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Short communication

The impact of forest structure on near-ground temperatures during two years of contrasting temperature extremes

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Abstract

The thermal environment of clear-cut, partially cut, and uncut forest sites in northern Wisconsin are examined for a warm year and a cool year. Temperatures at 0.5 m above and 0.05 m below ground, as well as base 5°C heat sums are computed for each site between May and September and differences between cut and uncut sites compared for the 2 years. Differences in average and minimum air temperature and soil temperature are less than instrumental error, $\varepsilon = 0.3$°C. Maximum air temperature differences between the clear-cut and uncut sites drop from 5.7°C in the cool year to 4.7°C in the warm year, while the difference for the partial cut drops from 3.2 to 2.7°C. The results suggest that studies of tree growth or forest development and climate change should consider the effects of forest structure on changes in daily extreme temperatures. Published by Elsevier Science B.V.

Keywords: Forest structure; Cut and uncut sites; Microclimate factors

1. Introduction

Development of silvicultural systems requires knowledge of the effects proposed treatments have on microclimate factors, which in turn determine the ability of the forest to reach a desired future condition. The effects of silvicultural treatment are immediate and their duration depends on the magnitude of the disturbance due to the treatment and the resulting forest structure, the rate of development of the forest, and weather conditions following the treatment. Because prolonged extreme weather conditions can determine whether a particular tree species flourishes or perishes, the effects of such extremes are of fundamental importance to forestry. A decade of locally "normal" weather will do less to favor one species over another than will one season of extreme conditions.

The effects of forest vegetation on sub-canopy climate have been extensively studied (Kittredge, 1948; Geiger, 1965; Calvert et al., 1982; Liechty et al., 1992; Morecroft et al., 1998; Aussenac, 2000). These studies have examined the effects of forest cover on microclimate under "normal" regional climatic conditions, or made no mention of the larger climatic context during the study period. There has been little or no work done on how an unusually hot or cold growing season might affect the differences in temperature between clear or partially cleared sites and unmanaged forest sites.

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We examine the effect of one extremely cool growing season (1996) and one extremely warm growing season (1995) on the temperature and heat sum differences between a clear-cut and uncut site, and between a partially cut and an uncut site. We define growing season as the months of May through September, inclusive. Our analysis considers air temperatures 0.5 m above ground and soil temperatures 0.05 m below ground; these are generally representative of the environment for regenerating hardwood species during the critical period of seedling establishment.

2. Background and methods

The study arose from a long-term monitoring project at the Willow Springs Ecosystems Process Site, on the Chequamegon National Forest (45°56′ North, 90°27′ West). Topography is gently sloping (0 to 5%) and the soil is a moderately well drained, sandy loam. The site was established in 1988 and includes three squares, adjacent 8 ha blocks. One block was uncut and maintained as a control with a fully closed canopy, one ("halfcut") was thinned to 50% crown cover, and a third block was clear-cut. Basal areas in the three sites were 32.4, 17.0, and $0.0\,m^2\,ha^{-1}$, respectively. The clear-cut and halfcut sites both contained significant near-ground vegetation during the 1995–1996 study period. In the clear-cut, regenerating aspen (*Populus* spp.) suckers and raspberry canes (*Rubus* spp.) had grown to a height of 1–1.5 m. In the halfcut, raspberry and other understory vegetation form a layer about 1.5 m thick over most of the ground. The control site is free of understory vegetation taller than 0.1 m.

Air and soil temperatures, T_a and T_s (or just T when applied to both), were monitored in the center of each block using copper/constantan thermocouples (with a Campbell Scientific T107 temperature probe for reference temperature) at 0.5 m above ground and 0.05 m below ground. We positioned soil thermocouples by augering a 0.15 m hole, then inserting them into the side of the hole in undisturbed soil about 2–3 cm from the edge of the hole. After the thermocouples were in place, we refilled the hole with soil and replaced the forest floor. Horizontal plates shielded the T_a thermocouples, as described in Pearcy et al. (1989).

The estimated sensor error, ε, is approximately 0.3°C. We replicated the thermocouple measurements three times within each block, with each thermocouple randomly located at least 10 m from the others. Thermocouples were scanned every 5 min and average conditions recorded hourly. Average daily T calculated from these data was recorded daily on Campbell CR-10 data loggers, along with instantaneous minimum and maximum T for the day.

As long as one or more thermocouples at a given site and hour were operational, we computed an average T for that site and hour. If there were any missing data for a given site/hour, then we did not compute a S.D. (σ) for that site/hour. In cases where T data were missing for all replicates at one site and hour, we eliminated that time for all three sites. This prevented a hot or cold spell from biasing one site while another had missing data. When computing base 5°C heat sums, H, from hourly data, we multiplied the calculated H for months with missing data by the ratio of the number of hours in the month to the number of hours available in the record. This was done because heat sums are cumulative and directly comparing a given month between years when 1 year had missing data would be inappropriate. There is no instrumental error for H, so we computed an effective error based on the thermocouple error. Since H is cumulative, a sensor with a systematic error $\varepsilon = 0.3$°C will yield a maximum growing season error of about 46 gdd.

We examine differences between the sites and compare these differences for the two study years. All intersite comparisons that follow involve either the clear-cut and control sites, or else the halfcut and control sites. For brevity, we use the symbol Δ to indicate these differences; Δ follows the term "clear-cut" or "halfcut" as appropriate, and has a subscript to indicate the particular quantity under consideration. For example, "clear-cut $\Delta_{a\,mean}$" refers to the difference in mean air temperature between the clear-cut and control sites. All differences result from subtraction of a control-site value from a treated-site value.

3. Climate context

The nearest National Weather Service surface data site with complete data for 1995–1996 is Rhinelander, Wisconsin. In 1995, the growing season in Rhinelander averaged 1.1°C warmer than the climate normal. This was largely due to a severe heat wave that gripped the upper Midwest in mid-July, causing numerous fatalities in Chicago and other midwestern cities. Karl and Knight (1997) found that during this heat wave, nocturnal temperatures did not drop to their usual lows, and thus the diurnal temperature range was reduced.

For the 1996 growing season, average temperatures in Rhinelander were 0.4°C lower than the climate normal, or 1.5°C colder than in 1995. To test the significance of this difference, we sampled daily average temperature from each year's growing season at 5-day intervals to account for autocorrelation (Madden and Shea, 1978) and applied the Smirnov test. This comparison showed that these 2 years are significantly different at the $\alpha = 0.05$ level.

Rhinelander precipitation in the two growing seasons was close to the climate normal of 48.3 cm. In 1995, there were 47.2 cm and in 1996 there were 42.9 cm. Applying the Smirnov test to weekly precipitation totals for the two seasons indicates that they are not significantly different at the $\alpha = 0.05$ level.

4. Results

In the cool year, control site average, maximum, and minimum temperatures were 14.5, 19.9 and 10.0°C, respectively. In the warm year, these parameters rose to 15.4, 21.1, and 10.8°C, respectively. Before looking at differences between sites in the 2 years, we first tested the clear-cut daily average and daily extreme temperatures for significant differences between the years, as we had done with the Rhinelander data. The results showed no significant difference at the $\alpha = 0.05$ level for any of the three variables.

Table 1
Differences in May through September growing season temperature parameters between cut sites (clear-cut or halfcut) and the uncut control site for cool (1996) and warm (1995) years

	Clear-cut		Halfcut	
	Cool	Warm	Cool	Warm
$\Delta_{a\,max}$ (°C)	5.7	4.7	3.2	2.7
$\Delta_{a\,min}$ (°C)	−3.3	−3.2	−0.8	−0.8
$\Delta_{a\,mean}$ (°C)	0.2	0.4	0.1	0.2
$\Delta_{a\,H}$ (gdd)	48	75	11	22
$\Delta_{s\,max}$ (°C)	0.4	0.6	0.5	0.3
$\Delta_{s\,min}$ (°C)	0.4	0.3	0.2	0.2
$\Delta_{s\,mean}$ (°C)	0.4	0.4	0.4	0.2
$\Delta_{s\,H}$ (gdd)	58	61	53	31

Growing season S.D. in T_a, σ_a within any given site was less than ε. Standard, deviations for T_s were also less than ε with the exception of the clear-cut in 1995, when σ_s was 0.5°C. When considering the importance of intersite or interannual differences in temperatures, we use ε for all comparisons except those involving the clear-cut in 1995, for which we use σ_s.

Fig. 1 and Table 1 show $\Delta_{a\,mean}$, $\Delta_{a\,max}$ and $\Delta_{a\,min}$ for the 2 years and two sites. Clear-cut $\Delta_{a\,mean}$ and $\Delta_{a\,min}$ show little difference between the 2 years.

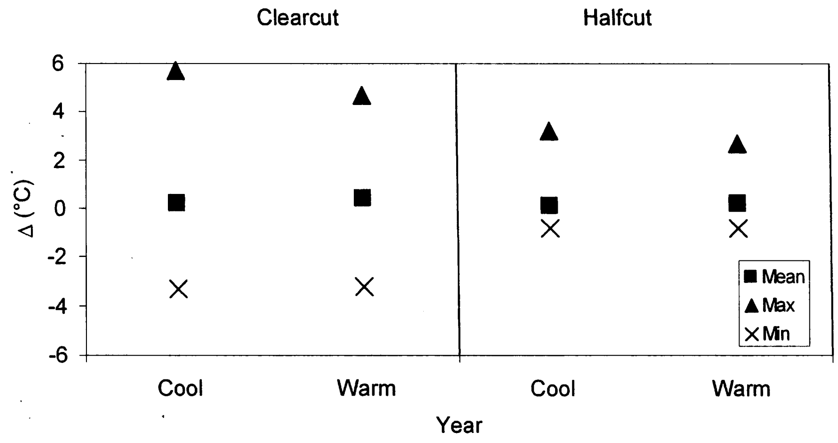

Fig. 1. Air temperature differences (mean, maximum, and minimum) between clear-cut or halfcut and control site for cool and warm years.

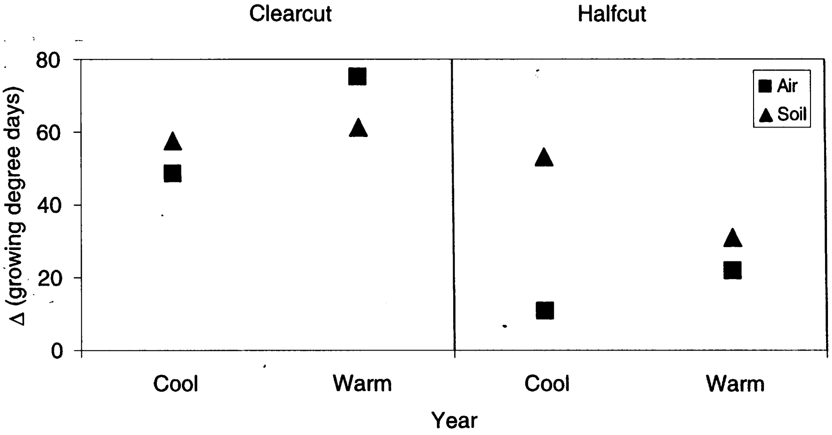

Fig. 2. Air and soil heat sum differences between clear-cut or halfcut and control site for cool and warm years.

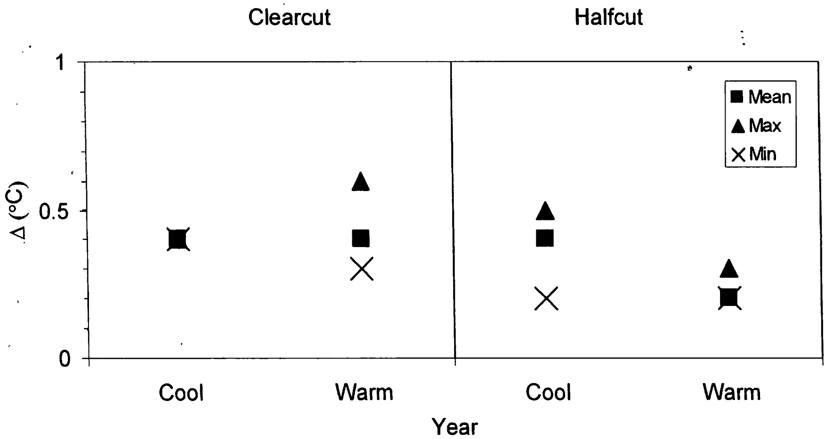

Fig. 3. Soil temperature differences (mean, maximum, and minimum) between clear-cut or halfcut and control site for cool and warm years.

Clear-cut $\Delta_{\mathrm{a\,max}}$ is 1°C greater in the cool year than in the warm year. Halfcut values, while less than clear-cut values, show a similar pattern. The change in halfcut $\Delta_{\mathrm{a\,max}}$ is 0.5°C from the cool year to the warm year. Differences in air heat sums, $\Delta_{\mathrm{a}\,H}$, are greater in the warm year than in the cool year (Fig. 2). In the clear-cut, $\Delta_{\mathrm{a}\,H}$ rises 27 gdd, or 56%, from the cool to the warm year. In the halfcut, the increase in $\Delta_{\mathrm{a}\,H}$ is 11 gdd (100%) from the cool to the warm year.

Soil values of Δ were generally smaller than the air values (Table 1, Fig. 3) and in no case did the difference between cool and warm years exceed ε. The most notable result for the soil is that clear-cut $\Delta_{\mathrm{s\,max}}$ was greater in the warm year than in the cool year, in contrast to clear-cut $\Delta_{\mathrm{a\,max}}$. There was little difference in $\Delta_{\mathrm{s}\,H}$ between the years for the clear-cut (Fig. 2). Halfcut $\Delta_{\mathrm{s}\,H}$ decreased by 22 gdd from the cool to the warm year, 41% of it's cool-year value.

5. Discussion

The significance tests show that even within a small region, there can be important differences in inter-annual climate variations. A statistically significant difference in one place may not manifest at other nearby locations. Rhinelander mean T_{a}, cited earlier, was 1.5°C warmer in the warm year than in the cool year, yet the control site was only 0.9°C warmer. Furthermore, at the study sites $\Delta_{\mathrm{a\,mean}}$ and $\Delta_{\mathrm{a\,min}}$ show less contrast between the 2 years than $\Delta_{a\,max}$ does. This suggests that simulations of the impact of climate change on tree growth or forest health (e.g. Constable and Retzlaff, 2000) should adjust the magnitude of imposed increases in maximum air temperature to reflect the density of the existing vegetation, while any increase in minimum air temperature or minimum or maximum soil temperatures can be site independent.

The results of the intersite, interannual analysis show that growing season temperature differences between cut and uncut sites can depend on the magnitude of overall temperatures. In the warm year studied, between-site differences in average air temperature were slightly larger than in the cool year, while differences in maximum daily air temperature were significantly smaller than in the cool year and differences in daily minimum air temperatures were unchanged.

Soil temperature and heat sum results differ from those for air. The differences in all soil-Δ's between the warm and cool years were less than ε; differences in $\Delta_{s\,H}$ are also questionable, as they are well below the effective error for H. Bearing that in mind, between-site differences in both average and daily extreme temperatures are more subdued, and differences in the extremes are much smaller than those for air. The degree of cutting on the treated sites affected the direction of the change in Δ from the cool year to the warm, as well.

Chen et al. (1999) mention the effect of structural changes on stand microclimate and the importance of prevailing daily weather conditions on the diurnal temperature patterns within a given stand. Our results show that the cumulative effects of these two factors over a growing season can be significant. This interplay between seasonal climate conditions and forest structure is an important factor in any attempt to understand ecosystem processes and dynamics.

The fact that temperature differences between sites depend on the prevailing weather conditions means that context is important if one is examining structure-microclimate relationships, especially if comparing sites or results from several studies. Authors should include a statement of the prevailing conditions for their study period (Wilson and Baldocchi, 2000), and/or use multiple-year averages to remove the interannual variations from their results (Morecroft et al., 1998).

It is tempting to use 1995 as a proxy for conditions under a globally warmed climate. However, any sustained long-term global climate change involves altered radiative balance as a primary cause of the change; the warm summer of 1995 resulted primarily from warm-air advection. Advection is relatively insensitive to the density of vegetation or canopy closure compared to radiation, and so any such extrapolation requires caution.

Another caution advised by this study pertains to the computation of heat sums. Values of H in the analysis came from the hourly temperature values, not from an average of maximum and minimum temperatures for each day or assuming a sine wave diurnal cycle between these two extremes, the two most common methods of computing H. Had we used either of the latter two methods, our results would have shown much smaller $\Delta_{a\,H}$ for the clear-cut and larger $\Delta_{a\,H}$ for the halfcut. The implication here is that there was a change in the shape of the daily temperature cycle for at least one of the sites considered. Growth models that rely on heat sums should make allowances for such variations, if they are to accurately predict the effects of climate variations on vegetation.

6. Conclusions

This study demonstrates that the relationship between temperature microclimate and forest structure is not constant, but depends on the magnitude of the temperature. The most notable impact is on daily $T_{a\,max}$, which shows less contrast between partially or fully open sites and closed sites in years of unusual warmth. These differences should be taken into account when modeling or simulating forest or tree growth interactions with climate variation.

Ideally, we would have liked to have vegetation data for these 2 years to study the feedback on seedling growth or shoot elongation. Because the Willow Springs study is long-term and there was no way to know in advance that these 2 years would be so different, vegetation surveys were not conducted in either of these years. As such we cannot examine how changes in the atmosphere influenced the vegetation. This question is important, and deserves future study.

The temperature and heat sum observations here point to the importance of the diurnal cycle in determining the thermal environment in a forest. Understanding differences in the diurnal cycle due to forest structure, and how the differences are or are not important to vegetation is an area that should be explored.

Finally, our study focussed on 2 years with strong temperature differences. Similar studies looking at vapor pressure, vapor pressure deficit, or precipitation would be valuable. Cases of strong precipitation differences could focus on dry versus wet years, or years with similar total precipitation but distributed differently in time (heavy, infrequent events versus moderate, frequent rains.)

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