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SPATIAL VARIATION IN GROWING SEASON HEAT SUMS WITHIN NORTHERN HARDWOOD FOREST CANOPY GAPS

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1. INTRODUCTION

When a gap forms in a forest canopy, the first and most immediate effect on the exposed area is an increase in radiative exchange near the ground. More sunlight reaches the ground during the daytime, and at nighttime the ground is more exposed to longwave radiation influences from the sky. These changes in radiation lead directly to a different near-ground temperature climate than what existed previously. Furthermore, spatial gradients in radiation and temperature now exist within the gap region that did not exist before the gap formed.

Work by Koski et al. (1985), Koski and Selkainaho (1982) and Bell and Johnson (1975) shows that phenological development of several tree species depends on both photoperiod and heat sum. Some studies have demonstrated correlations between tree (Norgren et al. 1996, Di Giovanni et al. 1996, Koski and Selkainaho 1982, Bell and Johnson 1975, Sarvas 1972) or insect (Weseloh et al. 1993, Fatzinger and Dixon 1996, Johansson et al. 1994) developmental stages and heat sums. Based on these earlier studies, there is strong evidence that plant and insect development will vary within forest gaps due to the temperature and sunlight patterns in the gaps.

Several studies have examined light regimes within gaps with respect to tree growth, reproduction and diversity (e.g., Minckler et al. 1973, Poulson and Platt 1989, Canham et al 1990.) Ringger and Stearns (1972) and Geiger (1965) described temperature distributions within gaps, but only in terms of daily maximum and minimum temperatures. We found no literature regarding heat sum patterns within forest gaps. Furthermore, calculation of solar energy fluxes at points within a gap is relatively simple compared to the complexity of a model to compute heat sum variations from physical principles. Heat sum patterns are much more easily determined by field measurement.

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The spatial variations in heat sums within a gap depend on the balance of incoming solar energy, incoming longwave radiation, outgoing longwave radiation, and air movement within the gap. These individual components and their net effect vary as gap size changes. Small circular gaps (small gap diameter to tree height ratio, D:H) have small variations in sunlight, little wind, and relatively small longwave energy loss. Their conditions are spatially rather uniform and similar to closed-canopy conditions. As gap size increases, gradations in sunlight from south to north increase. Wind in the gap increases, generally being greatest near the center and eastern portions. Longwave energy loss to the sky above increases everywhere, but is greatest near the gap center. These changes, depending on magnitude, can lead to a wide range of possible heat sum patterns within gaps of various sizes. If these patterns are known, they can be combined with knowledge of light patterns and plant or insect phenology to better understand and predict vegetation patterns within gaps, or patterns of insect development and maturation in gaps of differing proportions.

2. METHODS

The present study employs field data from several forest gaps in the Argonne Experimental Forest in Forest County, Wisconsin. Between 1964 and 1968, Dr. Forest Stearns collected temperature and humidity data using hygrothermographs situated 0.5 m above the ground in a variety of sizes of gaps, as well as under the canopy of several types of forest (hemlock, northern hardwood, spruce plantation, red pine plantation, jack pine plantation, and others.) The forest was logged in the first half of the 20th century, and the vegetation at the time of data collection comprised sugar maple, white ash, American basswood, yellow birch and eastern hemlock. The canopy top height was approximately 20 m. Further details of the study site appear in Ringger and Stearns (1972).

From Stearns' data, we examined the instrument records for five sites. Site 4-UP is rather large as naturally formed gaps go; it has D:H=4 with a surrounding northern hardwood forest. Site 2-UP has D:H=2, surrounded by northern hardwood-hemlock forest. The 4-UP and 2-UP sites were cleared specifically for this study, in 1964. The smallest gap we considered was one named "Tom's Church," (abbreviated TMCH) with D:H=1 and a surrounding northern hardwood forest. This was a pre-existing gap, present as a result of the earlier logging. No information is available on its exact age or vegetation at the time of this study, but it is believed to have had surface vegetation comparable to that in the other clearings. The 4-UP site was approximately 250 m south of the 2-UP site, and TMCH was about 2 km south-southeast of 4-UP. One site in a large clearing was also examined. This site, OPEN, had D:H=17.5. For our purposes, OPEN qualifies as an open field. Finally, we included one site, SUGR, under a closed northern hardwood canopy. This site was about 100 m west of TMCH. The original field experiment did not include replication of gap size. The scientists involved felt it was more useful to examine several gap sizes than to monitor multiple gaps of the same size (Stearns, personal communication).

Temperature data are available for the centers of all of the gaps for most of the 5-year study period. In addition, Dr. Stearns distributed multiple hygrothermographs in each gap for a period of several weeks in different years. In 4-UP, there were 12 instruments in the opening during late September and early October of 1966. Within site 2-UP there were 11 instruments in parts of June through September of 1968. In TMCH, 5 instruments recorded conditions during much of June through August of 1968. Table 1 indicates what dates were used for each gap, and figure 1 shows the instrument locations in the gaps during their respective periods of intensive monitoring. Data are available from the center of each gap, and from OPEN and SUGR, for all of these periods.

TABLE 1. *Study periods for gaps*

Gap name	Period examined
4-UP	29 September through 3 October 1966 and 7-8 October 1966
2-UP	12-24 July and 17 August through 1 September 1968
TMCH	14-24 June and 2-14 August 1968

After manually reading the daily midnight-to-midnight maximum and minimum temperatures from the hygrothermograph records, we computed heat sums for each instrument location using the method of Baskerville and Emin (1969) and a temperature base of 5 °C. This base is often used for northern hardwood ecosystems, where many plants are physiologically active at relatively low temperatures.

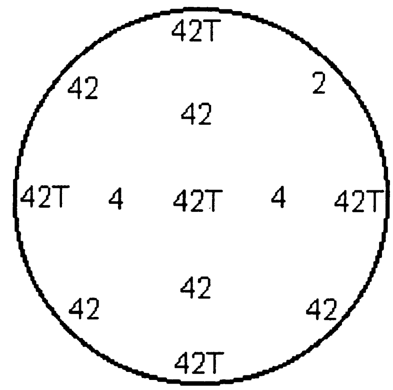

Figure 1. The numbers and letters in the circle indicate the locations of instruments within the 4-UP (4), 2-UP (2) and TMCH (T) gaps. North is at the top of the figure.

We examined the heat sums to address two questions. The first question was, do heat sums differ significantly among locations within gaps. Our hypothesis was that the sums do vary significantly, and that the amount of variation depends on the gap size. The second question was, do heat sums and heat sum gradients vary significantly among gaps. The hypotheses being tested here are (1) that the sums do vary as gap dimension increases and (2) that the gradients are strongest in gaps of some intermediate size. The second hypothesis reflects the fact that a very small gap is like a closed canopy, while a very large gap is like an open field. Both situations have little horizontal radiative or temperature variation. Between these extremes, shading and sunlight, as well as wind and shelter from longwave radiation loss, produce horizontal gradients in temperature and heat sums within forest gaps.

To address the first question, we examined the differences between north-south and west-east transects of each individual gap. This was done through linear regression analysis, determining (a) whether the heat-sum gradient along a transect was significantly different from zero and (b) whether the gradients along the two transects within a gap were significantly different. In these calculations, the west and north edges are considered the starting points for transects, and all distances are divided by gap diameter, D. By doing this, the center is always at a distance of 0.5 and the east or south edge is always at a distance of 1. For the comparison of west-east and north-south gradients to one another, we used absolute values of regression slopes since the choices of west-to-east over east-to-west, etc., were arbitrary and reflected no physical process.

To answer the second question, we compared the heat sums in the centers of the three gaps with the OPEN and SUGR sites. Because the 1966 and 1968 study periods reflect different seasons – early autumn and midsummer, respectively – we consider them separately for this analysis to allow for the possibility that the relationships vary through the year. In assessing the strength of the heat sum patterns and how they vary with gap size, we limit our comments to subjective, qualitative observations, due to the complexity of the patterns, the times of year that the data represent, and the fact the data come from two different years.

3. RESULTS AND DISCUSSION

Table 2 summarizes the heat-sum gradients for the transects in the three sites examined. There are strong north-south gradients in all three sites, though the gradient in TMCH does not appear to be significantly different from zero at the α=0.05 level. Since this gradient is based on regression with only 3 data points, the fact that it has a nonsignificant slope is not too surprising or disturbing. The magnitudes of the west-east gradients are one-half to one-twentieth of their associated north-south gradients. Only in 4-UP did the west-east gradient differ from zero at the α=0.05 level.

TABLE 2. *Directional heat-sum gradients within 4-UP, 2-UP, and TMCH gaps. Values marked with an asterisk are significantly different from zero at the 0.05 significance level*

Gap name	North-south	West-east
4-UP	-2.68*	1.24*
2-UP	-3.04*	0.20
TMCH	-2.2	-0.60

When we compared the west-east and north-south gradients within each gap, only 2-UP showed a statistically significant difference (α=0.05) in gradients. However, in TMCH, both gradients were effectively zero, while in 4-UP the gradients were both significantly nonzero.

Figure 2 is a free-hand plot of the average daily heat sums measured in 2-UP. There is a maximum on the northeast edge of the gap, a minimum on the south edge, and a local minimum in the center. We believe this minimum is caused by the fact that the center has the greatest exposure to the sky at night, and experiences the greatest cooling at that time. The 4-UP results are generally similar, though the heat sums increase smoothly from the west to the east edges, with no center-minumum.

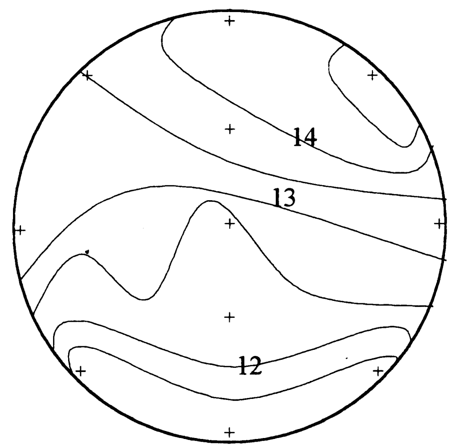

Figure 2. Free-hand contour plot of daily average heat sums in 2-UP. Contour interval is 0.5 growing degree days, + indicates measurement locations. North is at the top of the figure.

Figure 3 shows the average daily heat sums in the gap centers and at SUGR for the 1966 study period and the combined 1968 study periods. The results for 1966 show heat sums decreasing as gap size increases from zero (full canopy) to a D:H of about 2. From D:H=2 to D:H=4, the heat sum increases, then drops slightly as D:H increases further. The results for 1968 are exactly the opposite. The gap with the greatest heat sum is D:H=2, with lower heat sums at all the other ratios.

The 1966 curve being almost a mirror image of the 1968 curve probably stems from the periods studied in the two years. At the latitude of these sites (near 46° N), the center of 2-UP is shaded by the southern canopy after September 17. This shading alters the balance of daytime heating and nighttime cooling, lowering overall temperatures in 2-UP relative to other gaps that still receive direct sunlight in the gap center. In short, the balance of longwave and shortwave radiative fluxes in the 2-UP gap crosses a threshold between the dates of these two sets of measurements.

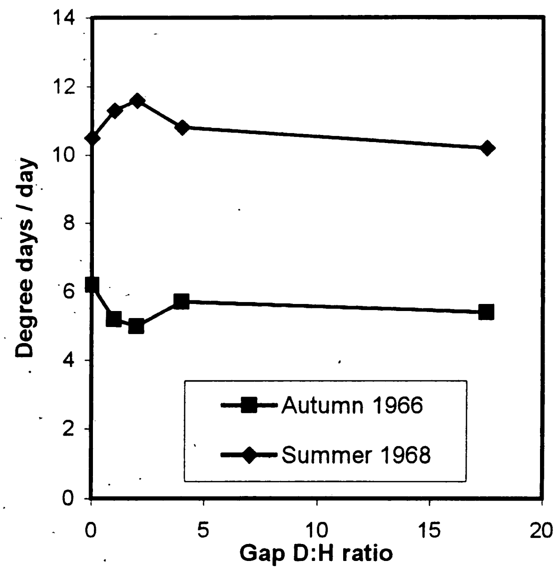

Figure 3. Daily average heat sums in the center of several circular forest gaps.

Whether or not these patterns are robust is difficult to determine. When we performed linear regression on each set and tested whether the slopes were significantly different from zero, the results showed neither the 1966 nor the 1968 data had a significant slope (α=0.05). Still, visual examination of the data clearly show that any pattern is nonlinear, and the utility of linear regression is minimal.

4. CONCLUSIONS

The results indicate that there are, as expected, spatial variations in the heat sums within forest gaps. These variations are not great, and perhaps not significant, in smaller gaps such as TMCH. In larger gaps they can be significant. Vegetative regeneration patterns may reflect these variations, with greater growth on the northeast side of gaps where heat sums were largest for both 2-UP and 4-UP and where there is abundant sunlight.

There is evidence that the variation in heat sums as gap dimensions change may also be significant. The largest variation in this study appears between D:H=0 and D:H=4, but the data do not offer adequate coverage to examine this range in a meaningful way. Because heat sums depend on the balance of longwave and shortwave energy fluxes throughout the day, the size of the gap with the greatest central heat sum depends on latitude and time of year.

Two important questions raised by this study are (a) how do gap heat-sum patterns vary through the growing season, and (b) how does the gap-center heat sum curve (Fig. 3) depend on D:H, latitude, and time of the year. Answers to these questions are necessary if foresters are going to consider heat sums in planning for forest regeneration and gap dynamics.

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