfall (mm/day)	16.8	8.1	32.7	24.6	11.2	8.7	0.0

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1999 Old Growth	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	33.7	114.1	51.1	71.3	63.5	46.5	37.1
# Rainy Days	9	14	11	15	27	15	14
Max Rainfall (mm/day)	8.6	35.0	22.5	31.4	18.9	20.8	10.0

1999 Uneven-aged	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	2.8	88.6	6.5	68.5	15.7	24.0	31.8
# Rainy Days	4	15	4	11	22	16	15
Max Rainfall (mm/day)	1.6	18.6	2.3	18.7	4.4	10.2	5.5

1999 Even-aged	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	25.9	77.1	44.9	85.3	53.8	43.9	36.0
# Rainy Days	9	23	24	27	17	14	13
Max Rainfall (mm/day)	2.6	33.0	17.1	26.9	8.0	7.4	7.6

1999 Unmanaged Second	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	22.5	84.2	49.1	95.0	68.4	56.2	96.9
# Rainy Days	9	13	11	23	15	13	17
Max Rainfall (mm/day)	6.8	20.2	29.0	24.5	20.3	17.6	6.9

1999 MOGC	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	0.5	100.7	54.0	29.1	7.0	32.2	34.2
# Rainy Days	1	14	19	3	6	15	13
Max Rainfall (mm/day)	0.5	33.5	21.5	17.7	2.9	11.6	8.4

2000 Old Growth	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	35.4	34.9	75.2	68.7	41.1	37.9	44.7
# Rainy Days	14	20	20	23	10	11	13
Max Rainfall (mm/day)	5.8	11.3	20.3	25.2	20.0	10.8	15.9

2000 Uneven-aged	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	27.1	14.7	20.3	54.8	29.2	33.3	24.7
# Rainy Days	15	14	5	6	8	13	10
Max Rainfall (mm/day)	3.4	3.6	15.4	37.7	16.0	10.3	12.5

2000 Even-aged	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	36.3	31.4	44.8	25.5	35.7	26.9	35.9
# Rainy Days	17	16	24	6	8	13	12
Max Rainfall (mm/day)	10.3	7.8	10.0	15.9	24.2	8.1	20.0

2000 Unmanaged Second	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	31.7	27.0	39.1	76.8	3.0	50.2	38.3
# Rainy Days	17	15	23	13	2	18	9
Max Rainfall (mm/day)	5.5	6.3	12.4	58.6	2.9	22.1	23.6

2000 MOGC	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Monthly PPT (mm)	32.8	24.3	67.8	42.3	42.1	54.7	40.4
# Rainy Days	16	13	10	7	10	16	11
Max Rainfall (mm/day)	6.4	4.7	26.2	34.5	23.3	27.6	24.0

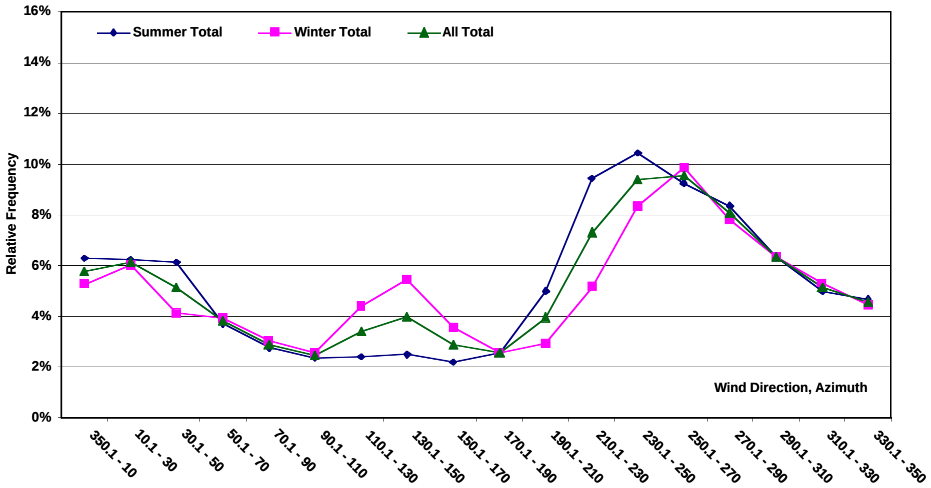


Figure 6. — *Average wind direction (azimuth°) by season for the old-growth forest based on 1995-2000 measurements. The summer season is May through October; the winter season is November through April. Winter direction is plotted by 20° classes and is based on hourly measurements of wind direction. (Missing data points accounted for 6.66% of the total).*

(fig. 7a-f). In all years, winds from the southeast were more common during the winter and winds from the southwest were more common during the summer.

Lower maximum wind speeds were generally recorded during the summer (June, July, August, and September), although the highest rates recorded during the study, 9.87 m s^{-1}, occurred during a July convective storm at the old-growth site in 1999 (table 2). In reference to this particular storm (JD 211) at the old-growth site, there was not only a maximum wind speed of 9.87 m s^{-1} but a daily total of 22.4 mm of rain and a 24-hr average wind direction of 242º (std = 40.13) azimuth. At the managed uneven-aged site, a maximum wind speed of 6.2 m sec^{-1} was recorded with a daily total of 13.6 mm of rain and 24-hr average wind direction of 210.8º (std = 30.04). At the unmanaged second-growth site, a maximum wind speed of 6.7 m s^{-1} was recorded with a daily rain total of 5.6 mm and a 24-hr average wind direction of 244.5º (std = 30.06). The managed even-aged site had a maximum-recorded wind speed of 4.4 m s^{-1}, a daily rain total of 22.1 mm, and a 24-hr average wind direction of 107.7º (std = 50.42). Finally, the MOGC site had a maximum-recorded wind speed of 4.5 m s^{-1}, a daily rain total of 17.7 mm, and a 24-hr average wind direction of 217.7º (std = 29.7) (appendix 1, table 2).

Significant reductions in PAR beneath the canopy during the growing season occurred between 1995 and 2000. Although light levels varied greatly among days, the mean values reached 250 µmol m^{-2} s^{-1} early in the 1995 growing season (fig. 8a) compared to 160 µmol m^{-2} s^{-1} in the 2000 growing season (fig. 8b). At maximum leaf area, mean daily PAR commonly reached 100 µmol m^{-2} s^{-1} in 1995, but only 80 µmol m^{-2} s^{-1} in 2000.

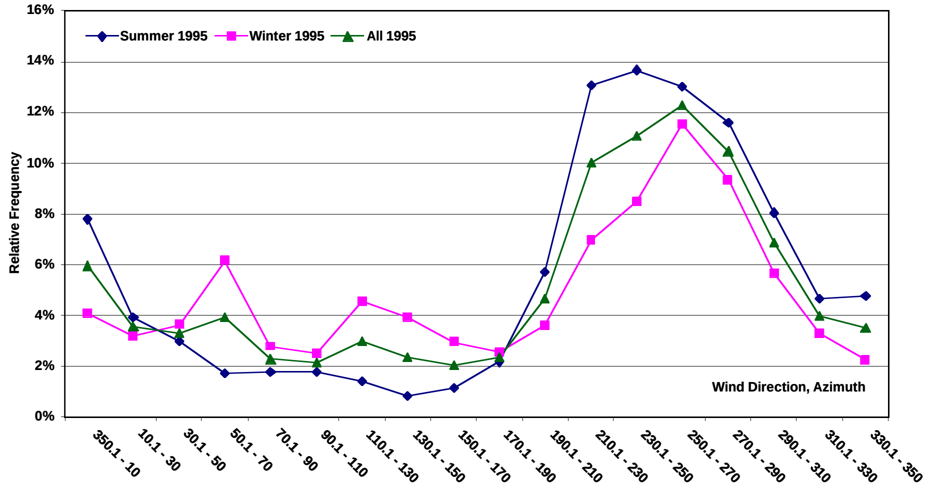
Comparisons Among Treatments and Baselines

Comparisons of mean hourly PAR (µmol m^{-2} s^{-1}) values among treatments and baselines showed substantial differences during the January, April, and October leaf-off periods as well as during leaf-on (July) (fig. 9a-d). Comparisons were reported for 1999 due to

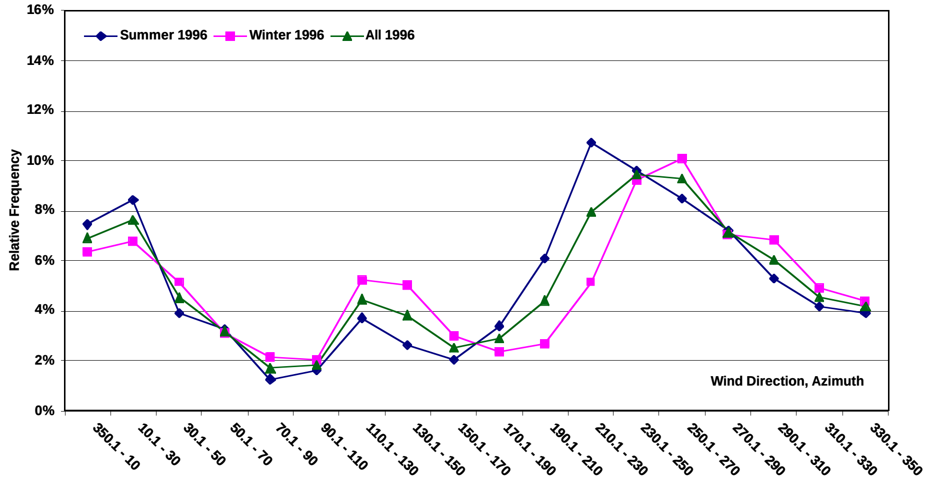
Table 2. —*Maximum wind speed (m s^{-1}) recorded for each month at each study site for 1995-2000*

1995	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Old Growth	5.2	7.2	5.3	6.3	6.2	8.2	3.6	3.3	4.9	6.3	6.3	7.5
Uneven-aged	6.4	8.0	4.8	6.4	6.0	7.9	3.3	2.6	3.3	6.6	5.7	6.6
Even-aged	7.2	7.5	6.2	7.4	6.5	2.6	3.8	3.4	2.8	6.7	6.1	7.4
Unmanaged SG	5.0	5.2	4.2	5.7	5.9	2.8	3.4	2.8	2.8	5.2	5.0	5.1
MOGC	7.3	6.2	7.0	6.7	6.2	3.0	4.6	4.3	4.0	7.3	6.2	6.9
1996	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Old Growth	5.8	5.7	5.9	6.1	6.9	3.8	3.1	3.1	3.1	7.6	7.9	4.4
Uneven-aged	2.5	5.7	7.0	5.5	6.4	3.7	3.0	3.7	2.9	7.6	6.9	5.6
Even-aged	7.1	5.6	6.2	5.7	6.8	3.4	2.3	2.3	3.0	6.0	6.9	5.4
Unmanaged SG	6.1	4.6	6.0	4.6	5.1	4.3	2.6	4.5	2.5	6.3	5.5	5.7
MOGC	6.2	7.2	7.3	5.8	6.7	3.8	3.3	3.9	4.3	7.9	7.8	6.6
1997	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Old Growth	5.3	7.2	6.4	7.3	8.1	3.4	3.5	2.6	3.9	6.5	5.5	4.5
Uneven-aged	5.4	7.0	5.9	6.3	5.9	3.1	2.3	0.6	3.3	6.0	4.6	5.2
Even-aged	5.8	6.8	6.8	6.7	7.0	3.1	3.08	1.9	3.1	6.4	4.3	5.6
Unmanaged SG	6.4	4.8	5.8	4.7	5.8	3.0	2.4	1.6	3.0	5.0	4.7	4.2
MOGC	6.6	7.0	6.5	6.8	6.6	3.6	4.8	3.0	4.6	7.8	7.8	5.4
1998	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Old Growth	4.8	5.8	5.6	7.1	4.2	3.80	3.5	2.9	3.4	7.0	7.7	6.08
Uneven-aged	5.2	5.4	7.2	7.0	4.2	3.0	4.6	2.2	3.4	7.0	6.4	5.2
Even-aged	5.2	3.1	4.8	9.0	4.1	3.3	3.5	2.8	3.9	7.6	3.8	1.0
Unmanaged SG	4.6	5.2	6.0	5.2	3.7	2.8	4.5	3.5	2.8	4.3	5.4	4.9
MOGC	5.7	7.1	7.1	7.2	4.9	3.6	3.4	3.4	4.1	6.4	9.9	5.7
1999	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Old Growth	5.8	6.7	4.2	5.7	4.6	4.3	9.9	3.2	4.5	6.7	4.5	8.4
Uneven-aged	6.1	6.4	4.7	5.7	4.7	2.5	6.2	2.4	5.3	7.4	8.0	8.8
Even-aged	0.2	0.2	7.0	5.7	5.5	3.9	4.4	3.3	4.0	8.4	7.5	9.3
Unmanaged SG	4.9	6.0	0.2	6.0	4.9	4.1	6.6	6.7	3.4	6.4	6.0	6.4
MOGC	5.7	6.2	5.4	5.2	6.6	5.2	4.5	2.5	5.1	7.6	7.9	7.0
2000	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Old Growth	5.4	6.2	7.4	5.8	4.9	3.9	2.9	2.6	3.4	4.8	6.0	5.6
Uneven-aged	6.0	7.3	7.5	6.1	5.6	3.2	2.6	3.0	3.1	4.3	5.5	5.4
Even-aged	5.8	6.3	6.9	6.2	5.8	4.8	3.0	3.4	3.4	6.0	6.1	5.8
Unmanaged SG	4.5	4.2	5.4	5.7	4.0	3.4	2.4	2.0	2.8	4.0	5.4	4.8
MOGC	6.0	6.4	5.4	6.4	5.7	4.9	4.6	3.2	4.8	5.1	7.0	5.9

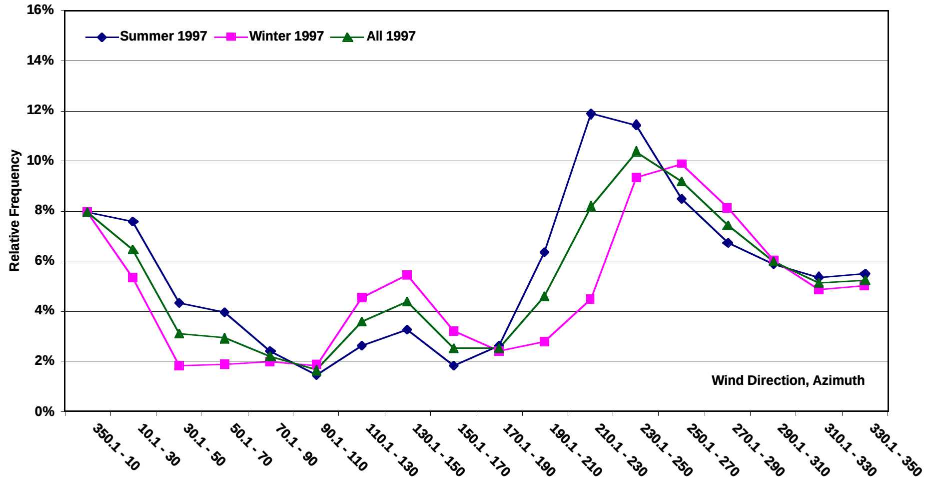
7a


Summer 1995
Winter 1995
All 1995
16%
14%
12%
10%
8%
6%
4%
2%
0%
Relative Frequency
Wind Direction, Azimuth
350.1 - 10
10.1 - 30
30.1 - 50
50.1 - 70
70.1 - 90
90.1 - 110
110.1 - 130
130.1 - 150
150.1 - 170
170.1 - 190
190.1 - 210
210.1 - 230
230.1 - 250
250.1 - 270
270.1 - 290
290.1 - 310
310.1 - 330
330.1 - 350

7b


Summer 1996
Winter 1996
All 1996
16%
14%
12%
10%
8%
6%
4%
2%
0%
Relative Frequency
Wind Direction, Azimuth
350.1 - 10
10.1 - 30
30.1 - 50
50.1 - 70
70.1 - 90
90.1 - 110
110.1 - 130
130.1 - 150
150.1 - 170
170.1 - 190
190.1 - 210
210.1 - 230
230.1 - 250
250.1 - 270
270.1 - 290
290.1 - 310
310.1 - 330
330.1 - 350

7c


Summer 1997
Winter 1997
All 1997
16%
14%
12%
10%
8%
6%
4%
2%
0%
Relative Frequency
Wind Direction, Azimuth
350.1 - 10
10.1 - 30
30.1 - 50
50.1 - 70
70.1 - 90
90.1 - 110
110.1 - 130
130.1 - 150
150.1 - 170
170.1 - 190
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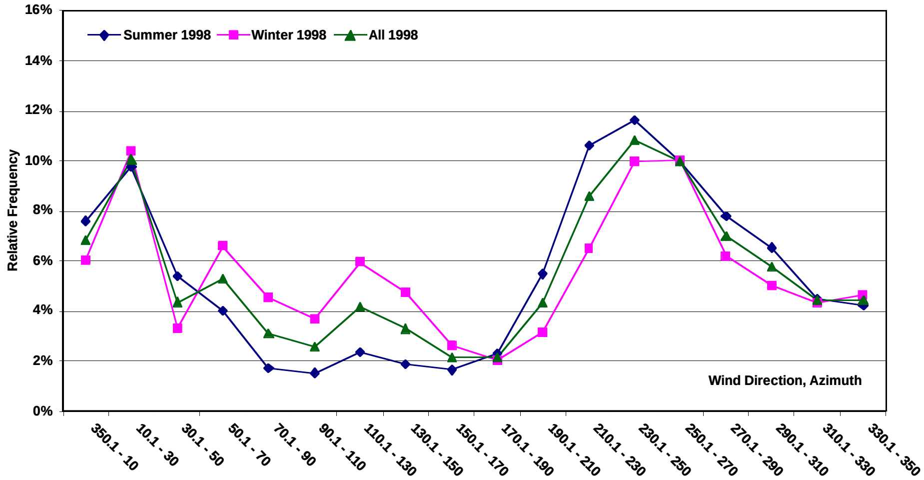
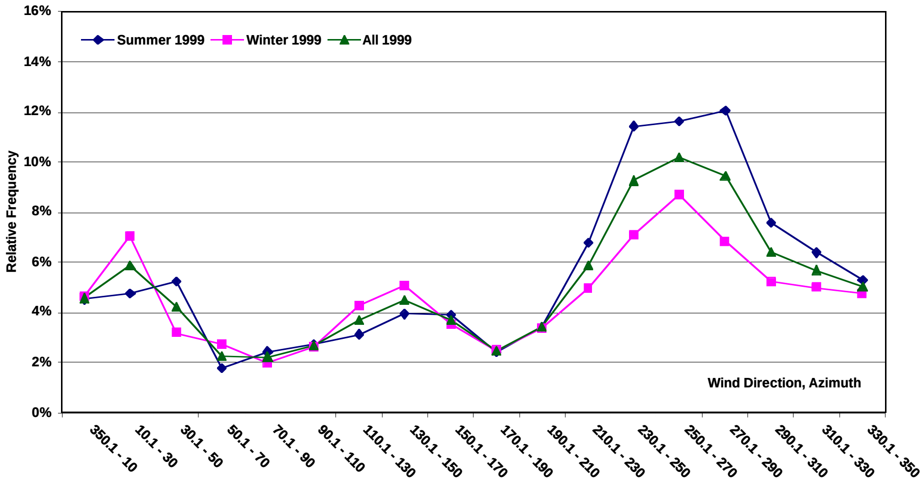
310.1 - 330
330.1 - 350

7d



7e



7f

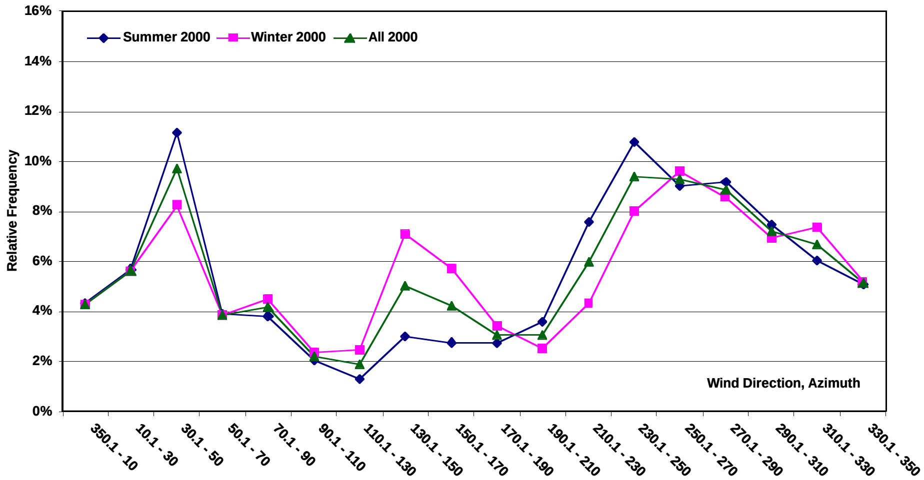


Figure 7a-f. — *Average wind direction (azimuth°) by season and year (7a, 1995; 7b, 1996; 7c, 1997; 7d, 1998; 7e, 1999; and 7f, 2000) measured in the old-growth forest. The summer season is May through October; the winter season is November through April. Winter direction is plotted by 20º classes and is based on hourly measurements of wind direction. (Missing data points accounted for 6.24% of the total for 1995, 7.60% for 1996, 6.62% for 1997, 0.63% for 1998, 8.47% for 1999, and 0.31% for 2000).*

8a

8b

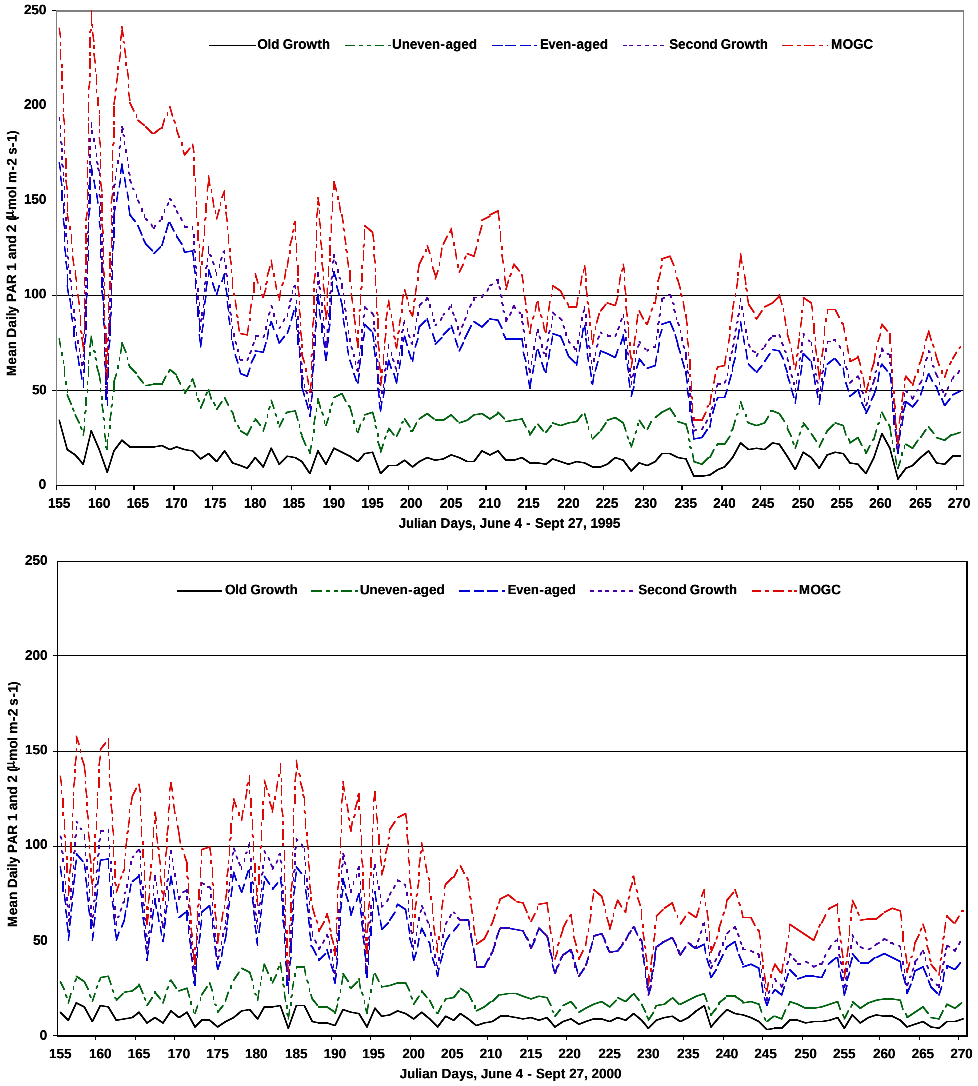
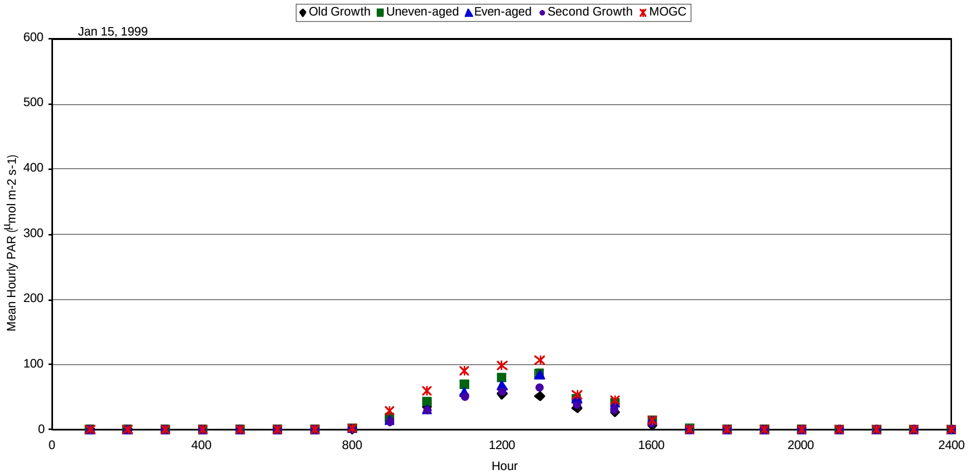


Figure 8a,b. — *Mean daily PAR* (μ*mol m*$^{-2}$ *s*$^{-1}$) *for growing season (June – September), 1995 and 2000.*

9a



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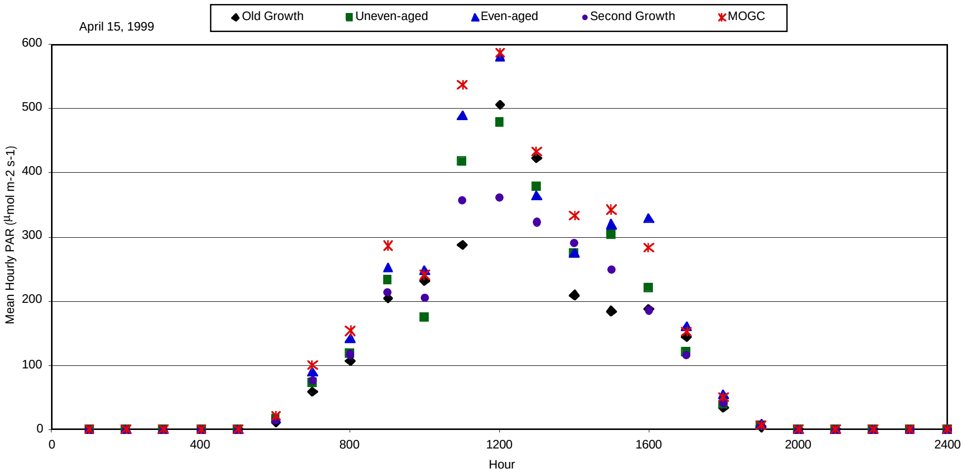

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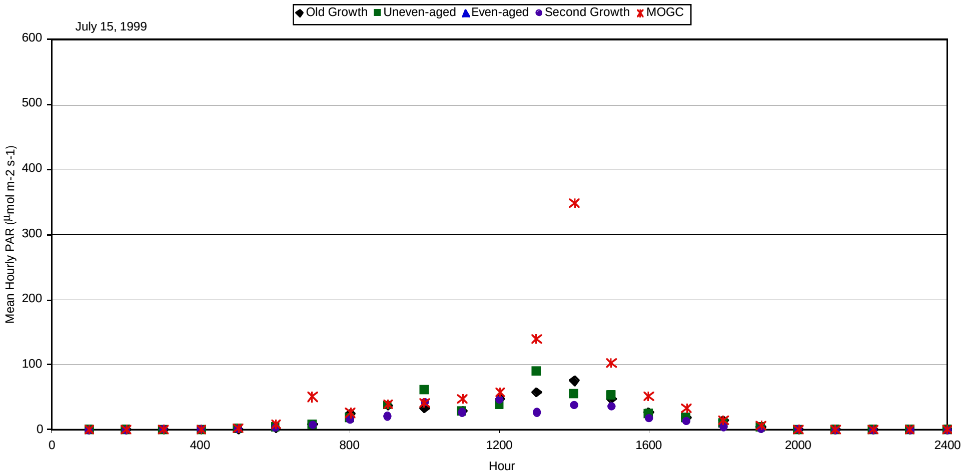


9d

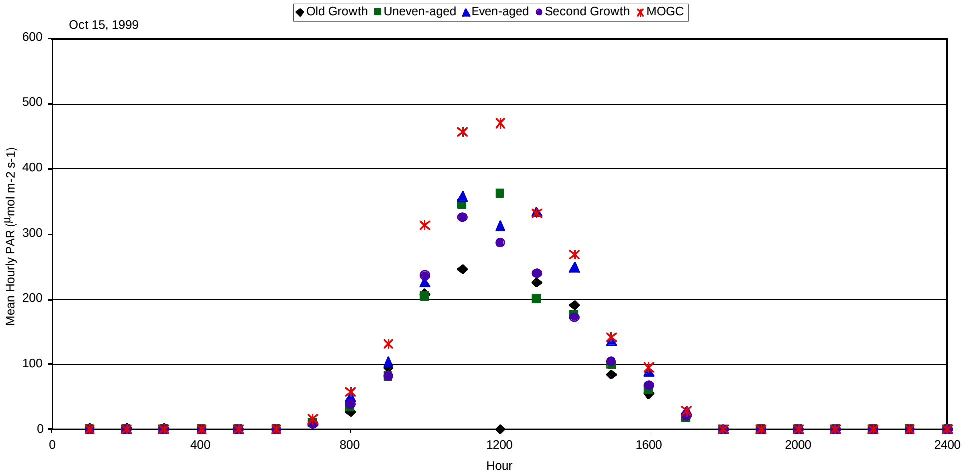
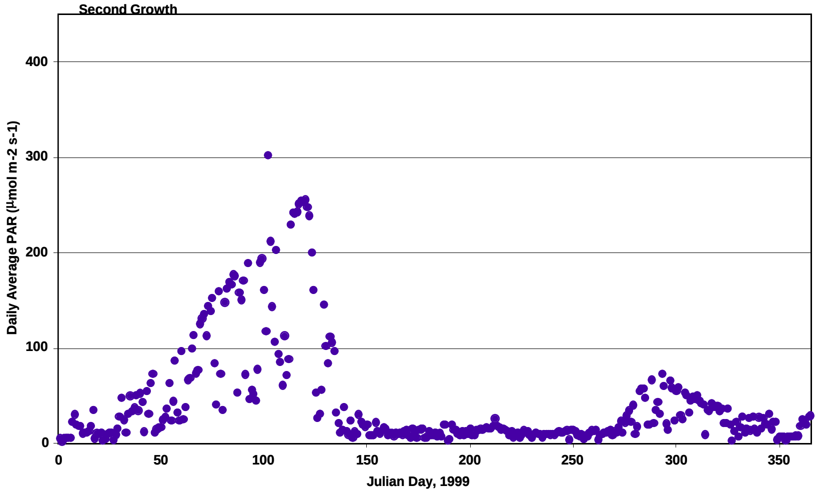


Figure 9a-d.—*Mean hourly PAR (µmol m^{-2} s^{-1}) are compared among baselines and treatments for January 15 (a), April 15 (b), July 15 (c), and October 15 (d), 1999.*

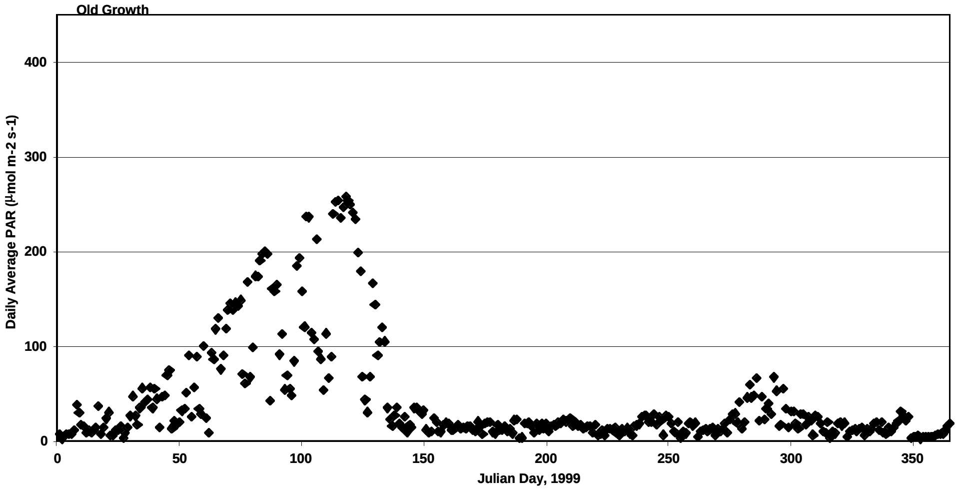
the completeness of the record for that year. As expected, the high values were measured in the spring (fig. 9b) when the sun angle was relatively high and before leaf flush occurred in the overstory, and the low values were measured during the summer because of canopy coverage and during the winter because of low sun angle (fig. 9a, c). The greatest absolute differences in mean hourly values were also measured in April, when average PAR values ranged from 360 µmol m^{-2} s^{-1} for the unmanaged second growth to nearly 600 µmol m^{-2} s^{-1} for even-aged and MOGC (fig. 9b). The greatest relative differences between highest and lowest average PAR values, however, occurred in July (fig. 9c). The July averages also had a number of outliers that suggest the influence of sun flecks.

Understory light declined abruptly with leaf expansion (fig. 10a-e). Peak values, which are a function of leaf phenology, occurred at approximately Julian Day 120-130 in the study areas, depending on the year. In 1999, daily averages based on measurements taken at 1 m above the forest floor were about 250 µmol m^{-2} s^{-1} for the unmanaged forests (fig. 10a, b), compared to peak values of 300 to 450 µmol m^{-2} s^{-1} for the three managed forests (fig. 10c - e). During leaf-on, average daily PAR in the understory generally ranged from 5 to 15 µmol m^{-2} s^{-1} for unmanaged second growth, 5 to 30 µmol m^{-2} s^{-1} for old growth, 10 to 60 µmol m^{-2} s^{-1} for even-aged, 5 to 25 µmol m^{-2} s^{-1} for uneven-aged, and 5 to 70 µmol m^{-2} s^{-1} for MOGC. A secondary spike in daily average PAR occurred in the fall

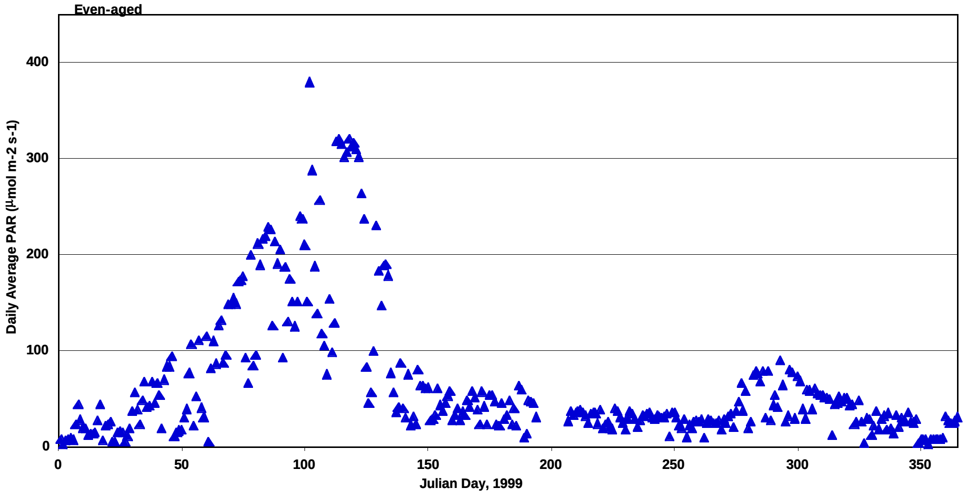
10a



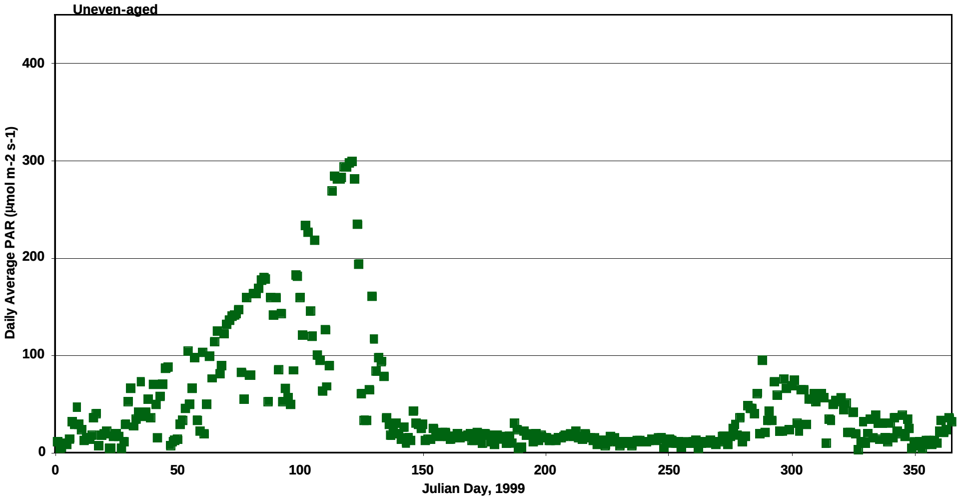
10b



10c



10d



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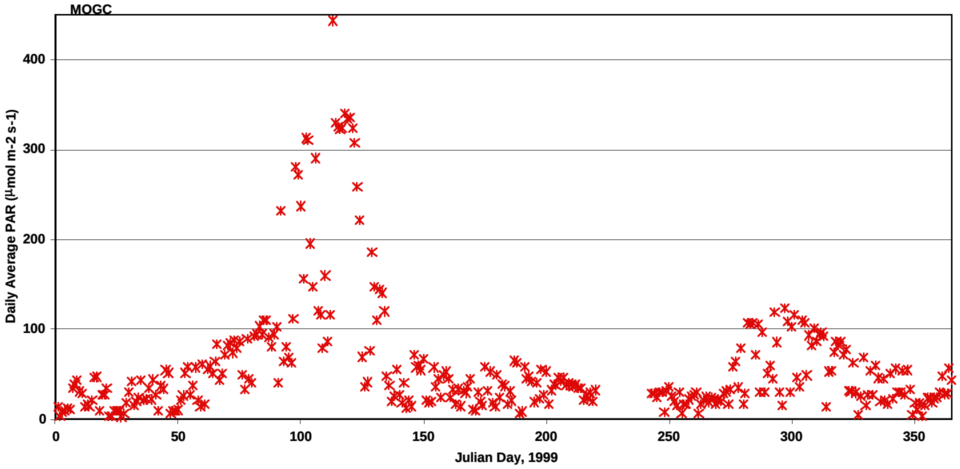
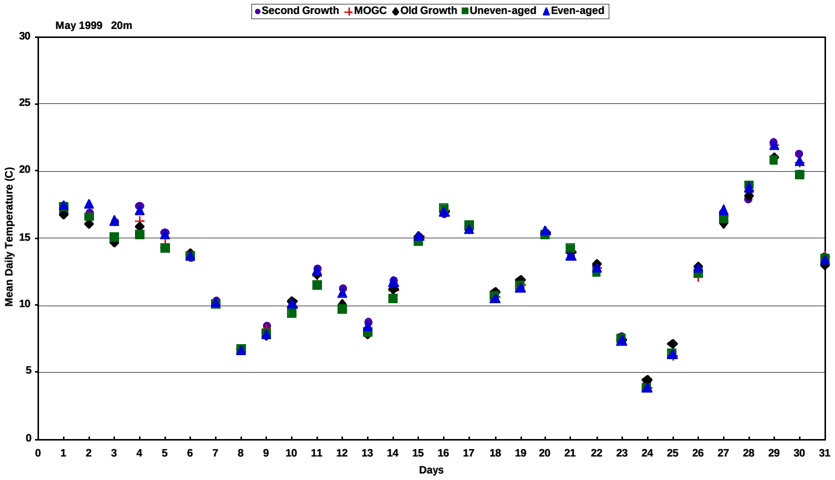


Figure 10a-e.—*Daily average PAR (*µ*mol m^{-2} s^{-1}) plotted by baselines (second growth, a; old growth, b) and treatments (even-aged, c; uneven-aged, d; MOGC, e) for the year 1999. Zero values indicate missing data.*

following leaf drop. Although the peak values were lower than those in the spring due to the lower sun angle, peak values were still higher in managed compared to unmanaged forests.

There were no significant differences (P>0.05) among the aboveground daily mean temperatures by treatment or baseline at 20, 10, 2, and 0.05 m for any of these months (see fig. 11a - d for May 1999 and fig. 12a - d for July 1999). Significant differences did exist among treatments when day temperatures (0600-1800) were compared with night temperatures (1900-0500) at 20 m (F=17.3, df =4, P<0.01) and 2 m (F=23.2, df = 4, P<0.01) for July 1999. Although the effect of treatment was highly significant when comparing day to night temperatures, the amount of variation accounted for by Julian Day and time of day in the ANOVA model was far greater at both 2 m (F=1635.6 for Julian Day and F=13817.6 for time) and 20 m (F=344.6 for Julian Day and F=2202.0 for time).

11a



11b

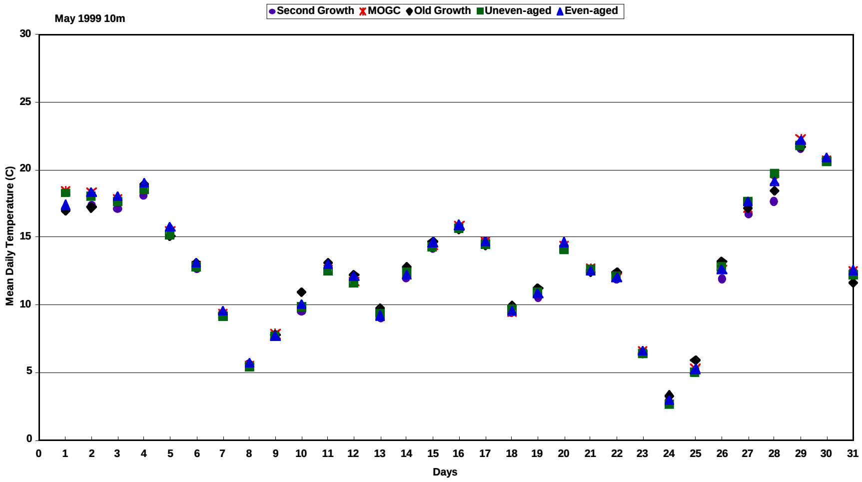
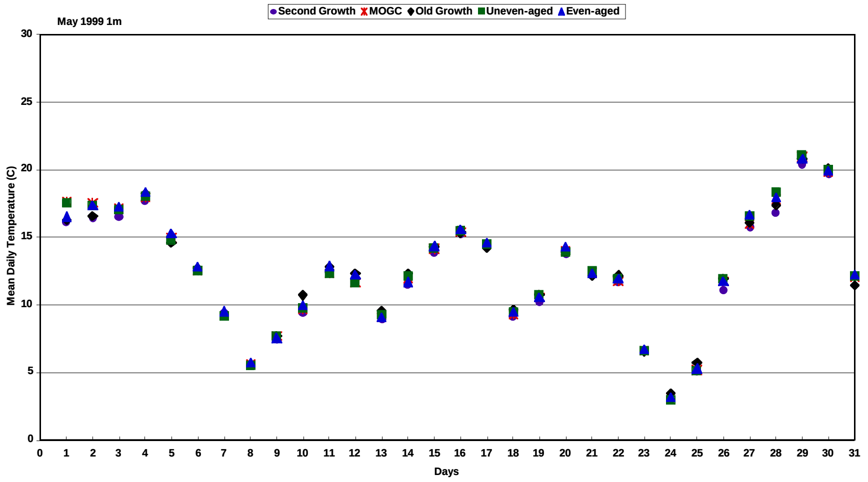
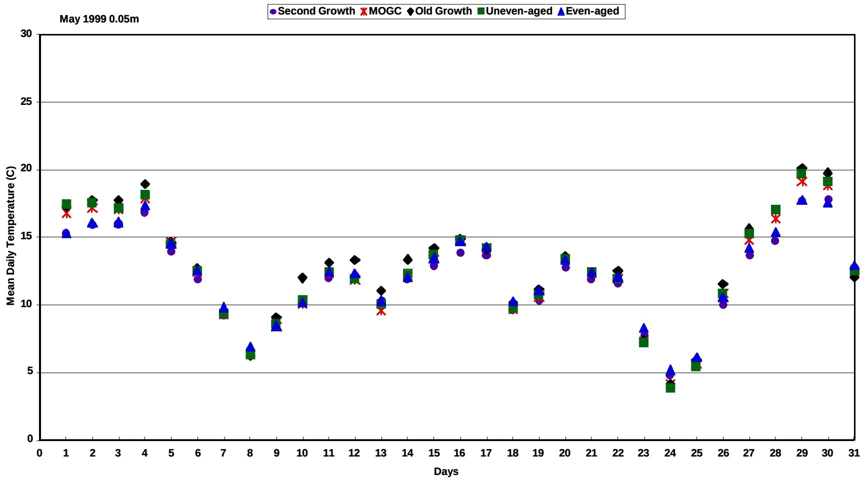


Figure 11a-h. — *Mean daily temperature (º C) during May 1999 by treatment. Aboveground measurements were taken within the canopy at 20 m (a), within the subcanopy at 10 m (b), and above the forest floor at 1 m (c), 0.05 m (d), and on the forest floor (e). Belowground measurements were taken at –0.05 m (f), -0.2 m (g), and -1.0 m (h).*

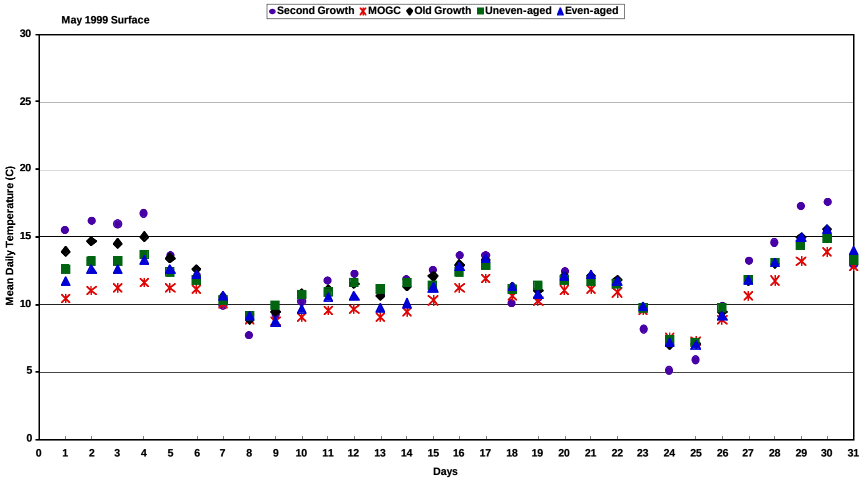
11c


● Second Growth ✕ MOGC ◆ Old Growth ■ Uneven-aged ▲ Even-aged
May 1999 1m
Mean Daily Temperature (C)
0
5
10
15
20
25
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Days

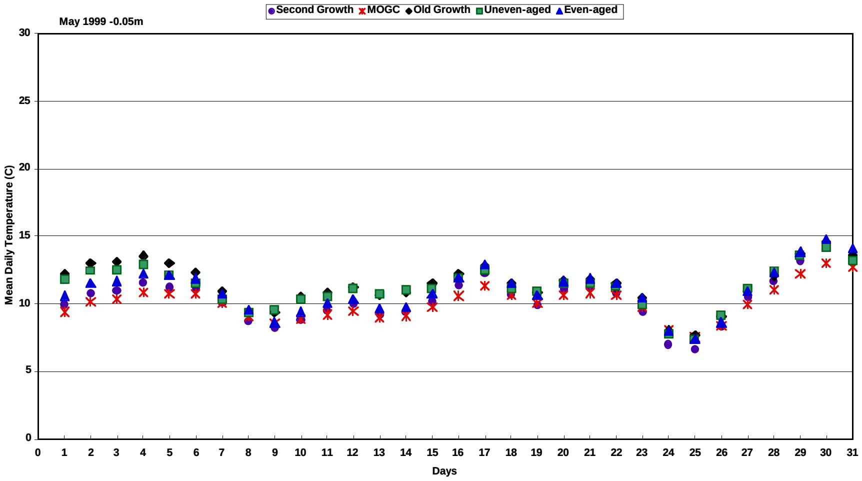
11d


● Second Growth ✕ MOGC ◆ Old Growth ■ Uneven-aged ▲ Even-aged
May 1999 0.05m
Mean Daily Temperature (C)
0
5
10
15
20
25
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Days

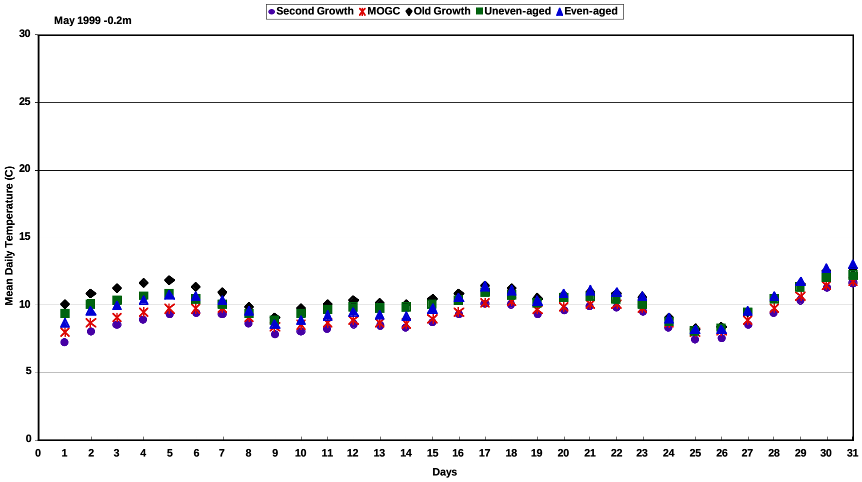
11e


● Second Growth ✕ MOGC ◆ Old Growth ■ Uneven-aged ▲ Even-aged
May 1999 Surface
Mean Daily Temperature (C)
0
5
10
15
20
25
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Days

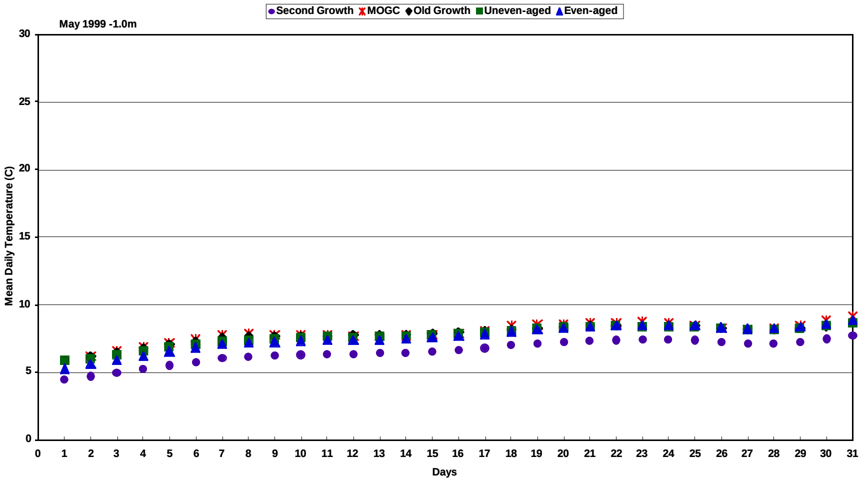
11f


● Second Growth
✕ MOGC
◆ Old Growth
■ Uneven-aged
▲ Even-aged
May 1999 -0.05m
Mean Daily Temperature (C)
0
5
10
15
20
25
30
Days
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

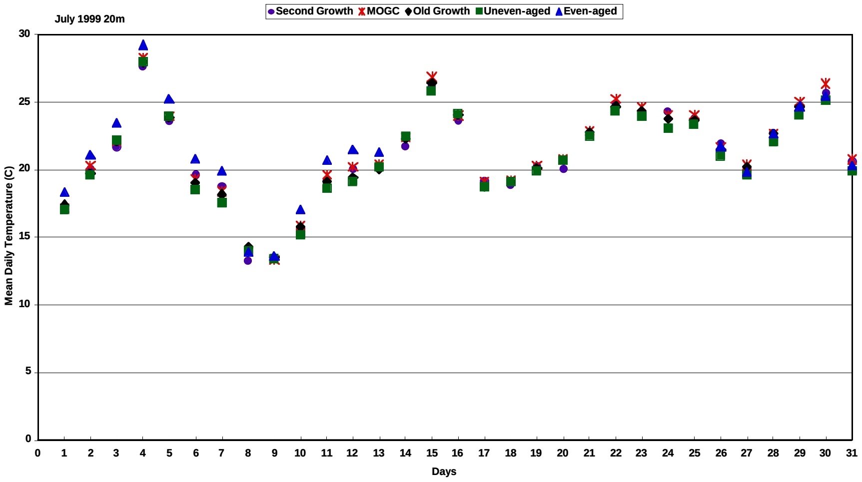
11g


● Second Growth
✕ MOGC
◆ Old Growth
■ Uneven-aged
▲ Even-aged
May 1999 -0.2m
Mean Daily Temperature (C)
0
5
10
15
20
25
30
Days
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

11h


● Second Growth
✕ MOGC
◆ Old Growth
■ Uneven-aged
▲ Even-aged
May 1999 -1.0m
Mean Daily Temperature (C)
0
5
10
15
20
25
30
Days
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

12a



12b

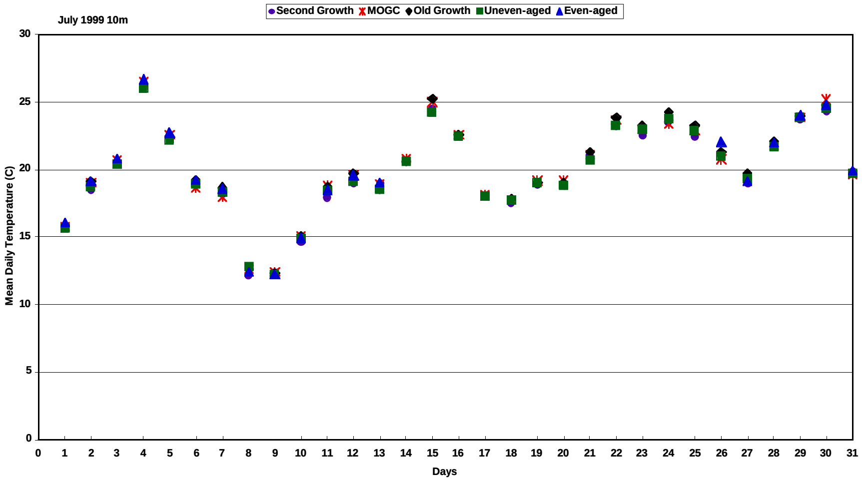
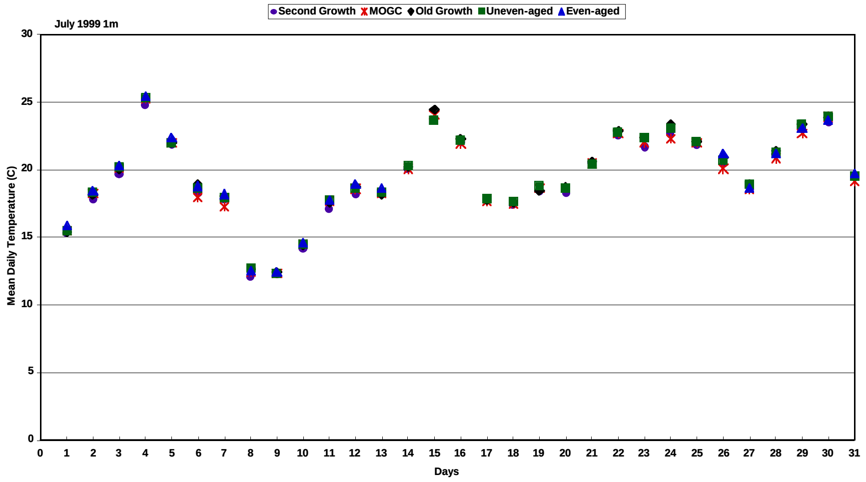
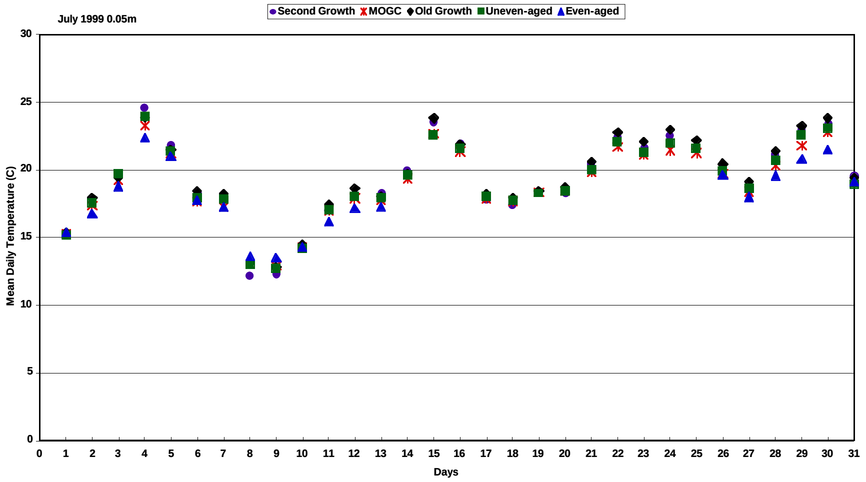


Figure 12a-h. — *Mean daily temperature (º C) during July 1999 by treatment. Aboveground measurements were taken within the canopy at 20 m (a), within the subcanopy at 10 m (b), and above the forest floor at 1 m (c), 0.05 m (d), and on the forest floor (e). Belowground measurements were taken at -0.05 m (f), -0.2 m (g), and -1.0 m (h).*

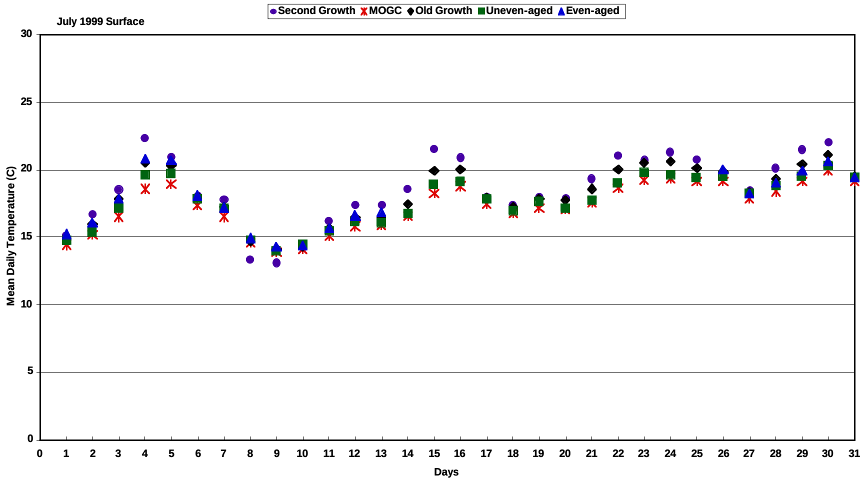
12c


●Second Growth ✗MOGC ◆Old Growth ■Uneven-aged ▲Even-aged
July 1999 1m
Mean Daily Temperature (C)
0
5
10
15
20
25
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Days

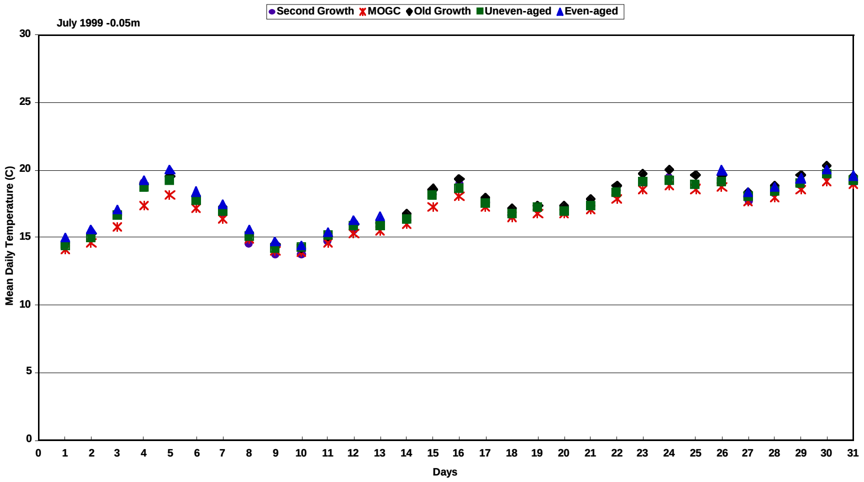
12d


●Second Growth ✗MOGC ◆Old Growth ■Uneven-aged ▲Even-aged
July 1999 0.05m
Mean Daily Temperature (C)
0
5
10
15
20
25
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Days

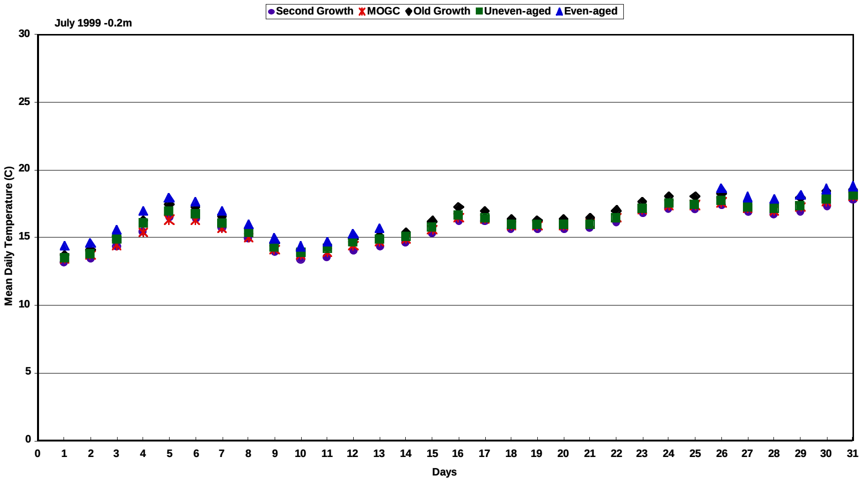
12e


●Second Growth ✗MOGC ◆Old Growth ■Uneven-aged ▲Even-aged
July 1999 Surface
Mean Daily Temperature (C)
0
5
10
15
20
25
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Days

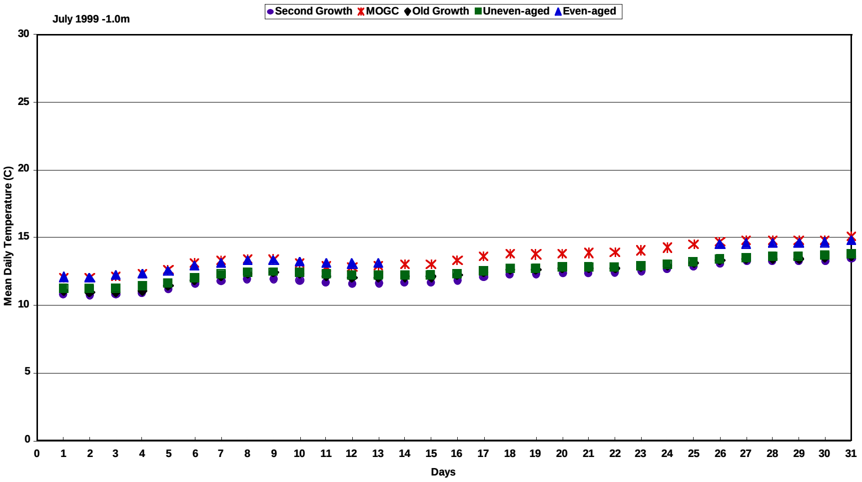
12f


●Second Growth ✕MOGC ◆Old Growth ■Uneven-aged ▲Even-aged
July 1999 -0.05m
Mean Daily Temperature (C)
0
5
10
15
20
25
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Days

12g


●Second Growth ✕MOGC ◆Old Growth ■Uneven-aged ▲Even-aged
July 1999 -0.2m
Mean Daily Temperature (C)
0
5
10
15
20
25
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Days

12h


●Second Growth ✕MOGC ◆Old Growth ■Uneven-aged ▲Even-aged
July 1999 -1.0m
Mean Daily Temperature (C)
0
5
10
15
20
25
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Days

Significant differences in mean daily temperatures among treatments also occurred at the forest floor and belowground (P<0.05), although the relative position of the means among the various treatments varied (see fig. 11e - h for May and fig. 12e - h for July 1999). Before leaf flush in the overstory (May 1 - 5, 1999, fig. 11e), the mean daily temperatures on the forest floor varied by 6 to 7° C among the unmanaged baselines and treatments, with Second Growth>Old Growth>Uneven>Even>MOGC.

Different trends in daily mean temperatures occurred with increasing soil depth. Again, considering the period before leaf-out in early May 1999, the relative temperatures were:

> Old Growth>Uneven>Even>Second Growth>MOGC at -0.05 m (fig. 11f),
>
> Old Growth>Uneven>Even>MOGC> Second Growth at -0.2 m (fig. 11g),
>
> MOGC>Old Growth>Uneven>Even> Second Growth at -1.0 m (fig. 11h).

For comparison, the relative belowground temperatures after leaf fall in late October 1999 were:

> Uneven>MOGC>Even>Second Growth>Old Growth at -0.05 m,
>
> Uneven>MOGC>Second Growth> Even>Old Growth at -0.2 m,
>
> Uneven>Even>MOGC=Second Growth>Old Growth at -1.0 m.

The differences among treatments and baselines in all cases, both spring and fall measurements at all depths, were generally <2° C.

Effective accumulative temperatures (EAT, >5° C) by treatment or baseline for each month and year showed some differentiation in the spring and summer of 1995, but fewer differences in subsequent years (fig. 4a-f). The differences cannot be sorted by management condition, e.g., managed forests > unmanaged forests, but they do offer a comparison among years.

During the winter of 1996-1997, snow depths varied significantly among measurement dates (F=1022.4, df=4, P<0.001), among treatments and baselines (F=18.7, df=4, P<0.001), and marginally among the three measurement stakes at each site (F=3.8, df=2, P=0.03). Based on Tukey's Studentized Range (HSD) Test, mean snow depths for the old-growth, even-aged, and second-growth forests, 40.0, 39.3, and 36.5 cm, respectively, differed significantly from mean snow depths for the MOGC and uneven-aged forests, 32.5 and 31.7 cm, respectively. As suggested by F-values, differences in snow depth among measurement dates accounted for the vast majority (95%) of variation in the ANOVA model.

Discussion and Conclusions

Measurements of light, temperature, and precipitation provide baseline information for a study of the impacts of silviculture treatments on the composition, structure, and function of northern hardwood forests (Crow *et al.* 2002; Fisk *et al.* 2002; Kent *et al.*, in press). During the period of the study, 1995-2001, the variation in mean monthly temperatures and monthly precipitation suggests that the study was conducted under a wide range of climatic conditions including warmer and drier than normal as well as cooler and wetter than normal. This is important because the relationship between microclimate temperatures and forest structure is not constant but varies depending on the magnitude of the temperature (Potter *et al.* 2001). In their study of the impact of forest structure on near-ground temperatures, for example, Potter *et al.* (2001) found that differences in daily maximum temperatures between partially or fully harvested sites and closed-canopy forests were reduced during unusually warm years. Because of the variety of conditions during the 6 years of our study, it is likely that many of these effects were “averaged out.”

Variation in precipitation during the growing season can produce substantial differences in the amount and abundance of herbaceous vegetation from year to year, and extremely wet or extremely dry conditions should be accounted for when making comparisons in plant communities among years. The extremely dry conditions during August, September, and October 1996, for example, resulted in the early senescence of understory vegetation and produced lower coverage in vegetation <1 m in height compared to other years (Kent *et al.*, in press).

A number of factors, including advection, changes in the atmospheric pressure gradients, the Coriolis effect, vertical fluxes of momentum, and drag effects due to the presence of vegetation, affect the direction and velocity of wind beneath and within the forest canopy (Heilman and Zasada 2000). Although a wide array of wind directions were measured within the forest canopy in our study, there were seasonal differences in wind direction. The combination of direction and velocity can be important when considering the dispersal of pollen or seed in a landscape (e.g., Johnson 1988). Near-surface wind speeds and wind shear also play a major role in the flux of heat, moisture, and chemicals within vegetation layers. Both wind and water are important vectors that move organic matter within and between landscape ecosystems. Much of the movement occurs during extreme events such as high rainfall (table 1) and high winds (table 2).

In the managed forests, reductions in PAR under the canopy occurred between 1995 and 2001 because of canopy closure and increased leaf biomass following the thinnings that were conducted during the early 1990s. These decreases in PAR values, however, were less than the differences in understory PAR measured between the managed and unmanaged forests for any given year. In the managed forests, harvesting reduced the basal area by about 30 percent compared to the unmanaged baselines (Crow *et al.* 2002). This reduction in stocking reduced canopy density and created canopy gaps. The PAR values generally correlated with the basal area of the forest, with the lowest average values measured in study areas with the highest basal areas (i.e., old growth and unmanaged second growth).

The combination of disturbance to the forest floor and increased solar radiation at the forest floor resulted in an increase in the abundance and variety of vegetation in the understory in managed forests compared to the unmanaged. Total cover of understory vegetation increased significantly under management, and managed forests contained twice the number of understory species compared to the unmanaged baselines (Kent *et al.*, in press). Differences in light levels in the understory between managed and unmanaged forests were less apparent during the growing season; yet consistently higher PAR values were recorded at 1 m in managed conditions. Research has shown that sunflecks may contribute 24 to 70 percent of solar radiation received by the understory (Evans 1956, Whitmore and Wong 1959, Chazdon and Fletcher 1984).

Differences in mean temperatures associated with increased solar radiation were not evident at or near intercepting surfaces such as the forest floor, at 1 m above the forest floor, or at -0.05 m and –0.2 m below the surface. Soil temperatures near the surface can show extreme variation, depending on the level of understory growth, while air temperature variations near the surface are reduced due to the turbulent nature of the atmospheric surface layer. Even so, no consistent differences were found in mean temperature between managed and unmanaged forests.

In our study, partial overstory removal did not create extreme changes in the understory microclimate as measured by light and temperature. The direct effects of harvesting—damage to the vegetation, destruction of the organic forest floor, loss of coarse woody debris, compaction of the soil—are likely to be far more important to ecosystem processes than the indirect effects caused by temporary increases in light and temperature.

Literature Cited

Albert, D.A. 1995.
Regional landscape ecosystems of Michigan, Minnesota, and Wisconsin: a working map and classification. Gen. Tech. Rep. NC-178. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 250 p.

Brosofske, K.D.; Chen, J.; Naiman, R.J.; Franklin, J.F. 1997.
Effects of harvesting on microclimatic gradients from streams to uplands in western Washington, USA. Ecological Applications. 7: 1188-1200.

Buckley, D.S.; Crow, T.R.; Nauertz, E.A.; Schulz, K.E. 2003.
Influence of skid trails and haul roads on understory plant richness and composition in managed forest landscapes in Upper Michigan, USA. Forest Ecology and Management. 175(2003): 509-520.

Chazdon, R.L.; Fletcher, N. 1984.
Photosynthetic light environments in a lowland rain forest in Costa Rica. Journal of Ecology. 72: 553-564.

Chen, J.; Xu, M.; Brosofske, K.D. 1997.
Microclimatic characteristics in the southeastern Missouri Ozarks. In: Brookshire, B.L.; Shifley, S.R., eds. Proceedings of the Missouri Ozark Forest Ecosystem Project: an experimental approach to landscape research. Gen. Tech. Rep. NC-193. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 122-135.

Chen, J.; Saunders, S.C.; Crow, T.R.; Naiman, R.J.; Brosofske, K.D.; Mroz, G.D.; Brookshire, B.L.; Franklin, J.F. 1999.
Microclimate in forest ecosystem and landscape ecology. BioScience. 49: 288-297.

Crow, T.R.; Haney, A.; Waller, D.M. 1994.
Report on the scientific roundtable on biological diversity convened by the Chequamegon and Nicolet National Forests. Gen. Tech. Rep. NC-166. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 55 p.

Crow, T.R.; Buckley, D.S.; Nauertz, E.A.; Zasada, J.C. 2002.
Effects of management on the composition and structure of northern hardwood forests in Upper Michigan, USA. Forest Science. 48: 129-145.

Evans, G.C. 1956.
An area survey method of investigating the distribution of light intensity in woodland, with particular reference to sunflecks. Journal of Ecology. 44: 391-428.

Fisk, M.C.; Zak, D.R.; Crow, T.R. 2002.
Nitrogen storage and cycling in old- and second-growth northern hardwood forests. Ecology. 83: 73-87.

Franklin, J.F. 1993.
Preserving biodiversity: species, ecosystems, or landscapes? Ecological Applications. 3: 202-205.

Geiger, R.; Huron, R.H.; Todhunter, P. 1995.
The climate near the ground, 5th ed. Friedr. Vieweg and Sohn Verlagsgesellschaft mbH, Braunschweig/Wiesbaden: 327-406.

Heilman, W.E.; Zasada, J.C. 2000.
Modeling the atmospheric dynamics within and above vegetation layers. In: Seventh Symposium on Systems analysis in forest resources. Gen. Tech. Rep. NC-205. St. Paul, MN: U.S. Department of Agriculure, Forest Service, North Central Research Station: 261-267.

Hura, C.E. 2001.
A comparison of snags and downed woody debris among managed and unmanaged northern hardwood forests. Ann Arbor, MI: University of Michigan. 72 p. M.S. thesis.

Johnson, W.C. 1988.
Estimating dispersibility of Acer, Fraxinus *and* Tilia *in fragmented landscapes from patterns of seedling establishment.* Landscape Ecology. 1: 175-187.

Kent, L.S.; Crow, T.R.; Buckley, D.S.; Nauertz, E.A.; Zasada, J.C. In press.
Effects of harvesting and deer browsing on attributes of understory plants in a northern hardwood forest, Upper Michigan, USA. Forest Ecology and Management.

Nauertz, E.A. 1999.
Impact of various silvicultural practices on the abundance and frequency of Lycopodium *species in northern hardwood forests.* Houghton, MI: michigan Technological University, M.S. thesis. 164 p.

Potter, B.E.; Teclaw, R.M.; Zasada, J.C. 2001.
The impact of forest structure on near-ground temperatures during two years of contrasting temperature extremes. Agricultural and Forest Meteorology. 106: 331-336.

Probst, J.R.; Crow, T.R. 1991.
Integrating biological diversity and resource management. Journal of Forestry. 89: 12-17.

Reifsnyder, G.M.; Furnival, G.M.; Horowitz, J.L. 1971.
Spatial and temporal distribution of solar radiation beneath forest canopies. Agricultural Meteorology. 9: 21-37.

SAS Institute Inc. 1999.
SAS/STAT® Users Guide, Version 8. Cary, NC: SAS Institute Inc. 3884 p.

Szabo, L.T. 2002.
Effects of forest management and deer browsing on the vascular species richness, cover, composition, and stature in sugar maple dominated forests, western upper Michigan. Ann Arbor, MI: University of Michigan. 157 p. M.S. thesis.

Whitmore, T.C.; Wong, Y.K. 1959.
Patterns of sunfleck and shade in tropical rain forest. Malays. Forestry. 22: 50-62.

Appendix 1: CD data collection description summary, CD file format, and abbreviations.

Summary:

In 1995, five Campbell Scientific, Inc., CR-10 XT digital data logger systems were obtained (Campbell Scientific, Inc., Logan, Utah). Using these systems, meteorological monitoring stations were set up as part of a comprehensive study of the impacts of silvicultural treatments on ecological diversity in a northern hardwood ecosystem that is common to the northern Lake States (NC-4153-94-03, USDA Forest Service, North Central Research Station, Landscape Ecology Research Work Unit, Impacts of Silvicultural Treatments on Biological Diversity in Northern Hardwood Ecosystems). Our goals were to characterize the variation that occurred in microclimatic variables throughout the study period (1995-2000), to compare the microclimatic variables in managed forests to those in unmanaged forests, and to make the microclimatic data available to others.

The five silvicultural treatments used in this study include two unmanaged sites (old growth, and second growth) and three managed sites (uneven-aged, even-aged, and managed for old-growth characteristics (MOGC)). The treatments are located within the Ottawa National Forest in the Upper Peninsula of Michigan, within Sub-subsection IX.3.2 (Winegar Moraine), and the same Ecological Landtype Phase (ELTP) 38, with b and c slopes that consist of moderately well drained, sandy loam and loamy sand soils. A fragipan layer is common and typically exists 45-90 cm below the soil surface.

A meteorological monitoring station was constructed in each of the treatments described above. Each station consists of an 18- or 22-m Rohn 25 gauge galvanized steel tower, with the height of the tower dependent on the canopy height within the treatment. The old-growth origin treatments have 22-m towers (unmanaged old growth, managed uneven-aged, and MOGC); and the second-growth origin stands have 18-m towers (unmanaged second growth and managed even-aged).

At each site, a Campbell Scientific CR-10 XT data logger was programmed to collect and summarize the data both hourly and daily. The 10- and 60-second readings were averaged for hourly summaries and then again for daily summaries. The data collected at 10-second intervals include

1) one wind direction (azimuth˚), wind speed with maximum values (m s^{-1}) using a RM Young Wind Sentry Set at 10 m on tower
2) total precipitation as rain (mm) using one Texas Instrument 525 tipping bucket located near tower
3) photosynthetically active radiation (PAR) with maximum values (µmol m^{-2} s^{-1}) using two LI-COR LI190SB quantum sensors each set at 1 m approximately 6 m from tower and 120˚ from each other relative to tower guide lines.

Data collected at 60-second intervals include

1) three relative humidity and temperature profiles (%) using Vaisala HMP35C RH/T probes enclosed in radiation shields set at 18 or 22 m, 10 m, 2 m on tower
2) one aboveground temperature profile with minimum and maximum values (˚ C) using ANSI Type T copper-constantan thermocouples at 1, 0.5, 0.25, and 0.05 m established near tower
3) one belowground temperature profile with minimum and maximum values (˚ C) using ANSI Type T copper-constantan thermocouples at 0.0 (surface), 0.05, 0.1, 0.2, 0.5, and 1.0 m established near tower

4) two pit and mound microtopographic temperature profile complexes with minimum and maximum values (˚ C) using ANSI Type T copper-constantan thermocouples at 0.05, 0.0 (surface), and –0.10 m established near tower.

Periodically, the raw data were downloaded from each meteorological system, reviewed (PC208 W software, Campbell Scientific, Inc.) and formatted (Microsoft Excel spreadsheet), and stored electronically. Hourly, daily, and monthly summaries exist for 1995, 1996, 1997, 1998, 1999, and 2000. A raw data set exists for 2001. Effective Accumulation Temperature (EAT) (defined as the sum of the daily average temperature (T_d) minus 5˚ C) totals for the aboveground and belowground temperature profiles are available for 1995 - 2000.

CD File Format:

The software format used is Microsoft Excel. Within each Excel file there are four worksheets and two graphs. The four worksheets include 1) hourly PAR / wind / rainfall summaries, 2) daily mean PAR / wind / rainfall summaries, 3) hourly temperatures / pit and mound / relative humidity summaries, and 4) mean daily temperatures / pit and mound / relative humidity summaries. The two graphs are 1) daily aboveground and 2) daily belowground temperature profiles for the month at that site.

The CD data sets are arranged in folders as follows:
(Year) Monthly Tables → Month → Site → Excel (.xls) file
For example, the file name TMMAR99 represents the record for the TM (Tamarack Lake, Unmanaged Second Growth) site for the month of March (MAR) for the year 1999 (99).

Abbreviations:

The abbreviation for each site, the site name, and the treatment/baseline name follow:
HL – Helen Lake, Old Growth
IM – Imp Lake, Uneven-aged Management
MC – Morrison Creek, Even-aged Management
TM – Tamarack Lake, Unmanaged Second Growth
TY – Taylor Lake, Managing for Old Growth Characteristics (MOGC)

Appendix 1 References:

Campbell Scientific, Inc. Logan, Utah 84321-1784 USA

Study Plan: NC-4153-94-03, USDA Forest Service, North Central Research Station, Rhinelander, Wisconsin. Landscape Ecology Research Work Unit, Impacts of Silvicultural Treatments on Biological Diversity in Northern Hardwood Ecosystems.

Nauertz, Elizabeth A.; Crow, Thomas R.; Zasada, John C.; Teclaw, Ronald M.
2004. **Microclimatic variation between managed and unmanaged northern hardwood forests in Upper Michigan, USA.** Gen. Tech. Rep. NC-236. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 31 p.

Temperature, light, wind, and precipitation were measured in the understory of managed and unmanaged northern hardwood forests in the Upper Peninsula of Michigan from 1995 through 2001. These measurements provide a baseline of information to compare the microclimate under managed and unmanaged conditions. Extreme climatic events may influence growth and development of forests.

KEY WORDS: Microclimate measurements, temperature extremes, weather data, Upper Peninsula of Michigan, managed and unmanaged northern hardwood forest.

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