INTRODUCTION

Summer frost can cause serious regeneration problems in conifer plantations in the interior of British Columbia. Studies have shown that frost can occur at any time during the growing season on many site types. It may limit successful regeneration of Engelmann spruce and Douglas fir in the IDF, SBS, SBPS, MS, ICH and ESSF biomeclimatic zones.

To better understand the nature of this phenomenon, and to enable foresters to identify high risk sites, a review was prepared by Bob Stathers on the causes of summer frost, the identification of frost-prone sites, and the effects of frost on conifer seedlings. Results of the review are highlighted here. Additional information is available in FRDA Report 073, available from the address given at the end of this paper.

TYPES OF FROST

Frost occurs when the temperature falls below 0°C. Two different processes cause frost and affect its occurrence over the landscape. First, on a calm, clear night, radiation frost can occur when a warmer ground surface cools as it radiates heat towards the cooler atmosphere. Second, the air that is radiatively cooled at one site may flow onto another site. A frost resulting from the transfer of cooled air is called an advection frost. To predict where frost is most likely to occur during the growing season, it is necessary to understand the conditions that produce a radiation or an advection frost. The nocturnal surface cooling that causes frost is influenced by the complex interaction of atmospheric conditions and site characteristics.

ATMOSPHERIC FACTORS AFFECTING FROST

Longwave Radiation

At night, the net flow of longwave radiation (i.e. heat radiation) from the ground surface towards the cooler night sky causes the surface temperature to drop. The rate of net heat transfer from the soil to the sky is reduced when clouds in the atmosphere absorb and re-radiate the heat back towards the ground surface. Consequently, radiation frosts are more likely in areas where the summer night sky is clear.

Physical Properties of Air

Dry air has less ability to store heat than either water or soil, so its temperature drops relatively rapidly as it radiates heat. Warm, humid air contains more heat than cold, dry air, and so requires more radiative cooling to reduce its temperature to the freezing point. As a result, the risk of radiation frost is greater in areas with dry climates.

As air cools, its density increases, causing it to settle near the ground surface. On a level site this creates a temperature inversion and a cold air layer is formed near the ground surface (Figure 1). Cold, dense air flows downslope on a sloping site and, where it collects in low-lying pools, it creates frost pockets.

Wind

Nocturnal ground surface temperatures are strongly related to wind speed during a period of radiation or advective cooling. Figure 2 illustrates the rise in surface temperature that resulted from an increase in wind speed at about 2200 hours during a radiation frost on a clearcut in the IDF. Under windy conditions, air cooled near the ground surface is rapidly mixed with warmer air above the surface, reducing the risk of radiation frosts at ground level. Exposed, windy sites are, therefore, less vulnerable to frost than sites sheltered from the wind at night.

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FIGURE 1. Stratification of cold air near the ground surface during a clear, calm night creating a temperature inversion.
gradual slopes or rolling terrain, mixing is much reduced and the dense air near the surface remains cold as it slowly flows downslope.

Aspect

Aspect influences the amount of solar radiation absorbed by the ground surface during the day, and the amount of heat available for transfer from the soil to the sky during the night. The more heat stored in the soil during the day, the longer the surface temperature can be maintained above freezing at night. South- and west-facing slopes, which receive more solar radiation, generally have a lower risk of frost than north- and east-facing slopes. Nights are also longer on northerly aspects, allowing more time for radiative cooling to occur.

Vegetation Cover

Vegetation cover can have either a beneficial or a detrimental effect on the occurrence of frost, depending on the height, structure, and density of the plant canopy. Vegetation canopies are warmer than the cold night sky and consequently decrease the radiative heat loss to the atmosphere by absorbing and radiating heat back towards the ground surface. However, vegetation also decreases the windspeed near the surface and can create a layer of still air that is prone to freezing. This effect is enhanced in short, dense canopies. Denser canopies also reduce the amount of heat stored in the soil during the day by shading the ground surface.

The risk of frost varies with the type of vegetation because canopy characteristics influence the rate of nocturnal surface cooling. A tall, closed canopy forest has relatively high foliage temperatures and shelters a seedling from the cold night sky. Such a canopy can reduce the frost hazard by reducing the net radiative loss from the ground surface. In contrast, the frost hazard can be high in a low, dense grass canopy (Figure 3).

SITE FACTORS AFFECTING FROST

Elevation

Air temperature typically decreases by about 0.7 °C per 100m increase in elevation, so higher elevation sites usually require less heat loss to reduce air temperatures to the freezing point at night. Rates of surface cooling are also greater at higher elevations because there is less overlying atmosphere to absorb longwave radiation and re-radiate it back towards the ground surface.

Slope and Topography

Slope and topography influence cold air drainage and accumulation in frost pockets. Slope angle and slope length affect the rate at which cold air flows downslope. Air flows more rapidly down steeper slopes (>10%) causing greater mixing with warmer overlying air. This reduces the risk of frost on the slope. The frost hazard at mid-slope positions is lower because air tends to drain away from these areas. On
EFFECTS OF FROST ON CONIFER SEEDLINGS

Frost Resistance of Seedlings

A seedling's resistance to frost varies during the year. Conifer needle, stem, and root tissues all show large seasonal differences in frost tolerance, as illustrated in Figure 4 for *Abies alba*, a European species. Frost resistance levels for most conifers in B.C. are not well established but, for many species, temperatures lower than -3 to -5°C during the growing season can cause tissue damage. Lodgepole pine and whitebark pine have probably the highest frost resistance of common B.C. tree species and may show little visible damage until growing season temperatures drop below -6 to -7°C. Engelmann spruce and white spruce have a lower resistance followed by subalpine fir, ponderosa pine, and western larch. Douglas-fir, western redcedar and western hemlock have a relatively low tolerance of growing season frost and may show visible damage when growing season temperatures fall below -3°C.

![Frost resistance graph]


SYMPTOMS OF FROST DAMAGE

Frost damage typically occurs on the current year's foliage, particularly on the terminal leader and on laterals that are directly exposed to the cold night sky. After a frost, symptoms usually begin to appear within a few days and are fully developed within 1-2 weeks. Damage is evident in the browning, yellowing, or death of new growth. Lateral shoots often take over when terminal shoots are frost-damaged. Older seedlings or saplings that have repeatedly experienced frost develop a bushy growth form. Healthy, vigorous seedlings and succulent new needles appear to be more vulnerable to summer frost damage. Sublethal frost damage may occur without visible symptoms. Such damage may render seedlings more susceptible to other environmental stresses. The precise impacts of sublethal injury are not yet well understood.

AN OPERATIONAL STRATEGY FOR FROST PROTECTION

Currently, the most feasible strategy for decreasing the risk of frost in conifer plantations involves the use of passive frost management techniques such as site preparation treatments and harvesting methods which reduce the risk of frost and the selection of hardy species for frost-prone sites. These techniques reduce the frequency or severity of frost without using additional energy sources (such as wind machines, radiant heaters, fog generators, etc.) during actual frost events. More information is required about the behaviour of frost for the development of detailed management guidelines based on these techniques.

A number of projects are currently underway to collect climate data that will be useful in developing such guidelines. In addition, a study is being undertaken by Ordell Steen and Bob Stathers to identify frost-prone areas in the Cariboo Forest Region. The results of these studies, plus increasing experience with the impacts of site preparation and vegetation management treatments on frost behaviour will provide the knowledge necessary to develop frost management guidelines that can be implemented in the pre-harvest silvicultural prescription.

For further information contact:

**Bob Stathers**
*Forest Microclimate Consultant*
166 Woodlands Place
Penticton, B.C.
V2A 3B2
604-493-8123

or

**Ordell Steen**
*Research Ecologist*
*Cariboo Forest Region*
540 Borland St.
Williams Lake, B.C.
V2G 1R8
604-398-4406

FRDA Report 073 is available from:

**Communications Assistant**
*Research Branch*
*Ministry of Forests*
31 Bastion Square
Victoria, B.C. V8W 3E7