PASSIVE FROST-RISK REDUCTION FOR FOREST MANAGEMENT IN NORTHERN HARDWOODS

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ABSTRACT.—Observational data and an atmospheric radiation model were combined to examine nocturnal cooling in a northern hardwood forest. The model provided a mechanism for examining which properties of the forest and atmosphere play a significant role in preventing radiative freeze or frost events. The results of the simulations suggest that site basal area exerts some control over heat loss, with higher basal areas providing more heat retention than lower basal areas. This information is extended in the form of maps for Minnesota, Michigan, and Wisconsin indicating the amount of basal area needed to protect against the magnitudes of late spring freezes historically experienced in different locations.

INTRODUCTION

When a forest experiences a late spring frost or freeze, some plant species suffer more than others. Oak and walnut are two examples of economically valuable trees that suffer from frost. Frost or freezing temperatures may kill the leader, leaves, or flowers. This mortality in turn affects regeneration and tree form. Because of these detrimental effects of frost, frost prevention can be a useful tool in forest management: it may not make or break a management plan in itself, but it can give desired species an advantage and allow more seedlings to survive other types of attack or disturbance.

There are two general types of freeze that can occur in a forest in late spring. One is an advective freeze, where cold air moves into the forest from another area. Cloud cover, strong winds, and precipitation may accompany an advective freeze. While temperatures drop below freezing, frost does not usually form on the ground. The arrival of a Hudson Bay air mass is often responsible for late spring advective freezes in the Lake States. In areas with significant topographic relief, drainage of cold air from exposed ridges may also produce freezes in low-lying areas. Because the cold air in an advective freeze comes from another location, managing a forest in a way that prevents all advective freezes is difficult or impossible.

The second type of freeze is a radiative freeze, in which radiative cooling of the ground at night cools the air immediately above it below the freezing point. A radiative freeze requires calm winds and is most common under clear skies. When the ground cools below the dewpoint, frost forms. As the night proceeds and temperatures continue to drop, the pool of below-freezing air may deepen to a meter or more. A radiative freeze may kill seedlings and leaders but will not usually affect flowers on taller, more mature trees. Because the cooling occurs locally, it is possible to take measures in a forest to reduce the risk of frost near the ground.

There are two principal ways by which forests reduce the risk of radiative freeze. One relies on the canopy foliage, which blocks radiation traveling upward from the ground and prevents the energy from escaping. The second results from the amount of heat stored in the trees and other vegetation. A given volume of wood, leaf, or rock at any temperature contains more energy than an equal volume of air at the same temperature. For this reason alone, more vegetation on a site provides protection against more severe radiative freezes. This is true whether or not leaves are on the overstory trees. While the former mechanism is often acknowledged in “conventional wisdom” and forest meteorological literature (e.g. Kittredge 1948; Geiger 1965; Wales 1967), the latter has been largely neglected or ignored. One reference in Geiger (1965) alludes to the fact that nocturnal cooling is reduced in

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leafless forests, but attributes this to trunks of trees blocking the outgoing radiation, not to their greater heat capacity and slower cooling.

I have used computer simulations of radiative energy transfer in the atmosphere, in conjunction with field data from three coterminous forest sites, to determine a relationship between heat storage in a forest and basal area. I then used the same model and the derived relationship to assess the amount of protection a given amount of basal area provides against potential frost. The results of this latter analysis provide guidance in determining how much vegetation one can remove from a site without unduly risking frost damage.

METHOD

Observational Data

In 1993, USDA Forest Service researchers installed meteorological instruments in three adjacent forest plots at Willow Springs on the Chequamegon National Forest near Park Falls, Wisconsin (Fig. 1). White ash, sugar maple, basswood, and red oak are the dominant species in the plots. The canopy top is approximately 20 m above the ground. In 1988, the researchers clearcut one plot, removed half of the overstory from a second plot, and left the third plot uncut. The basal areas measured in the clear-cut, half-cut, and uncut plots were 0.0, 17.0, and 32.4 m^2 ha^{-1}, respectively. Teclaw and Isebrands (1993) describe further details of the study site. The instruments in each plot measure and record air temperatures, humidities, and winds every hour at several heights between 0.25 m and 10 m. Further observational data used for verification in this study came from a field experiment currently underway at Helen Lake in the Sylvania Wilderness Area of the Ottawa National Forest (Fig. 1).[2] The Helen Lake site is unmanaged old-growth forest, dominated by sugar maple, ironwood, and yellow birch. It is substantially different from the Willow Springs site in this respect; it also has a higher canopy top (roughly 28 m).

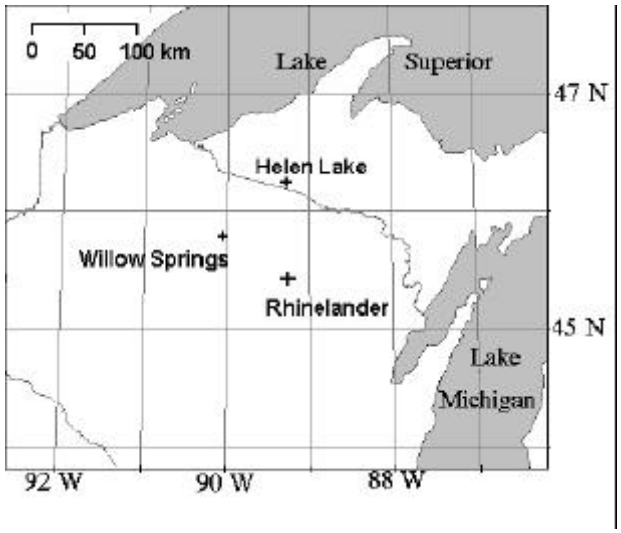

Figure 1.—Map of northern Wisconsin and Michigan's Upper Peninsula, showing source locations for the meteorological data used in this study.

Simulations

[2] Tom Crow, Project Leader, North Central Forest Experiment Station, Rhinelander, WI. Personal communication.

I selected 27 nights from 1994 for simulation with an atmospheric model, based on both hourly observations in the clearcut and surface observations at nearby Rhinelander, WI. These nights all showed little or no wind as measured in the clearcut and steady cloud cover without precipitation as recorded at Rhinelander. I then initialized an atmospheric infrared radiative transfer model (Liou et al. 1984) using the temperatures and humidities measured on these nights in each of the three sites. The model calculates atmospheric and ground-surface temperature changes based on water vapor content, temperature, and specific heat[3] of individual layers of the atmosphere. It also calculates condensation or evaporation for each layer, as appropriate, to maintain thermodynamic equilibrium. By minimizing the model's error in reproducing observed temperatures through each of the nights at each plot, I determined a statistical relationship between plot basal area and specific heat.

I used the derived relationship to compute a value of specific heat for each plot at Willow Springs, and resimulated all of the 1994 nights using these computed values. From these resimulations, I then derived an expression for model error at a height of 0.5 m as a function of basal area.

Verification

Since derivation of the relationship between basal area and specific heat used only three stand densities, I assessed the usefulness of the relationship with an independent set of observations. For this purpose, I selected 23 nights (again with little or no wind, and steady cloud cover without precipitation) from the 1995 data at the Willow Springs and Helen Lake sites. I simulated these nights using specific heats obtained from the regression relationship, and examined the temperature errors from the simulations.

Extension

Next I used the radiative model to simulate a number of hypothetical nights with varying initial atmospheric conditions. For each night, I used the model to simulate five different values of basal area (one being clearcut, or basal area=0). I then computed differences between final temperatures at 0.5 m from the clearcut simulations and each of the other four basal areas for a given night. By averaging these temperature differences over all nights for a given basal area, I obtained mean values of the amount of temperature protection provided by that basal area. Linear regression of the temperature differences as a function of basal area then provided a statistical relationship between the two quantities.

Application

Using 1961-1990 daily maximum and minimum temperature data for Michigan, Minnesota, and Wisconsin, I determined average freeze temperatures for freezes following growing degree day (GDD) accumulations of 250 and 300 degree days, base 5ºC. I chose these GDD accumulations based on observations of frost damage to actively growing red oak and white ash seedlings at the Willow Springs sites in 1994.[4] From the freeze temperatures and the statistical relationship between temperature protection and basal area, I generated maps of the basal area required to protect against freeze conditions typical of a given location after a given degree day accumulation has been reached.

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[3] Specific heat is the amount of energy required to raise the temperature of 1 kilogram of a substance 1 degree Celsius.

[4] John Zasada, Project Leader, North Central Forest Experiment Station, Grand Rapids, MN. Personal communication.

RESULTS

Table 1 summarizes the results of the optimization simulations. The large standard deviations reflect several important considerations. Foremost of these is the variability in the amount to which radiation dominated each night. Even though nights were carefully selected for the simulations, the selection criteria allowed for some degree of advective temperature change. The second factor influencing the standard deviation is soil moisture, which varies from day to day in a plot and which the model does not consider. The third important consideration is that the model results are somewhat insensitive to the exact value of the specific heat (c_f). Temperature errors for any given simulation vary by less than 0.01 ºC for values of c_f over a range of roughly 100 J kg^{-1} $ºC^{-1}$. The root-mean-square (rms) temperature errors for the simulations are comparable for all plots, although they show some decrease as basal area increases.

Based on these average values, linear regression of c_f as a function of basal area (*ba*) yields the equation

[1] $$c_f\,(ba) = 1140 + 109*ba,$$

with a correlation coefficient of r^2=0.98. As mentioned earlier, this relationship derives from only 3 data points, and requires independent verification. To produce a standard for comparison with the 1995 Willow Springs and Helen Lake dates, I resimulated the original sample of 1994 Willow Springs nights using values of c_f calculated from [1] for each plot. The average rms error for these simulations was 2.2 ºC. The rms errors from the verification tests using 1995 data are comparable: 2.3 ºC for the 1995 Willow Springs simulations and 2.6 ºC for the Helen Lake simulations.

Table 1.—Summary statistics for optimization simulations. The parameter δT_{rms} is the rms error for the model compared to observations.

Plot	c_f average ± standard deviation	δT_{rms}
		ºC
Clearcut	1,004 ± 0	1.38
Half-cut	3,120 ± 1,780	1.36
Uncut	4,300 ± 2,100	1.26
Both forested sites	N/A	1.31

The radiative transfer model was next used to simulate 432 different scenarios. Each scenario used a unique combination of atmospheric moisture (q), sunset temperature (T_s), canopy height (z_c), atmospheric temperature gradient (Γ), and *ba*. The latter variable was reflected in the model as c_f, based on [1]. I determined realistic ranges for each variable based on physical constraints and the 1994 Willow Springs observations. Table 2 shows the values of the five variables that I tested.

Table 2.—Values of parameters varied in idealized simulations of nighttime cooling

Parameter (units)	Test values
q (g kg^{-1})	3.0, 4.0, 5.0

T_s (ºC)	3, 6, 9, 12
z_c (m)	16, 24, 32
Γ (ºC km^{-1})	-50, 50, 150
ba (J kg^{-1} ºC^{-1})	0, 8.6, 17.3, 25.9, 34.5

For each chosen value of *ba*, I computed a temperature protection value, T_{prot};

[2] $$T_{prot}(q, T_s, z_c, \Gamma, ba) = T_{final}(q, T_s, z_c, \Gamma, ba) - T_{final}(q, T_s, z_c, \Gamma, 0),$$

where T_{final} is the temperature at 0.5 m at the end of the simulation. This represents the difference in cooling between a clearing and a forested area, given the same initial moisture and temperature profile as well as some value for canopy height in the forested area.

By holding one variable (hereafter referred to as *x*) constant and averaging over all other variables, I assessed the sensitivity of the model to *x*. The difference between the average T_{prot} values corresponding to the extrema for *x* shown in Table 2 indicates the comparative importance of *x* in controlling nocturnal cooling. Since several of the variables can vary over slightly wider ranges than those tested and shown in Table 2, I determined more extreme maximum and minimum values, and extrapolated the results from Table 2 to these new values. Table 3 shows the differences in T_{prot} across these wider ranges. Clearly, Γ has only a very weak influence. Canopy height, sunset temperature, and atmospheric moisture are an order of magnitude—almost 2 orders of magnitude—stronger, and all comparable to one another. Basal area has the strongest influence, roughly 3 times these other quantities. Furthermore, basal area and canopy height are the only parameters that both appear to have a significant impact on radiative cooling and can be manipulated in any real sense by people.

Table 3.—Influence of various parameters on nocturnal radiative cooling

Parameter (units)	Extreme values	Range of T_{prot}
		ºC
q (g kg^{-1})	2.0, 5.5	1.1
T_s (ºC)	3, 12	0.8
z_c (m)	10, 40	1.2
Γ (ºC km^{-1})	-50, 150	0.02
ba (m^2 ha^{-1})	0, 50.0	3.0

I used the values of T_{prot} obtained by holding *ba* constant in this analysis in a linear regression to relate these two quantities. As a correction, I then applied the known model bias at 0.5 m, determined as a function of *ba* from the simulations of the 1994 Willow Springs data using c_f from [1]. The final result is

[3] $$T_{prot}(ba) = 0.135 * ba + 0.297, \qquad r^2 = 0.96$$

I examined National Weather Service daily temperature records for Michigan, Minnesota, and Wisconsin from the years 1961 to 1990, inclusive. Among the stations in these States, 133 have records that are 99 or 100 percent complete. These stations are all in open areas, away from buildings or other cover that might influence the

measurements. By examining the daily maximum and minimum temperatures at these stations, I determined the dates each year on which a given station reached degree-day sums (base 5 ºC) of 50 through 350 at intervals of 50 degree days. To obtain average post-threshold freeze intensities, I averaged the temperatures of all freezes at a station after a given degree day threshold but before July 31 of each year. Using krigging for spatial interpolation, I mapped the freeze intensities following a given threshold for all 133 stations. Figure 2a shows an example of this, for the threshold of 300 degree days.

I then converted the maps of freeze intensity to maps showing how much basal area one would need to protect trees from the typical spring freeze at a location. This involved simply solving [3] for *ba*, and applying the resultant equation to the individual point values determined in the previous step. Figure 2b shows the subsequent map of protective basal area. It is clear from the figure that most locations in the these States considered require little basal area to provide the needed freeze protection.

The freeze climatology developed here employs temperatures measured at 2.0 m above the ground, usually in open areas. Equation [3], on the other hand, comes from model results at 0.5 m above ground. During a radiative frost, the 0.5 m temperature will be colder than the 2.0 m temperature because the frost is driven by ground cooling. Therefore, the temperatures in the freeze climatology are likely to be somewhat high with respect to what regeneration near the ground might experience. Typical temperature gradients between 0.5 m and 2.0 m suggest that the basal areas shown in figure 3 might be increased by 5 to 10 m^2 ha^{-1}.

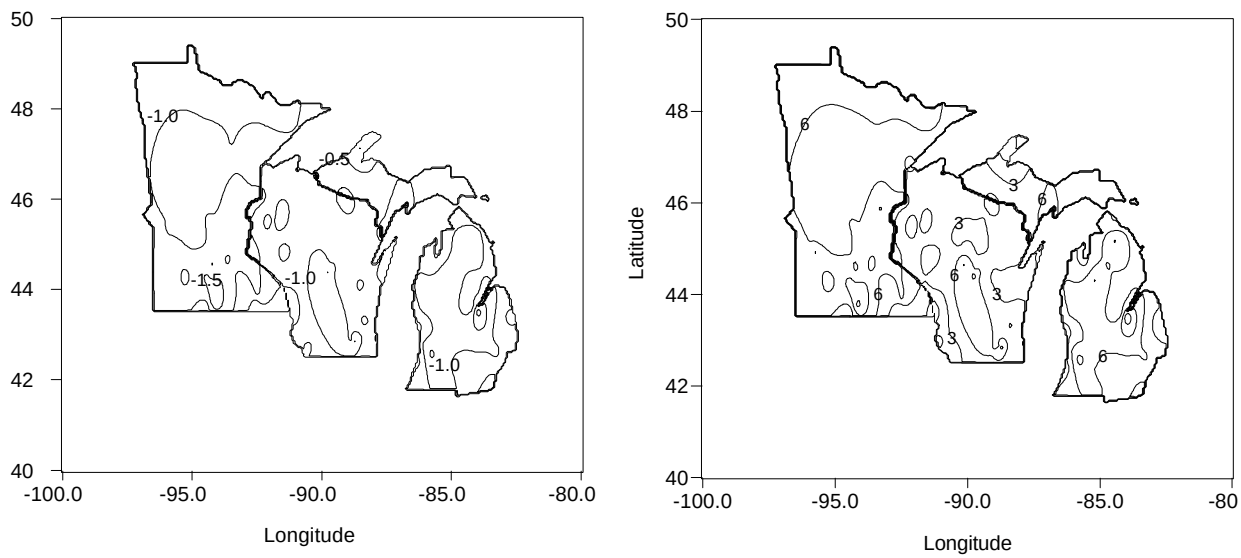

Figure 2.—(a) Temperature of average freeze following 300 degree days, base 5 ºC, contour interval is 0.5 ºC; minimum values are –1.9 ºC in south central Minnesota and –2.0 ºC below Saginaw Bay, Michigan. (b) Basal area to protect against temperatures in (a). Contour interval is 3 m^2 ha^{-1} with maxima of 12.7 m^2 ha^{-1} in south central Minnesota and 13.8 m^2 ha^{-1} south of Saginaw Bay, Michigan.

CONCLUSIONS

The results of this study are based on one field experiment, which, in conjunction with the heavy use of a computer model, leaves their applicability over broad regions open to question. The present analysis is limited by observational data, and no amount of simulation or model adjustment can verify or refine the final results unless it rests on further observations from new field studies. Such a study, or studies, would need to examine a variety of ecosystems and vegetation densities in order to provide the widest base of input data for the model to work from. The temperatures shown in figure 2a come from 99 stations in a broad geographic area. They do not reflect local or small-scale topographic effects in areas away from the stations. A forest manager concerned about such factors as

drainage winds from ridges, or dry, sandy soil prone to frost development would need to subjectively adjust the protective *ba* shown in figure 2b. In spite of the need for further data, the field observations and model results both suggest that forest managers can reduce the risk of frost in a stand by maintaining a certain amount of basal area on the site. The amount of basal area required depends on location and the physiology of the species of interest. Finally, Figures 2a and 2b represent the results for one specific degree-day threshold, with a given base. The same type of maps can be generated for other thresholds and bases, as needed for given species.

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