AN ABSTRACT OF THE THESIS OF

Lisa L. Melton for the degree of Master of Science in Soil Science

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Major Professor

A microclimatology study was conducted on a high elevation clearcut near the summit of Mt. Ashland in southwest Oregon to evaluate the effects of frost on Douglas-fir seedling growth and survival. Frost and low temperatures cause seedling stress through frost damage, frost desiccation, increased root resistance, and decreased rates of photosynthesis.

Five potentially damaging frost events in June and July were identified by evaluating diurnal trends in air temperature, dewpoint temperature, solar radiation and windspeed. Periodic seedling surveys allowed verification of frost damage in response to the identified events. The effects of four surface soil treatments that influence soil temperature and soil water content were compared: burn + scalp, burn (no scalp), scalp (no burn), and a control (no burn, no scalp).

No seedling frost damage was noted on any treatment until after a frost event on July 4, even though at least three frost events had occurred earlier in the season during periods when seedling were growing and so susceptible to damage. Soil temperature at 20mm depth dropped below air temperature during the July 4 frost, but not during an earlier frost event on

which did not damage seedlings. Air temperature was similar on both dates, indicating that there was a change in soil heat capacity between June 6 and July 4. As long as soil temperature remained above air temperature during frost events, no seedling damage was evident.

Seedling condition and damage, soil water loss, soil heat capacity (calculated from soil water loss) and soil temperature changes were compared between the 2 frost events. Seedlings growing on the 2 burn treatments (burn + scalp and burn) showed the least frost damage; seedlings growing on the scalp treatments showed the most. The effect of soil water on soil heat capacity is well documented; by June 4, water loss in the surface 250mm of soil was significantly greater on the scalp treatment than on either burn treatment. By the end of July, treatment ranking for soil water loss was identical to ranking for frost damage - scalp, control, burn, burn + scalp.

Control of surface vegetation had the greatest effect on water conservation; burning for vegetation control was a more effective means of conserving soil water than scalping, but combining the two treatments resulted in the lowest soil water loss.

Water has a high heat capacity and thermal conductivity relative to air or soil. Therefore, conserving surface soil moisture provides some measure of frost protection to seedlings during the early growing season by buffering soil temperature changes during a frost event.

Soil Surface Effects on Soil Water, Soil Temperature, and Douglas-fir Seedling Injury Following Radiation Frost Damage Events

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Lisa L. Melton

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Redacted for Privacy

Head of the Department of Soil Science

Redacted for Privacy

Dean of Graduate School

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SOIL SURFACE EFFECTS ON SOIL WATER, SOIL TEMPERATURE, AND DOUGLAS-FIR SEEDLING INJURY FOLLOWING RADIATION FROST DAMAGE EVENTS

INTRODUCTION

Frost causes significant reforestation problems on high elevation sites in southwest Oregon. The severity of the problem was first recognized on the Dead Indian Plateau, a high elevation forested region in the southwest portion of the Cascade Mountains. Frequent growing season frosts coupled with severe gopher damage were injuring and killing "most seedlings in many Dead Indian clearcuts" (Minore and Carkin, 1978). The problem was most serious in the clearcuts, where cold air drainage created frost pockets, and less serious in partial cuts - either shelterwoods, or smaller clearcuts - which act to limit cold air drainage near the ground surface and reduce radiative heat losses from an area during the night.

Frost as a factor in high elevation reforestation success in southwest Oregon is not limited to the Dead Indian Plateau. As timber cutting increases, and the timber base on easily accessed land decreases, there is a shift toward cutting on more marginal sites with significant environmental limitations. High elevation sites have a short growing season due to cool spring soil and low air temperatures as well as early autumn frost.

Frost events during the growing season are common, and when coupled with cool spring soil temperatures and limited soil moisture, can create stressful growth conditions for outplanted seedlings. In the spring, seedling roots and shoots must reach some threshold temperature in order to develop and function properly. Differences between soil and air temperature can cause the shoots to transpire at rates faster than the roots can supply water. Furthermore, if seedling tissues are damaged by frost, their control of transpiration through stomatal closure is impaired, and survival potential is further decreased.

Site management techniques can be used to reduce the severity of frost impact on seedling development. A frost event can develop in either of two ways: 1) by cold air draining into a low spot on a landscape - such as a clearcut in the midst of a forest, or a stream drainage - or 2) by loss of radiative heat to the atmosphere - usually occurring in the hours just before dawn following a clear night. Both processes are controlled by mesoscale climatic events, but their influence on a specific site can be reduced either by avoiding creation of frost drainage pockets or by decreasing net loss of radiation. A great deal of research in orchards has been dedicated to identifying and comparing the effects of various soil surface treatments on vegetation frost damage; some of those techniques can be used in the clearcut environment, as long as differences between the two systems are taken into account.

Soil moisture reserves, necessary for optimum seedling growth and development, increase heat storage capacity in the seedling environment and can therefore affect seedling response to frost. The rate of change in soil temperature during a frost event is controlled by the amount of heat stored in the soil and the rate of heat loss from the soil surface, which is directly related to soil water content.

Identification of site characteristics and site preparation techniques that improve outplanted seedling frost survival is vital to reforestation success on high elevation sites. Seedling establishment can become more difficult as time goes on as the seedling growth environment and conditions change rapidly after harvest. Regeneration success on high elevation sites might be improved if appropriate frost management techniques are used.

In this thesis, a case study of the effects of four site preparation methods on site frost potential is presented. Quantitative measurements of microclimate are used to show the mechanisms through which these techniques affect the seedling growth environment.

LITERATURE REVIEW

Forest Management and Frost in Southwest Oregon

The southwest Oregon forest resource region has a long history of regeneration failures (Strothman and Roy 1984). The high incidence of plantation failure, particularly on hot, south-facing slopes has caused the forest to consistently fall short of its expected production. These failures are generally attributed to complications brought on by the extended summer drought and to frost at higher elevations (Williamson and Minore 1978, Stein 1986, Emmingham 1988).

Precipitation is rare during warm summer months in the Pacific Northwest. In Oregon, the magnitude and duration of the summer drought is greatest in the southwestern corner of the state. The effects of the drought are amplified by large diurnal and seasonal temperature variability, creating a particularly difficult growth environment. The stresses on plantation seedlings brought on by these climatic factors have resulted in poor growth and high seedling mortality in some areas (Strothman and Roy 1984, Carkin and Minore 1974).

Native vegetation has adapted to the severe regional climate. Douglas-fir seedlings grown from southwest Oregon stock seed have been found to exhibit xeromorphic growth characteristics, such as low shoot to root ratios and dense root systems (Lavender and Overton 1972). High summer air temperatures, large diurnal temperature variability and limited water availability allow only the hardiest seedlings to survive.

Soil water deficits during periods of rapid growth greatly affect seedling development (Carkin and Minore 1974). This is an important factor in seedling survival potential on high elevation clearcuts, where snow levels control site access, and therefore the timing of planting. Often seedlings on high elevation sites in southwest Oregon are not outplanted until late spring or early summer when they have begun to break dormancy, and competing vegetation has started to grow and deplete soil water reserves. (personal communication, George Badura, USFS Soil Scientist, Medford, Oregon). Seedlings that are already stressed are more likely to succumb to the added stresses brought on by a frost event.

The regeneration problems encountered on high elevation sites are different from those at lower elevations. Conditions may be even more stressful; soil and air temperatures are colder, and frost potential is greater. Unfortunately, availability of high elevation clearcut microclimate data for southwestern Oregon is limited. Waring (1969) gave climatic variables and vegetational characteristics for various natural plant communities that exist at different elevations in the Eastern Siskiyous. But beyond his research and that resulting from the efforts of the group studying regeneration problems on the Dead Indian Plateau, a frost prone region located east of the city of Ashland (Minore et al 1982, Minore and Carkin 1978, Minore 1978, Williamson and Minore 1978), there is little information describing seedling growth conditions on high elevation sites for this region.

Some factors affecting seedling survival have been identified, however. Regeneration problems on the Dead Indian Plateau have been blamed primarily on topography defined frost pockets and gophers (Minore 1978). Furthermore, the effect of summer drought on seedling survival and growth was considered to be tertiary to the effects of frost and gopher damage.

There is no question of the importance of frost damage in relation to seedling survival and growth in that area. Due to ease of access, the Dead Indian was harvested years before other high elevation sites in the surrounding region. After harvest, localized cold air masses drained into clearcuts and other low areas which had previously been protected by heat trapping characteristics of the forest canopy; a frost problem developed. Frost is not uncommon as a factor in poor clearcut regeneration in southwest Oregon (McNabb 1987) and not limited to the Dead Indian Plateau. On sites greater than 1100m elevation, some care should be taken to protect seedlings from frost damage (Emmingham 1988).

Effects of Cold Temperature and Frost on Seedling Development

Cleary (1968) found that in the laboratory, Douglas-fir seedlings exhibited optimum growth when air temperatures were approximately 30°C and soil temperatures were approximately 20°C. He also found that Douglas-fir root temperatures of 10°C reduced seedling growth by more than 40% relative to that at 20°C, regardless of the shoot temperature. Lavender et al. (1973) found that root growth of Douglas-fir seedlings was inhibited severely until soil temperatures exceeded 5°C. Lavender and Overton (1972) found that root growth increased rapidly only when soil temperatures exceeded 10°C. Heninger and White (1974) found that optimum soil temperature for overall growth of Douglas-fir seedlings was between 15 and 27°C.

The late-planted seedlings on the high elevation sites must be able to initiate root growth and develop photosynthetically active shoot vegetation rapidly in order to set bud and enter the drought induced summer dormancy in good condition before soil water reserves have been exhausted. Lopushinsky (1987) stated that low soil temperatures have both direct and indirect impacts on seedling performance: 1) water relations problems, decreased photosynthesis, decreased stomatal conductance, altered patterns in carbohydrate accumulation, delayed budburst, decreased root and shoot growth, and 2) long term effects caused by reduced nutrient uptake and reduced nutrient availability due to lower rates of microbial breakdown in the cold soils. Van den Dreissche (1987) found that once seedlings break dormancy, current photosynthate was the primary source of carbon for new root development. Passioura (1984) stated that when water is extremely limited, the rate of photosynthesis is set by the plant shoot, by balancing the tradeoff between carbon dioxide uptake and water loss. If the seedling is unable to photosynthesize properly, new root development and subsequent ability to tap new sources of stored soil water will be diminished. DeLucia (1987) found that temperatures of -2.5°C caused a temporary 2-10% reduction in photosynthesis for spruce seedlings; however, temperatures below -4°C caused an irreversible decrease in photosynthesis as well as the ability to assimilate internal CO_2. Low photosynthetic rates have been found to correlate with low air temperatures particularly in the early growing season (prior to mid-June) and low soil temperatures in the later growing season (mid to late June) in subalpine forests (DeLucia and Smith 1987).

Early season water uptake by plants is controlled by changes in soil temperature; cold roots are not efficient in water uptake (Lopushinsky and Kaufmann 1984, Tranquillini 1982, Running and Reid 1979, Lavender 1972, Kramer 1940) and are more susceptible to damage than shoots under freezing conditions (Cremer 1985). Furthermore, the initiation of a new root system in the seedling takes precedence over shoot development (Krueger and Trappe 1967).

Grossnickle and Blake (1985) found that jack pine and white spruce seedlings grown at low soil temperatures (10 or 16°C) experienced greater water stress than those grown in warmer soils (22°C) until new root development occurred. Krueger and Trappe (1967) estimated that newly outplanted Douglas-fir seedlings needed at least four weeks of available soil water to adjust to the new environment and develop a new root system. Until the soil temperature growth threshold is exceeded, root development and function - and therefore shoot development - are limited.

Therefore, if the seedling is to survive, it must develop quickly once it breaks dormancy, not only to avoid the stresses of midsummer drought, but to avoid damage from frost events that occur while the seedling is going through stages of rapid growth and development. Raitio (1987) found that if Pinus radiata seedlings are frost damaged during periods of active growth, even if they survive, they are more susceptible to damage from later stress events and subsequent development is retarded. If budset is not attained prior to the onset of summer drought, the young growing tissues above and below the soil surface will be even more susceptible to damage by a frost event.

Even before the seedlings have burst bud, they can become "frost desiccated" due to reduction or interruption of water transport either in the soil or in seedling tracheids (Tranquillini 1982). The term, frost desiccation, is loosely defined, and damage identified as such is not necessarily a result of frozen tissues. It is not clear whether the damage is caused by ice crystal blockage of transport through tracheids, or simply a differential between the rate of transpiration and the rate of uptake caused by increased resistance to water flow at cold root temperatures (Kramer 1940). This phenomenon is common in the spring on high elevation sites, particularly when direct solar radiation causes seedling shoot tissues to warm and initiate growth while seedling roots are still cool and relatively inactive. For frost desiccation to occur, air and soil temperatures do not have to be below 0°C. Root resistance increases exponentially with decreases in temperature and although water may be plentiful, the rate of uptake may be so slow that a water deficit occurs (Tranquillini 1982, Running and Reid 1979).

Site Conditions That Influence Frost Potential

Frost has proven to be a major factor in reduced seedling survival in some high elevation areas in SW Oregon (Minore et al 1982, Minore and Carkin 1978, Williamson and Minore 1978). As elevation increases, the incidence of frost events during the growing season also increases. Frost damage potential on any site is dependent on many interactive factors, but can be evaluated as a function of site heat storage and loss potential. The magnitude and direction of microsite heat energy flow is influenced by moisture content of local soil, air and vegetation, soil texture, soil mineralogy, soil surface characteristics, vegetation type, canopy cover, aspect and slope. On a regional scale, solar radiation, relative humidity, air temperature and cloud cover control frost (Cannell 1984, Sharratt and Glen 1988). Heat reradiated from the soil surface can warm surface air temperatures and offset the effects of regional cold air temperatures for some time, thereby reducing frost potential in the seedling growth zone. At night, as the supply of stored surface heat is depleted, air temperatures begin to drop, and just before dawn, they reach a minimum. Therefore, if the sky is clear and heat storage in the radiating surface is low, predawn frost potential is high.

Many variations of the basic heat flow equation have been derived in the attempt to properly quantify and identify the various components of a site energy budget (Campbell 1977). The energy budget for the soil surface is described in the following formula.

$$R_{in} + L_c + H_s = R_{out} + L_e + H_l \qquad 1)$$

R_{in} represents incoming radiation; L_c represents latent heat gained from water vapor condensation; H_s represents soil heat flux; R_{out} represents outgoing radiative energy; L_e represents latent heat lost by evaporation; H_l represents sensible heat flux.

The magnitude of R_{in}, including short and longwave components, and is controlled by the emissivity and temperature of the sky and objects in the immediate environment, such as local vegetation or surrounding hills. Clouds and vegetative canopies have higher emissivities and temperatures than clear sky, so will cause R_{in} to increase if they are present.

L_c is controlled by the amount of water vapor in the environment and by temperature. As temperature deceases, the capacity of the air to hold water in the vapor form also decreases. As the water vapor condenses, heat is stored.

H_s is controlled by the properties of the soil, particularly the surface layer. The ability of the soil to store and conduct heat depends primarily on soil texture, mineralogy and water content (Campbell 1977). As soil water content increases, so does heat capacity. Water has a greater specific heat than soil minerals, and has a higher thermal conductivity, so can enhance heat conduction into the soil and increase soil heat storage.

R_{out} is controlled by the soil surface temperature and emissivity. During the day, R_{in} is usually greater than R_{out} due to solar radiation. At night, R_{out} is generally greater than R_{in}, especially if the sky is clear. The major energy source at night is heat stored in the soil and surrounding vegetation. The heat stored during the day is reradiated during the night, keeping the air from cooling as rapidly. Heat flux from subsoil to the radiating soil surface is greater in moist soils and can moderate air temperature depression at night near the soil surface (Mahrt 1985) thereby decreasing frost potential (Fritton and Martsolf 1981). Therefore, if environmental moisture is plentiful, radiation frost potential is diminished.

L_e is controlled by temperature and water vapor content of the air above the soil surface. As temperatures increase, the water vapor holding capacity of the air also increases. Soil surface water evaporates, and stored energy is lost to the atmosphere.

H_l, sensible heat flux, is a heat exchange between the soil surface and the air. It is affected by wind or air drainage, and is controlled by topography. Plateaus, drainages or bowl shaped depressions can act as cold air traps, creating localized cold conditions. However, if there is sufficient wind to mix warm air aloft with cool air near the soil surface, frost pockets are less likely to form.

Effects of Soil Water on Soil Heat Capacity and Temperature

Soil water has an effect on soil latent heat properties, emissivity, heat capacity and thermal conductivity. Changes in soil water content therefore cause large changes in the soil thermal regime, which is reflected by the rate of change in soil temperature in response to changes in the energy budget.

Water, whether in the air or in the soil acts to moderate temperature extremes (Horton and Wierenga 1983, Cremer and Leuning 1985). Therefore, the effects of a potentially damaging frost are reduced when sufficient water is present.

During the night, air temperature drops until it approaches the dewpoint. As temperature decreases, the ability of the air to hold water vapor decreases. When air temperature reaches dewpoint temperature, water vapor condenses. This change of state will temporarily maintain air temperature near dewpoint temperature. Cremer and Leuning (1985) found that as long as soil water potential is in the 0 to -1.3 MPa range, phase changes in soil water will maintain soil temperatures between 0 and -1°C for some time, the duration of which is dependent on macroclimate conditions that control the magnitude of the frost event (or the rate of change in air temperature).

Since water has a high heat capacity and emissivity relative to that of dry soil, soil water also affects the timing and the amount of reradiated energy. A reduction of water content in an average soil from 35 to 25 percent will reduce the soil heat capacity by 16 percent (Marshall and Holmes 1988). Cremer (1985) found that moist soil surfaces remain warmer during nights of radiation frost than adjacent dry soils. Fritton and Martsolf (1981) stated that a moist soil can protect vegetation from frost due to its heat storage capabilities. Cremer and Leuning (1987) found that leaf temperatures of eucalyptus seedlings were higher over a moist soil surface than over a dry soil surface during a frost event.

The soil-air-water medium stores heat during the day and reradiates heat at night. If the heat capacity is large enough, reradiated heat can keep air temperatures near the soil surface from dropping below freezing. Reforestation site preparation treatments could be evaluated for frost protection capabilities based in part on water conservation effects.

Effects of Site Preparation and Reforestation Treatments

Soil and air temperatures on high elevation sites remain cool later in the growing season, which can have the effect of limiting seedling development (Lopushinsky and Kaufmann 1984, Sorensen and Campbell 1978). Site preparation techniques such as scalping, burning or surface mulching can be used on high elevation sites to moderate the harsh clearcut environment and improve seedling survival. Since water and temperature interact to affect initiation and rate of seedling development, a treatment that enhances both factors within the climatic limitations of the high elevation site is desireable. Shelterwoods are more difficult to manage than clearcuts, but have many advantages on sites prone to frost damage (Emmingham 1985, Mahrt 1985). Depending on the density of the shelterwood, canopy effects can enhance mixing of warm air and favorably modify the longwave radiation balance under the canopy by radiating longwave energy at higher temperatures than the sky (Minore and Carkin 1978, Childs and Flint 1987). However, they are not practical on all sites, and other reforestation practices must be applied. Clearcutting is a less expensive, easily managed method of tree harvest, but creates a very harsh environment for seedling growth. Site preparation methods, such as mulching, burning and scalping are three techniques commonly used to improve the harsh environment.

There are many different types of soil mulches, but all cover the mineral soil surface and insulate it from aboveground effects. In an agricultural setting, they are used to reduce evaporation and moderate soil temperatures. However, in an environment where the soil surface can dry out considerably, as is common on for clearcuts in the summer season, a mulch has minor effects on surface evaporation rates. Once the evaporating surface is dry, the evaporation rate depends on the rate of water supply from subsoil moisture reserves to the surface (Papendick et al. 1972, Hanks et al. 1960).

In an environment where the night-time flux of stored soil heat into the air provides protection from cold air temperatures, a surface mulch can be detrimental. Glenn and Welker (1987) found that heat flux was greatest from a bare, cultivated soil, as compared to three other treatments that manipulated a surface mulch to varying degrees. Fowler and Helvey (1981) found that air temperatures above a surface mulch of broadcast, untreated slash were cooler than those above adjacent burned surfaces. Ludlow and Fisher (1976) also found that leaves of a pasture legume sustained more frost damaged if the soil surface below was covered with litter.

Soil temperatures can be reduced under a mulch treatment due to poor heat conduction through the mulch. Fowler and Helvey (1981) found that soil temperatures were cooler beneath a chip mulch treatment than under scarified or burned treatments. Maintenance of an intact surface duff layer around the seedling can therefore reduce soil temperature extremes below the soil surface, but cause air temperatures above the soil surface to be cooler. A mulch effect on soil evaporation rates, while not great, will decrease evaporative loss relative to that from a bare soil surface (Hanks et al. 1960).

Scalping has been a site preparation tool for decades (Cleary et al. 1978, Strothman and Roy 1984), but, depending on the scalp dimensions, as well as local geographic and edaphic characteristics, the effects of scalping can be highly variable. Scalping is defined as removal of the surface duff, and sometimes soil, from a planting or seeding surface. The scalp can be only centimeters deep and the width of a planting hoe, or it can be a great gouge of indeterminate size and depth created by mechanically scraping holes on a slope in order to capture surface runoff. In regions such as southwest Oregon that receive only limited growing season precipitation, the increased evaporation rates that result from large scalps can create stressful moisture conditions for seedlings. Therefore, prior to creating general hypotheses about scalp treatment results, it is important to identify the type of scalping.

In British Columbia, under near saturated soil conditions, a scalp treatment resulted in lower than average temperatures (Macadam 1988). However, under normal conditions, scalping reduces vegetative competition with adjacent seedlings and increases early season soil temperatures (Dobbs and McMinn 1977).

Increased root zone soil temperatures in the early growing season could improve seedling survival on a high elevation clearcut. Increases in soil temperature between 10°C and 20°C improved spruce seedling development in British Columbia, and scalping increased mean diurnal soil temperatures in the root zone from 14°C to 17°C (Dobbs and McMinn 1977). Increased soil temperatures in the spring can cause the seedling to initiate growth earlier and so avoid late season water deficits (Sorensen and Campbell 1978). Hungerford and Babbitt (1987) found however that extreme surface temperatures caused by loose, dry surface soil could negatively affect seedling survival. This characteristic of the scalp is caused by an increased rate of water loss which negatively affects the soil heat capacity. The dry soil surface temperature will change more rapidly than it would if the soil was moist and so had a higher heat capacity.

Since scalping increases the rate of evaporative loss of stored soil water, it can also have deleterious effects in some areas where availability of soil water is limiting (Hobbs 1982, Helgerson 1985), where frost potential is high when soils are dry (Cremer 1985), or where high soil temperatures may cause seedling damage (Miller et al. 1982, Seidel 1986). Nagpal and Boersma (1978) found that wet, coarse soils experienced greater rates of evaporative loss than fine soils during periods of high evaporative demand; the soils in the area studied are gravelly, sandy loams.

The loss of moisture through evaporation can greatly affect seedling survival of drought and frost. Hobbs (1982) found that by late summer, xylem pressure potentials in Douglas-fir seedlings planted on a southwest aspect at a low elevation in southern Josephine County ranged from -1.5 to -2.7 MPa. Seedling survival declined as the summer progressed, and mortality was blamed on effects from heat and water stress. Flint and Childs (1987) found that when competing vegetation was controlled with an herbicide, a treatment which would control transpiration and evaporation, seedlings showed significantly greater diameter growth than seedlings grown on scalp treatments which were designed to control only transpiration. They also found that scalping for vegetation control was significantly less effective in controlling water loss than the treatment that actually killed the vegetation.

Slash burning has also been widely used as a reforestation tool (Cleary et al. 1978, Strothman and Roy 1984). It has been shown to reduce fire hazard, to decrease vegetative competition for soil water, to create a good seedbed and to cause increases in soil temperature and moisture, dependent on the type and severity of the burn and the soil type (Cleary et al. 1978, Ahlgren 1981, Fowler and Helvey 1981, Hungerford and Babbitt 1987).

Burning provides vegetative control for several years by killing existing growth as well as seeds in the duff layer. Soil water deficits can decrease seedling survival in environments where competition for stored soil water is severe (Williamson and Minore 1978) and frost potential is high (Cremer 1985). Ahlgren (1981) found that soil water content at 5cm depth increased for the first season following slash burning. He also found that relative humidity on the site increased for several years following a burn.

Increases in soil temperature observed following slashburning could have negative effects on seedling survival in areas where soil temperatures are already dangerously high. Early in the growing season however, high soil water contents in the burned areas may moderate soil temperatures. If the seedlings develop rapidly and reach dormancy before soil water is limiting, they will be less susceptible to environmental stresses brought on by the loss of the buffering effects of soil moisture. Whether or not seedlings benefit from the burn treatment may be seasonally dependent and affected by soil water conditions in the early spring.

RATIONALE AND OBJECTIVES

Reforestation success on high elevation sites in SW Oregon requires seedling avoidance or tolerance of damage from frost events. Frost is not an aberration, but a normal climatic occurrence on the high elevation sites, and therefore must be taken into account when devising management strategies. Seedling survival depends on 1) frost event severity 2) site moisture status and 3) previous seedling condition. Site preparation treatments that enhance conservation of soil water will cause seedlings to suffer less frost damage. Techniques that cause early season soil temperatures to rise will improve early season seedling root and shoot development, thereby enhancing seedling ability to survive a frost event if it does occur.

This study was designed to evaluate the environmental factors affecting severity of seedling frost damage. Evaluation of two site preparation treatments - scalping and burning - on water and temperature in the seedling environment was a primary goal of this study. Specifically, three factors were considered:

1) treatment effects on soil water loss over the growing season,
2) the relationship between changes in soil water content, soil heat capacity and soil temperature,
3) treatment effects on seedling frost damage and survival.

To accomplish those objectives, I collected seedling microsite climatic data, and conducted periodic seedling surveys to isolate when damaging events occurred. Microclimatic measurements allow evaluation of microsite frost potential, which can be thought of as site (or treatment) specific resistance to climate change in response to mesoscale climate events. Soil temperature and soil water data collected for each treatment were analyzed in relation to potential frost events which were identified by analyzing weather station data - air temperature, dewpoint temperature, solar radiation and windspeed. Seedling damage did not occur on all such identified frost events, so a comparison was made of seedling microsite conditions during damaging and non-damaging events.

By measuring microclimatic changes, I was able to evaluate interactive factors that combined to create a unique seedling growth environment for each treatment. Microclimatic effects on seedling microsite growth conditions are extremely variable, but, detailed measurements of microclimate can aid in the identification of mechanisms that control seedling response to frost. By focusing on evaluation of physical processes that created microclimatic differences between treatments, I was able to extract more useful information from this case study than would have been possible with a simpler, observational approach of seedling response to treatment.

METHODS AND MATERIALS

Site Description and History

The clearcut study area is located in Jackson County approximately one mile east of the peak of Mount Ashland in the Ashland Ranger District of the Rogue River National Forest (T40S R1E S14). All visible rock outcrops in the area are granitic, which weather to form coarse sandy-loam soils overlying dense grus or bedrock. The soils in the study area are shallow, ranging from 350 to 700mm depth. The slope is 25%; aspect is 220° (southwest); and elevation is approximately 1600 m. Average annual precipitation ranges from 900 to 1150mm, most of which falls during the winter as snow; the soil moisture regime is xeric, and the soil temperature regime is frigid (Badura and Jahn 1987).

The site lies in the upper elevations of the Principal Forest Zone (ZONE-II) of the Siskiyou portions of the Rogue River National Forest (Badura and Jahn 1987). The dominant timber species are Pseudotsuga menziesii and Abies concolor. Other conifer species found in the zone are Pinus lambertiana, Pinus ponderosa and Taxus brevifolia. Common hardwoods and shrubs are Acer macrophyllum, Cornus nuttallii, and Rubus ursinus (Badura and Jahn 1987).

The site was clearcut in the summer of 1984. Slash was broadcast burned to minimize future fire hazard and to prepare the site for planting. The burn resulted in intermittent burned areas in the portion of the clearcut chosen for this study. There was some evidence of soil disturbance by logging equipment; these areas were avoided when laying out the study plot. By the spring of 1986, various invader grasses and forbs were beginning to populate the clearcut. The unburned and burned areas had a moderate amount of duff cover, visually estimated to be 10 to 75mm thick. The unburned areas were supporting approximately 50% more vegetation than were the burned areas.

Seedling Survey Data Collection

A plot was chosen on a southwest facing slope that contained both burned and unburned soil surfaces. On April 7, 1986, 192 Douglas-fir seedlings (2-0 stock) were randomly planted in both burned and unburned areas, some in scalps, some without scalps. The scalps were approximately 45cm in diameter; surface duff and vegetation were removed. The resulting treatments were as follows:

i) burn+scalp, (42 seedlings)
ii) burn (no scalp), (53 seedlings)
iii) scalp (no burn), (51 seedlings)
iv) control (no burn, no scalp), (46 seedlings)

Seedling surveys were taken periodically from May 16 to

September 22 recording:

i) general seedling condition (good, fair, poor or dead),

ii) current phenological stage (dormant, budburst, actively rowing, budset, second budburst and second budset)

iii) cause of seedling damage (ravel, drought, browsed, broken, frost).

During this study, second budburst and damage from factors other than frost and drought were minimal. A Chi square statistical analysis was used to evaluate treatment differences at the 95% confidence level for survival, frost damage, frost death and phenologic stage on each survey date.

Site Climate Measurements

The weather station (Comstock Instrument Company, Albany, Oregon) was designed to measure:

i) solar radiation (photodiode pyranometer, Li-Cor, Inc. Lincoln, NE),

ii) air temperature (thermolinear thermistor, Yellow Springs Instr. Co., Yellow Springs, OH),

iii) dewpoint temperature (dewcel hygrometer, Comstock Instrument Co., Albany, OR),

iv) windspeed (contact closure cup anemometer, Met One Instruments, Grants Pass, OR),

v) precipitation (contact closure tipping bucket, Texas Electronics).

A portable datalogger was used with a cassette tape data recorder to record weather station measurements as directed through programming (Model CR21, Campbell Scientific Instruments, Logan, UT). The datalogger was programmed to give:

i) hourly averages of solar radiation, air temperature, dewpoint temperature and windspeed,

ii) hourly summations of precipitation,

iii) daily maxima and minima of air temperature, and

iv) daily summations of solar radiation and precipitation.

Daily minimum air temperatures, dewpoint temperatures, solar radiation and windspeed were used identify days when frost events may have occurred.

Soil Temperature Measurements

Thermistors (thermolinear, Yellow Springs Instr. Co., Yellow Springs, OH) were placed at 20mm., 200mm. and 300mm. depths under the mineral soil surface in the four treatments. Three replications were made of each treatment. A second datalogger with a cassette recorder was used to collect temperature data once an hour throughout the summer (Model CR5, Campbell Scientific Inc., Logan, UT).

Daily averages, maxima, minima and ranges were calculated from this data set, put through a rank transformation and evaluated in one week time increments using non-parametric analysis of variance of the ranked data as described by Conover and Iman (1981). Soil properties have great spatial and temporal variability in a natural environment, which greatly reduces the effectiveness of traditional analysis of variance techniques. Furthermore, temperature variability under the two scalp treatments was much greater than under the unscalped treatments, causing the data to have a non-normal distribution. Using ranked data reduces the range of variability, but still allows evaluation of relative magnitude. The absolute value of the change in temperature between treatments on this study was not considered to be as important as whether the temperatures were simply high or low more often on any treatment.

Diurnal trends in soil temperatures were evaluated to identify differences in treatment response to environmental changes that could be linked to seedling damage response during frost events.

Soil Water Measurements

Soil water data were collected prior to each seedling survey using a gamma attenuation device (model 2376, Troxler Instrument Co., Research Triangle Park, N.C.). Six replications of each treatment were established resulting in a total of 24 soil profile moisture samples being taken on each sampling date. Measurements were taken at 25mm increments from the surface to the bottom of each soil profile (depths ranged from 350mm to 700mm). Output from the gamma attenuation device was converted into wet bulk density values for each 25mm depth.

Changes in wet bulk density from one sampling date to the next were attributed to a change in water content due either to evaporation, transpiration or precipitation. Soil water loss through drainage was considered to be negligible. Factoring in precipitation allowed calculation of total water loss from the treatments. Simple changes in water content between sampling dates (precipitation input ignored) was used to calculate changes in soil heat capacity for each treatment.

The data were analyzed by depth increment on five sampling dates to identify significant differences between treatments. The depth increments analyzed were 0-125mm, 125-250mm, 0-250mm and the entire profile depth. The sample dates analyzed were June 4, June 14, June 24, July 30 and August 28.

Water loss was summed for the listed depths and analyzed to find least significant differences at the 90% level of confidence for both cumulative and short term[1] water loss between treatments on each date.

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[1] Defined as water loss since last sampling date, or non-cumulative water loss.

RESULTS AND DISCUSSION

Frost damage was found to be a significant factor in seedling mortality and was greatly affected by seedling response to treatment alterations of microsite conditions. The seedling survey analysis will be discussed first, since it clearly shows treatment differences and was used to isolate real damage events in time. Then, the identification of potential frost events by analysis of climatic measurements are compared to the seedling survey results. It will be shown that the seedlings did not succumb to frost damage until well into the growing season even though potentially damaging events did occur earlier. Soil temperature analysis results will be presented to show differences in root zone temperatures between two frost events, one on June 6 that did not damage seedlings, and one on July 4 that did. Finally, a discussion of the soil water analysis will present changes in soil water content that occurred as the season progressed. These differences are thought to be responsible for the varying degrees of frost damage and death in the four treatments.

Seedling Survey

The four treatments had varying effects on seedling survival, phenologic development, frost damage and frost death. Evaluation of seedling phenology and response to frost allows a more precise evaluation of the factors controlling seedling survival on this site. Survival data will be presented first, followed by a discussion of those controlling factors.

Survival Four seedlings growing on scalp treatments were killed by gophers before June 14. When those seedlings were excluded, mortality for all treatments was low and very similar until the survey taken on July 5 (Figure 1a). On that date, seedlings growing on the two burn treatments (burn+scalp and burn) had significantly greater than expected[2] survival when compared to those grown on the unburned treatments (scalp and control): 97% and 96% survival as compared to 88% and 76%. By the end of the season, differences in survival were even larger, 86% and 51% for seedlings growing on the burn+scalp and the burn treatments as compared to 14% and 7% for seedlings growing on the scalp and the control treatments.

The effects of scalping alone were not significant to seedling survival by the end of the season. It is true however that seedlings growing on the scalp treatment had better survival rates than seedlings on the control treatment, and seedlings on the burn+scalp treatment had better survival rates than those on the burn. Therefore,

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[2] Chi square analysis evaluates treatment response variation from an "expected" response.

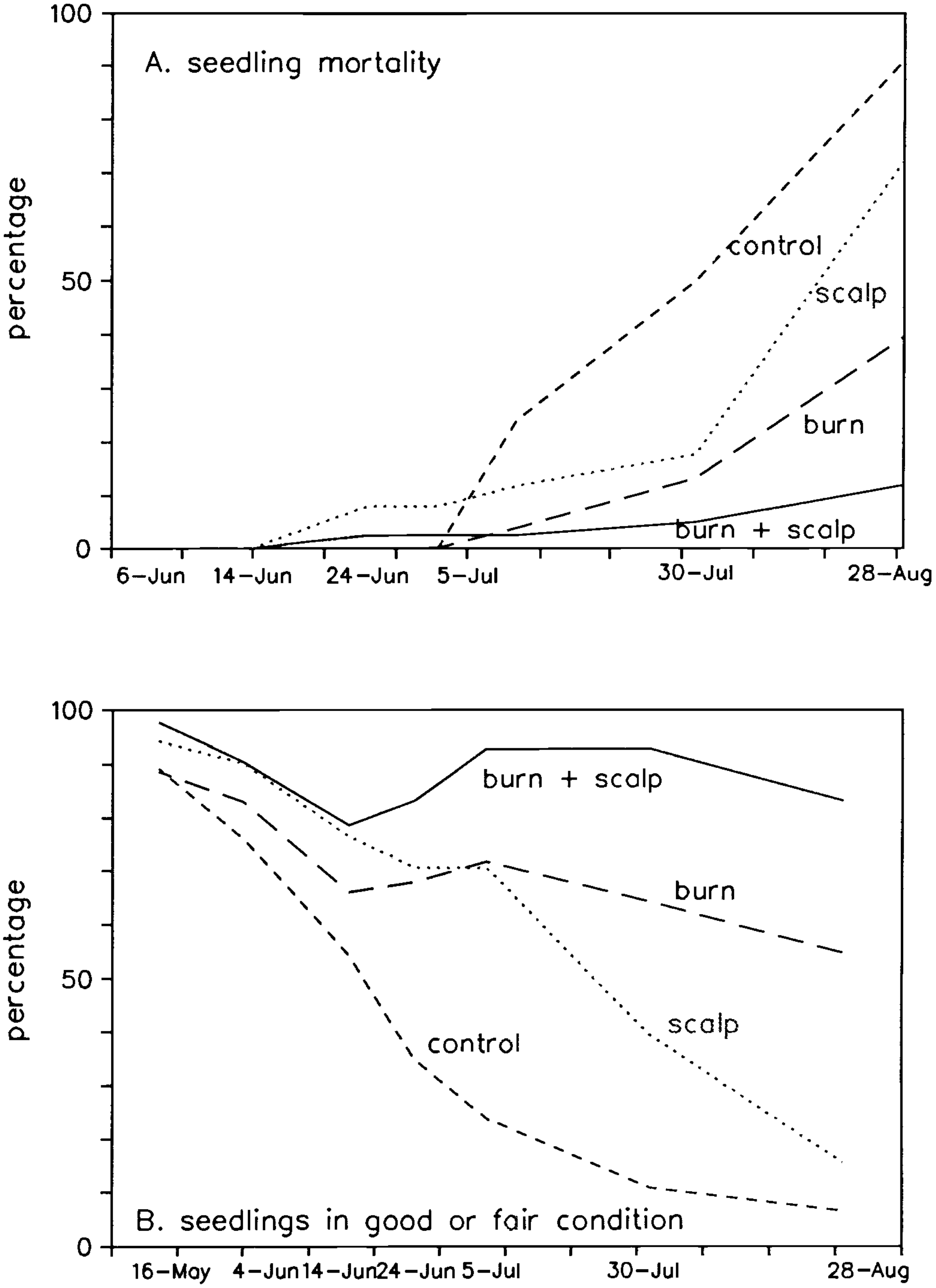

Figure 1. Effect of treatment on seedling mortality and condition throughout the summer season.

scalping improved seedling survival conditions, but were secondary to the effects of burning.

Phenologic development The seedlings growing on the control treatment exhibited the slowest development rates of all four treatments. By May 29, significantly fewer than expected were in good or fair condition than in the other three treatments (Figure 1b). They burst bud significantly later than the other three treatments (Figure 2a) and began to die rapidly by early July, many without ever reaching a stage of active growth[3]. It was apparent that the control treatment - unscalped and unburned - created an environment that was the most stressful of the four treatments.

Seedlings growing on the two scalp treatments developed significantly faster in the early season than seedlings grown on the two unscalped treatments; by June 14, 64% and 58% of the seedlings growing on the burn+scalp and scalp treatments had completed budburst and were actively growing (Figure 2b). At that same time, only 40% of the seedlings growing on the burn treatment and 15% of those growing on the control treatment were actively growing. These relationships held until July 5 when the condition of seedlings growing on the scalp treatment began to decline rapidly. By July 30,

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[3] Defined as the period between when leaf primordia developed into needles and grew away from the budscale sheath, and when the seedling set bud and entered dormancy.

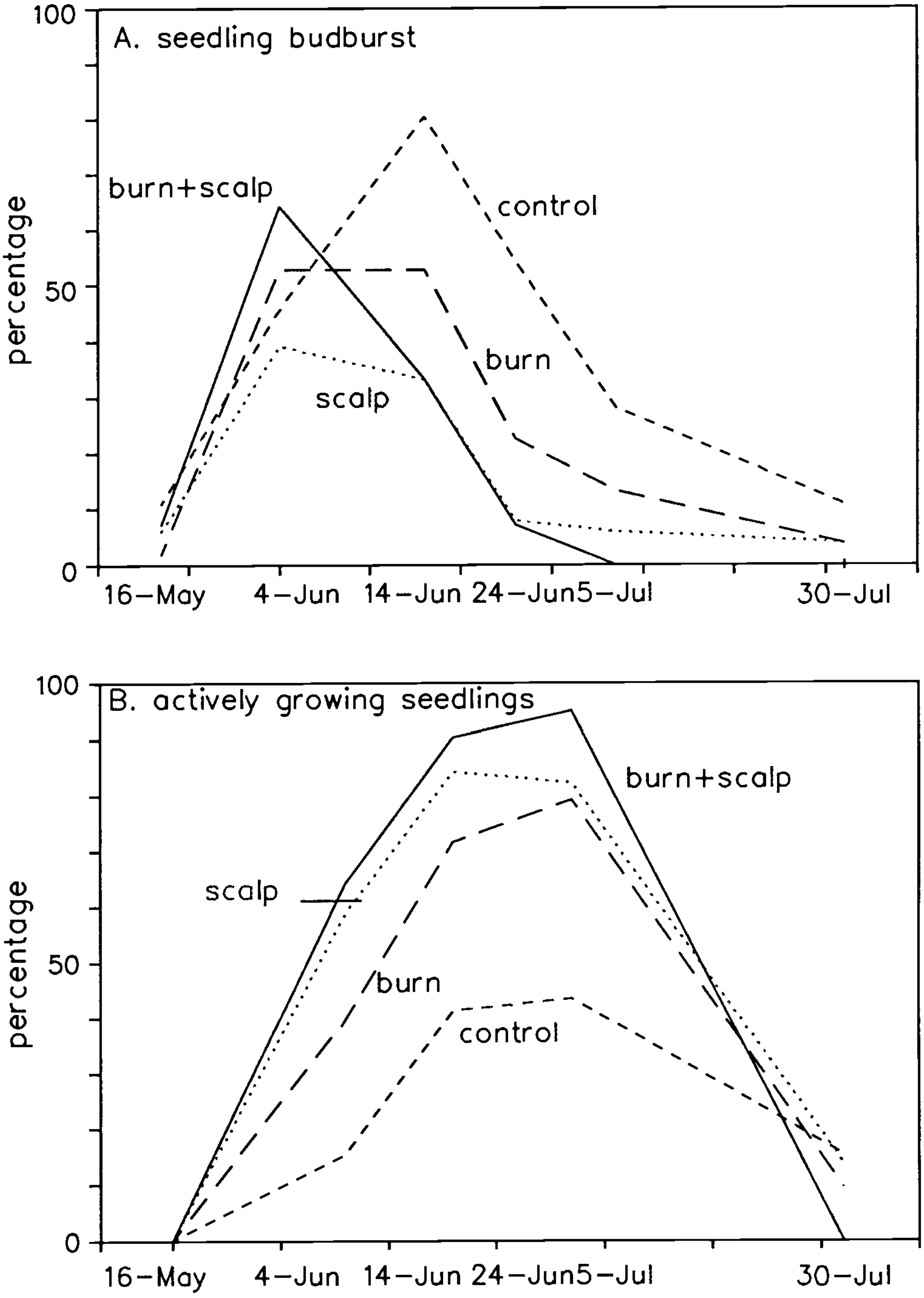


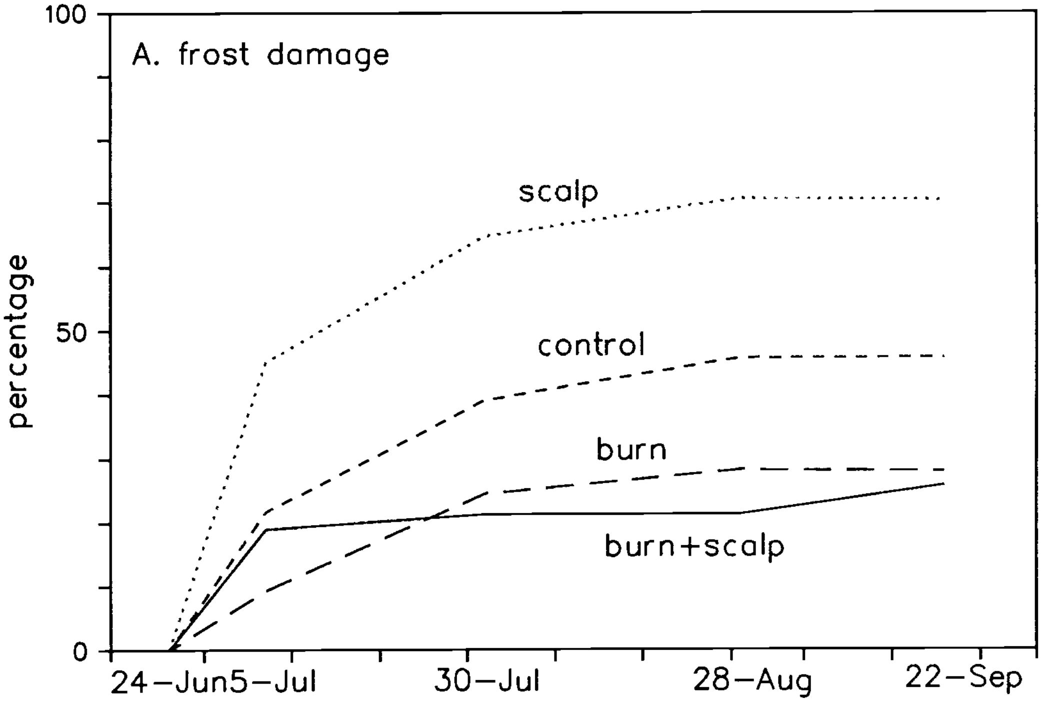
Figure 2. Effect of treatment on seedling phenologic development. Peaks should be interpreted to represent when most seedlings were in that specific growth stage.

too few seedlings remained alive on the scalp and control treatments to make statistical comparisons.

Frost response The first visible evidence of frost damage was noted on the July 5 survey (Figure 3a). On that date, seedlings on all treatments showed evidence of both new and old frost damage (newly wilted needles and brown,desiccated needles). Since there had been no visible evidence of frost damage on June 24, at least two frost events must have occurred between June 24 and July 5. Weather station measurements showed that frost events occurred on June 27 and on July 4.

All treatments showed evidence of frost damage, but the scalp treatment was affected most. Seedlings growing on the scalp treatment showed significantly more damage throughout the summer; 45% seedling damage was noted on the scalp treatment on July 5, 71% by the end of the season (Figure 3a). One should note that frost events were recorded throughout the summer: three in June, three in July, one in August and several in September and October. Frost events therefore were common, but not always damaging to seedlings. During the summer of 1986, frost damage appeared to be seasonally dependent, occurring later in the growing season.

Frost damage was a major cause of seedling mortality, particularly for seedlings on the two unburned treatments - scalp and



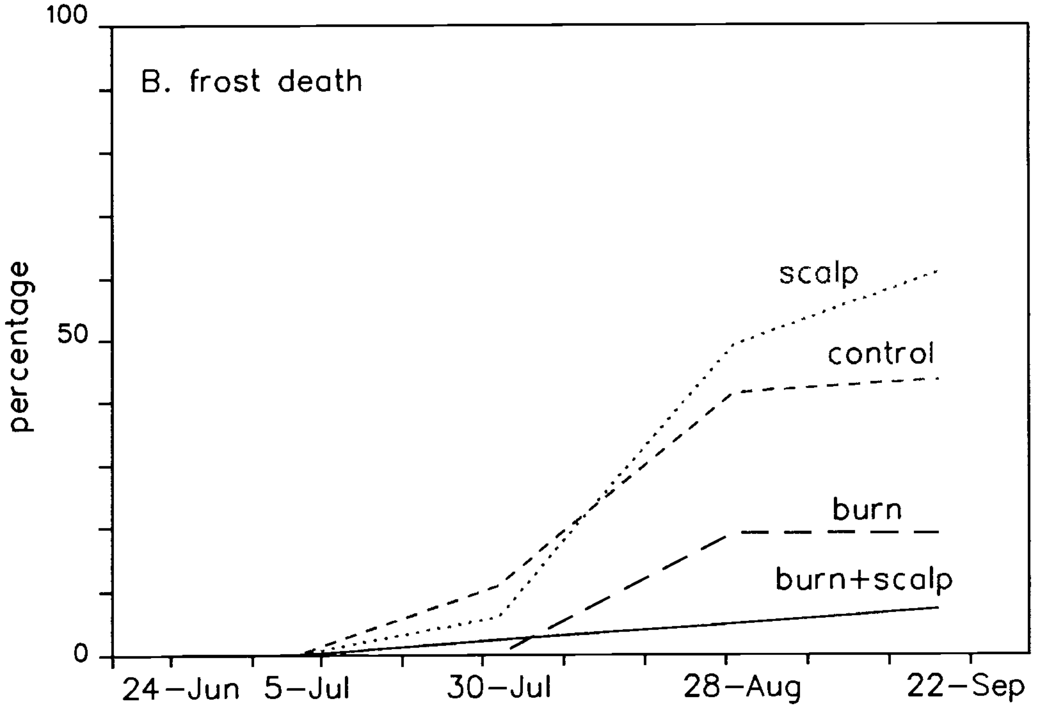


Figure 3. Effect of treatment on seedling frost damage and seedling death following frost damage.

control (Figure 3b). 92% of the seedlings growing on the control treatment and 86% of the seedlings growing on the scalp treatment died if they had been damaged at least once by frost, as compared to 63% of the seedlings growing on the burn treatment and 23% of the seedlings growing on the burn+scalp treatment.

Seedlings growing on the scalp treatment had significantly greater frost damage and frost related death than the other three treatments. Although seedlings growing on the control treatment had significantly greater mortality overall (Figure 1a) (93% for the control as compared to 86% for the scalp), the seedlings growing on the scalp treatment had significantly greater frost related mortality (Figure 3b) (61% for the scalp as compared to 43% for the control). The first appearance of visible frost damage on seedlings coincided with a rapid decline in seedling condition on all treatments, but particularly on the scalp treatment (Figure 1a) which by July 30, translated into increased mortality rates.

The condition of seedlings growing on the control treatment also declined rapidly after the frost event on July 5. Prior to that time, unlike the other treatments, seedlings growing on the control treatment were already showing signs of stress (Figure 1b). Development rates were slower (Figures 2a and 2b), and less than 50% of the control seedlings survived past the budburst growth stage. Earlier season environmental stresses resulted in poorly developed, weak seedlings which were more susceptible to frost damage. This may have been an important additive factor in the amount of frost damage and death suffered by the control seedlings, different from factors in the damage and death of the scalp seedlings which were vigorous and developing rapidly relative to the control seedlings prior to the first recorded frost damage.

Seedlings growing on the burn treatment had significantly less frost damage than those growing on the scalp or control treatments throughout the season, but 64% of the burn treatment seedlings that were frost damaged eventually died. That is a lower frost related mortality rate than for either the scalp or the control treatment, but significantly higher than that of the burn+scalp treatment (23%).

By the end of the summer season, frost related mortality accounted for less than 40% of total mortality on the burn treatment; the majority of seedling death was instead attributed to drought or heat stress. For all other treatments, frost death accounted for 50% or more of the total seedling mortality (Figure 4).

Seedlings on the burn+scalp treatment had the highest overall survival rate (86%), the second lowest frost damage rate (31%) and only 23% of those frosted eventually died. These seedlings also developed faster, bursting and setting bud earlier than the other three treatments. By July 30, all seedlings on the burn+scalp treatment had set bud while many seedlings on the other three treatments were still

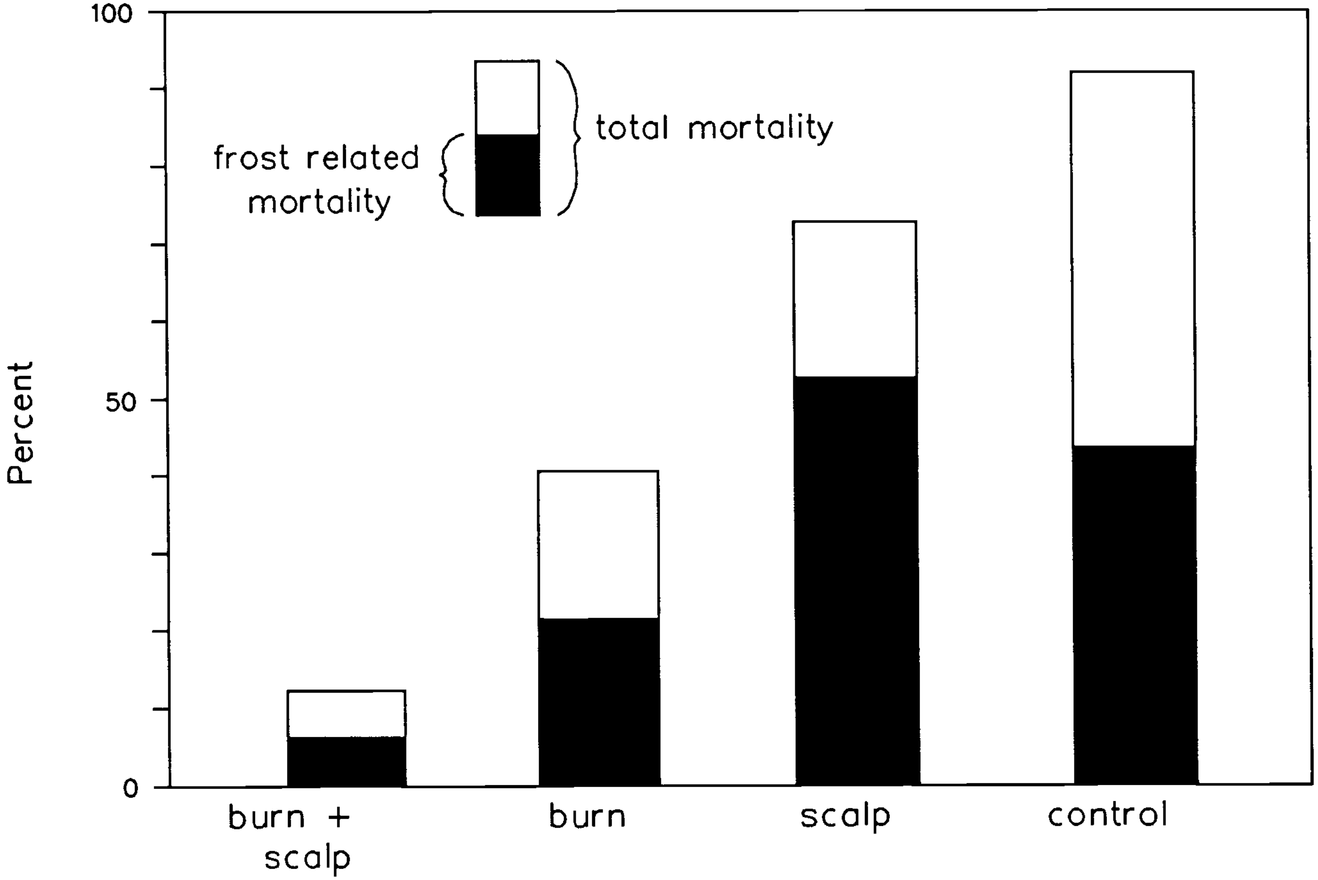


Figure 4. End of season comparison of total mortality and frost related mortality between treatments. Trends were significant throughout the season.

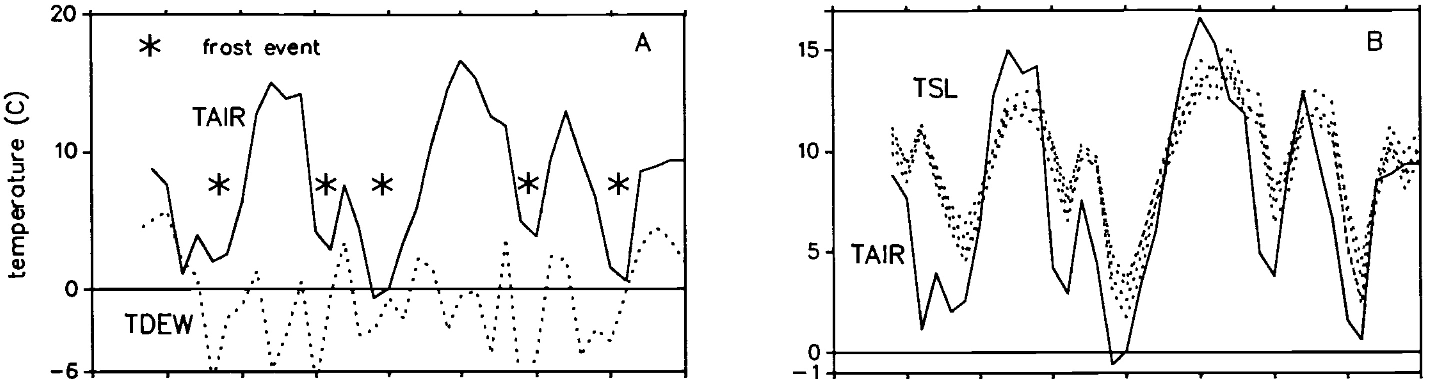
in earlier developmental growth stages. Faster development is an indicator of good seedling vigor and may partially explain why seedlings on the burn+scalp treatment were better able to resist and survive the effects of the frost damage events.

Site Frost Potential Evaluation

A comparison of dewpoint and minimum air temperatures combined with evaluation of diurnal radiation trends were used to identify frost events (Figure 5). The criteria used to identify potentially damaging radiation frost events were:

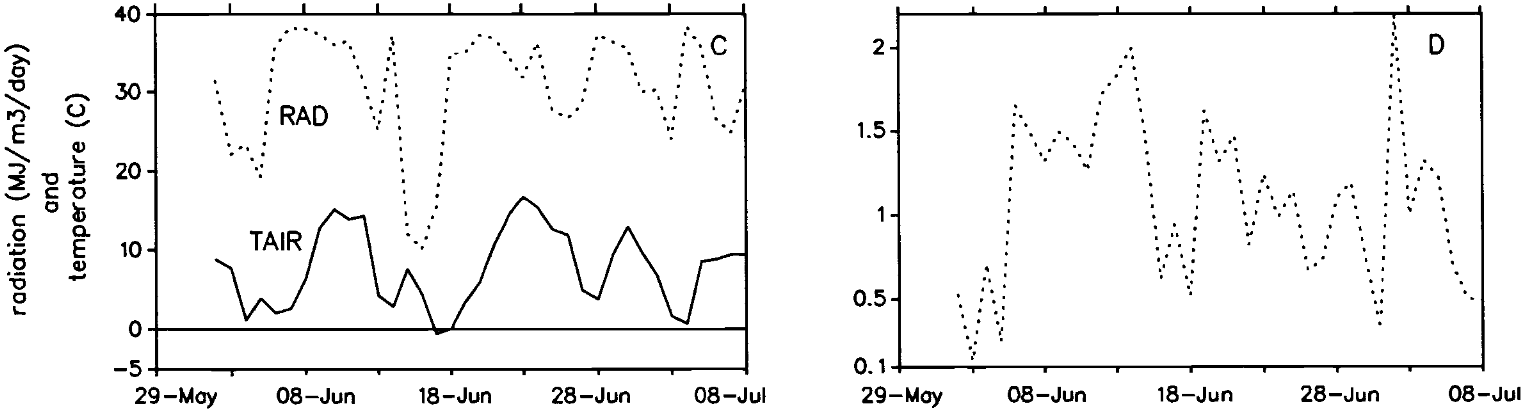
1) 2m air temperatures below 10°C'
2) 2m dewpoint temperature less than 0°C,
3) Daily total solar radiation greater than 25 MJ/m^2 day (indicating clear skies, therefore high radiative energy loss potential),
4) Predawn 3m windspeed greater than 1 m/s (to assure mixing of air and to differentiate between a radiation and a drainage frost event).

Heat released by dew formation as air temperature decreases and nears dewpoint causes air temperature to remain at dewpoint temperature for some time (Cremer and Leuning 1985). If dewpoint temperature remains above freezing, cooling of the air will slow down



Predawn dewpoint temperatures (TDEW) and minimum air temperatures (TAIR)

Minimum 20 mm depth soil temperature (TSL) for 4 soil treatments and minimum air temperatures (TAIR)



Solar radiation (RAD) and minimum air temperatures (TAIR)

Predawn windspeed (m/s)

Figure 5. Site climate measurements were used to identify frost events that had potential to damage growing seedlings.

and freezing will be avoided. Other factors also influence site frost potential. For maximum potential of radiation frost, there must be few clouds or water vapor in the atmosphere to capture outgoing longwave radiation.

Using these criteria, we identified potentially damaging radiation frost events on June 7, June 14, June 18, June 28 and July 4. Dewpoint temperature was not measured after July 9; evaluation of frost potential after that date was based only on air temperature and radiation.

Analysis of frost damage data from the seedling survey enabled evaluation of whether damage occurred during the five identified frost events. Since no visible signs of frost were recorded until after June 24, the potential frost events of June 7, June 14 and June 18 appear not to have caused any significant seedling damage.

Soil Temperature

Soil temperature data was statistically analyzed for weekly intervals from May 17 to October 2 at 20mm and 200mm depths by ranking the daily averages, ranges, maxima and minima of each replication of the four treatments, then comparing the ranks using analysis of variance techniques. This analysis revealed basic trends in treatment response, evaluating whether temperatures recorded were more often high or low in relation to each other. A table of the weekly soil temperatures and analysis results can be found in Appendix A.

Weekly soil temperature analysis

Average temperatures. At 20mm depth, average temperatures under the burn+scalp, control and scalp treatments were high significantly more often[4] than the burn treatments until late June. After that time, average temperatures under the scalp treatments began to decrease and were significantly lower than the burn+scalp and control treatments until early August. From early August until the end of the season, average temperatures under the control treatment were significantly higher (Figure 6b).

At 200mm depth, average temperatures under the control treatment were significantly higher than the other treatments for most of the summer season (Figure 7b).

Maximum temperatures. At 20mm depth, daily maximum temperature trends were similar to early season average temperature trends until early July. By mid-July, maximum temperatures under

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[4] Soil temperature analysis was done on ranked data, therefore significant differences reveal only whether each treatment tended to record temperatures that were relatively high or low for each week throughout the season. This method reduces variation and controls the effect of outlier data points.

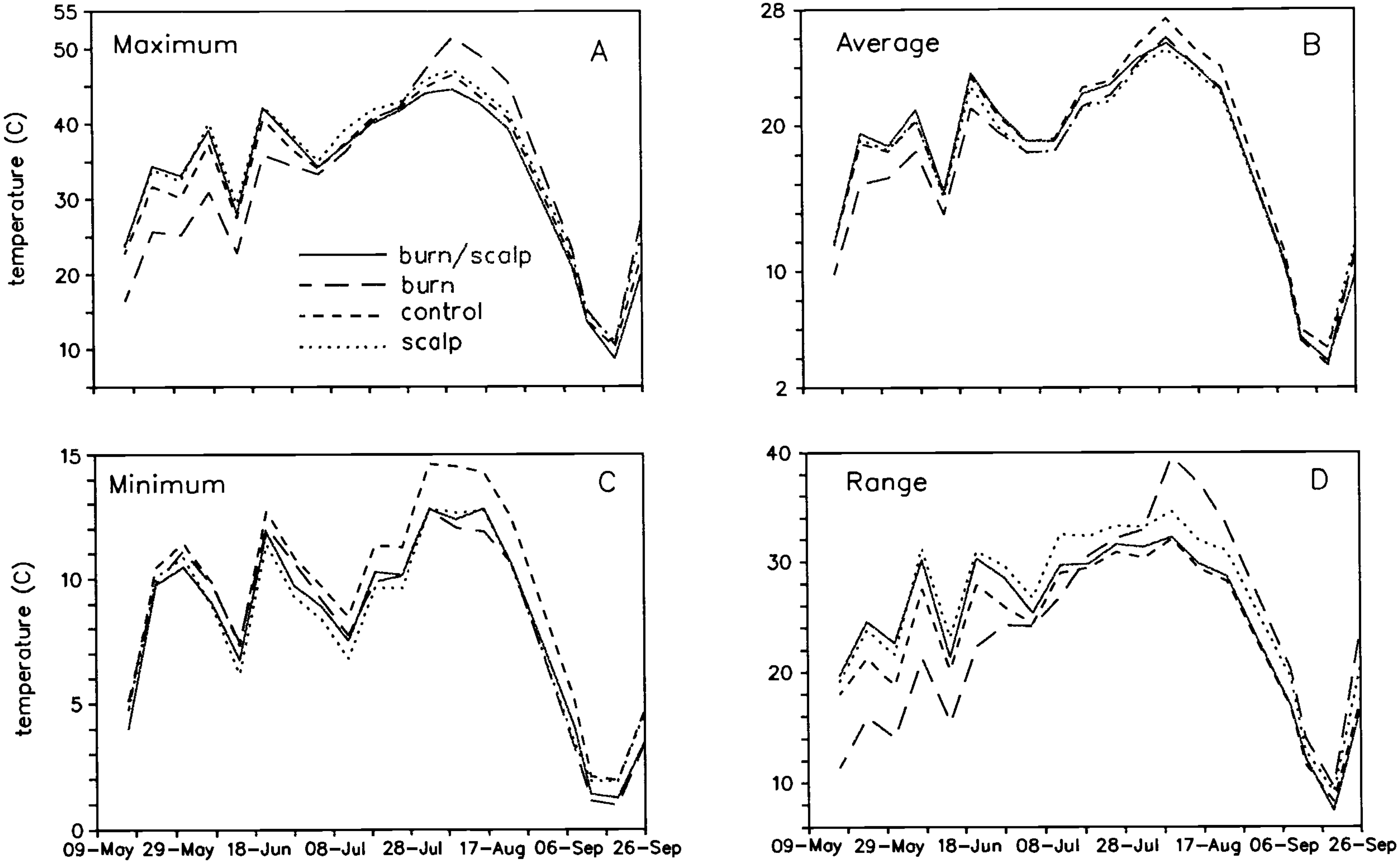

Figure 6. Soil temperature at 20 mm depth. See Appendix A for results of statistical analysis on ranked temperature data.

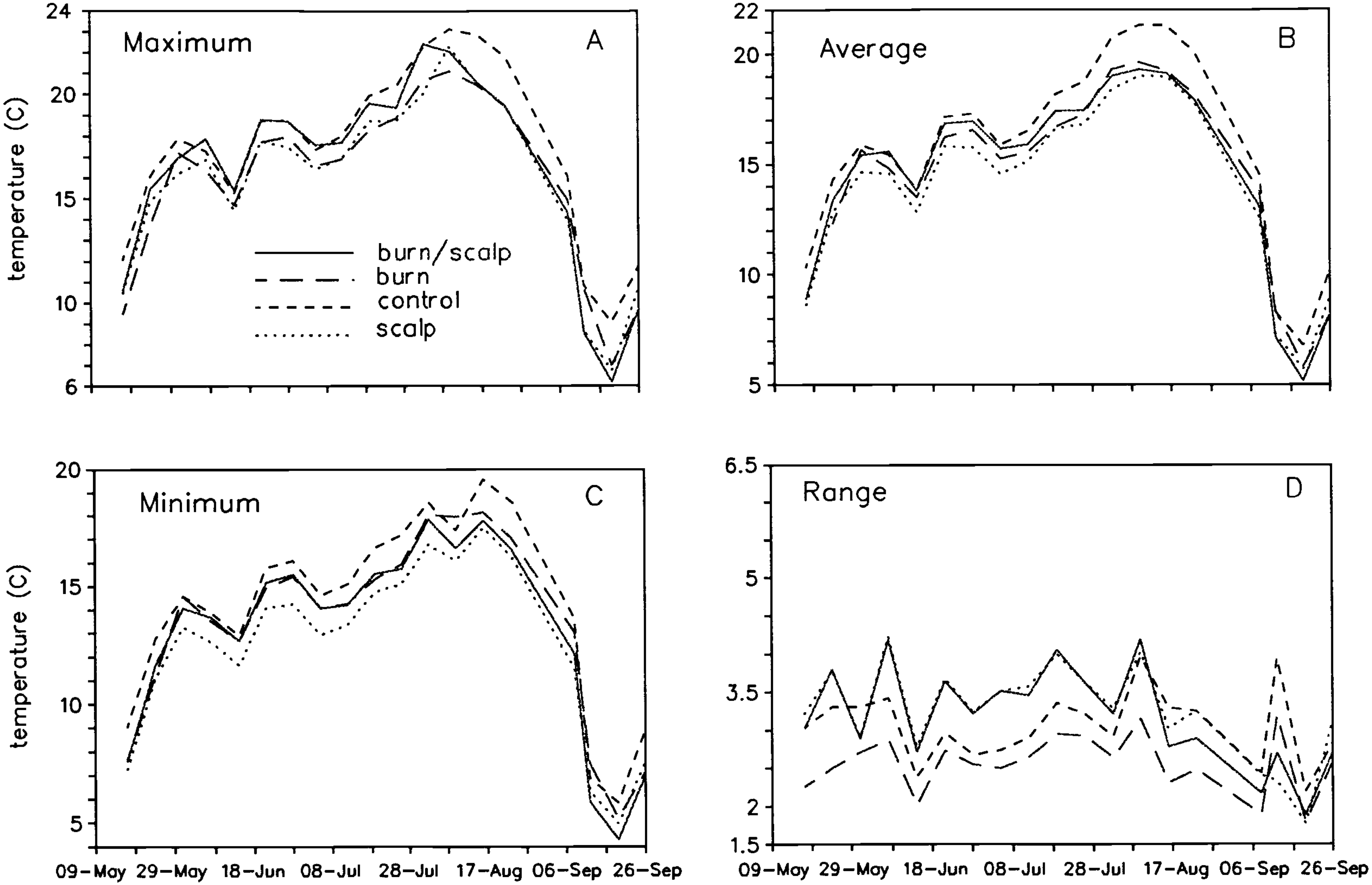

Figure 7. Soil temperature at 200 mm depth. See Appendix A for results of statistical analysis on ranked temperature data.

the scalp treatment were significantly higher than those under either burn treatments (burn+scalp and burn). From early August until the end of the season, maximum temperatures under the burn treatment were significantly higher than those under the other treatments (Figure 6a). The scalp treatment recorded the second highest maximum temperatures.

At 200mm depth, maximum temperatures were significantly lower under the burn treatment until late July, when maximum temperatures under the control treatment were significantly greater than the other treatments for the rest of the season (Figure 7a).

Minimum temperatures. At both 20mm and 200mm depth, minimum temperatures under the control treatment were generally higher throughout the season. Temperatures under the scalp treatment was generally lower. By late August, minimum temperatures under the burn treatment were low significantly more often than those under the other treatments (Figure 6c and 7c).

Temperature ranges. At 20mm depth, the diurnal range of soil temperature was significantly smaller for the burn treatment until Mid-July. By August, diurnal range in soil temperature was greatest under the burn and the scalp treatments (Figure 6d).

At 200mm depth, the unscalped treatments had generally smaller temperature ranges than the unscalped treatments throughout the season (Figure 7d).

Summary Lower average temperatures under the scalp treatment occurred almost 5 weeks earlier in the season than under the burn+scalp treatment.

Minimum near-surface (20mm depth) temperatures under the two scalp treatments were often lower than the two unscalped treatments when the seedlings were growing early in the season. Minimum temperatures under the scalp treatment were often lowest deep in the soil (200mm).

Maximum near-surface temperatures under the two burn treatments were generally lower than those under the two unburned treatments. The scalp treatment recorded high temperatures more often during the early season.

The scalp treatment generally showed higher maximums, lower minimums and wider ranges of soil temperature, creating a stressful growth environment for seedlings that was reflected in high mortality rates and poor resistance to and recovery from frost damage.

Soil temperature changes during frost events

Comparisons of diurnal changes in soil temperature in response to air temperature during the identified frost events made it possible to evaluate treatment effects on the seedling environment during periods of seedling damage. A comparison was made of air temperature and soil temperatures on the four treatments between the June 6 and July 4 frost events. Since seedlings were not damaged until the July 4 frost event, these comparisons were used to evaluate and explain the change in seedling response.

Diurnal curves of solar radiation, air and dewpoint temperatures show that frost potential was high during the early morning hours on June 6 (Figures 8a and 8b). The sky was clear, and both air and dewpoint temperatures were below 5°C. Between 12:00 A.M. and sunrise at 6:00 A.M., air temperature and dewpoint temperature dropped to approximately 2°C. Soil temperatures under the scalp and the burn+scalp treatments were slightly warmer throughout the day and cooler at night than the burn or control treatments at 20mm depth.

The most notable feature of the soil temperature data is the relationship to air temperature. For all treatments, soil temperature at 20mm remained between 7°C and 9°C for the hours from midnight to 6:00 A.M. when air temperature dropped to 2°C (Figure 8c). It is important to remember that air temperature and dewpoint temperature were measured at 2m height. Temperatures at the soil surface will generally be more extreme. Therefore, a predawn measurement of 2°C at 2m indicates even colder temperatures at the

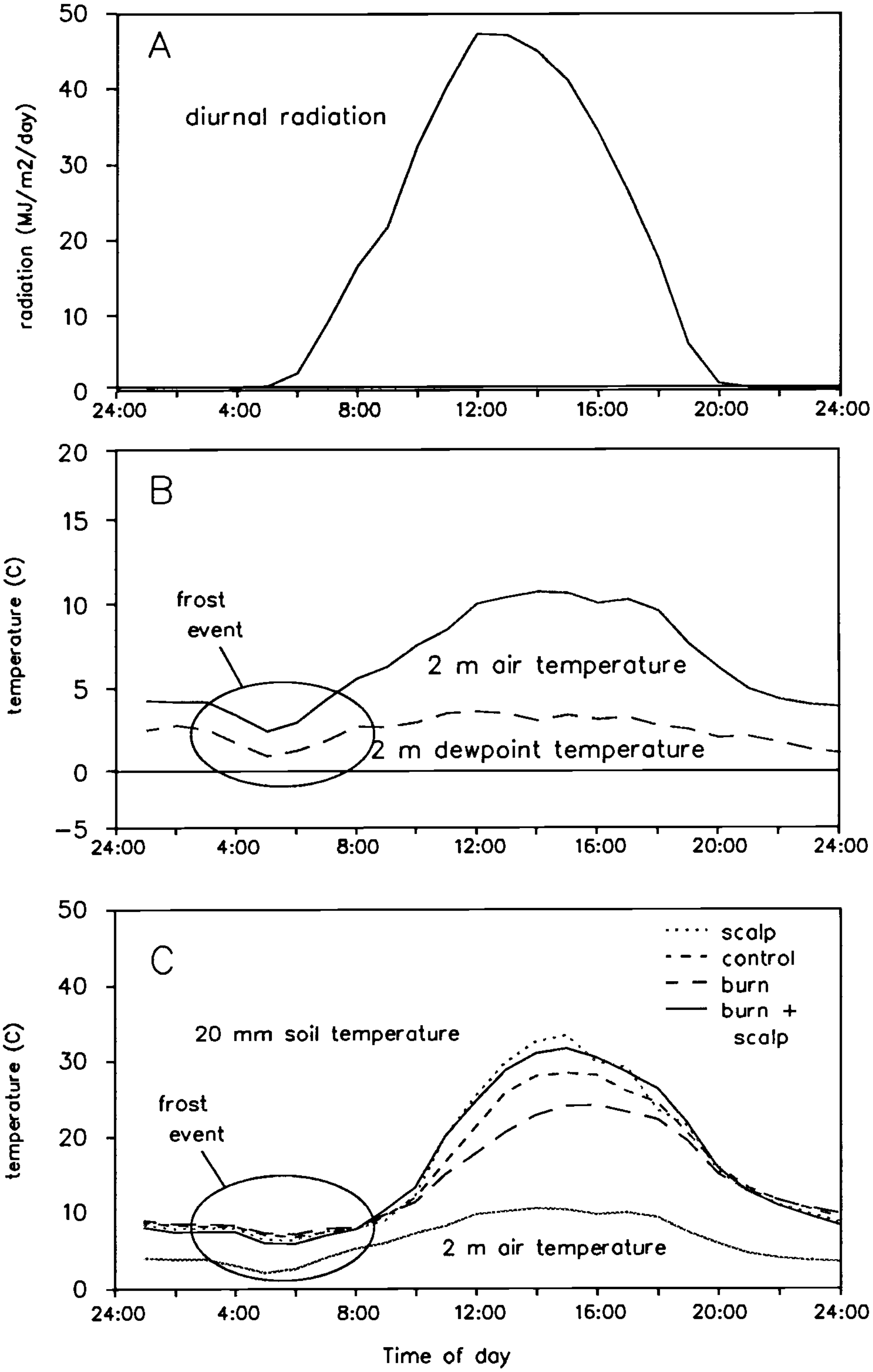

Figure 8. June 6 frost event soil and air climate variables.

soil surface.

The soil cools at night as a result of loss of longwave radiation and sensible heat from the soil surface. If the soil heat capacity is large, stored heat from radiative input during the day will maintain the soil at temperatures higher than air temperature. Apparently, soil heat capacity must have been large enough to supply heat and maintain soil temperature higher than air temperature on this date.

Diurnal curves comparing air temperature, solar radiation and dewpoint temperature trends show that frost potential was again high on the morning of July 4 (See Figure 8a and 9b). Air temperature was below 5°C and dewpoint temperature was below 0°C; skies were clear. Predawn dewpoint temperatures were 4°C lower on July 4 than on June 6, but air temperatures were within 1°C of each other, and the duration of cold air temperatures was shorter on July 4 than on June 6.

The relationship of soil temperature to air temperature was different than that of the June 6 frost event. Midday 20mm depth soil temperatures for the scalp treatment on July 4 (33°C) were just as warm as those on June 6. During the night of July 4, soil temperatures were colder than those on June 6 by approximately 4°C (Figures 8c and 9c).

Soil temperature was colder for all four treatments during the July 4 frost event than for the June 6 frost event. Soil temperature on

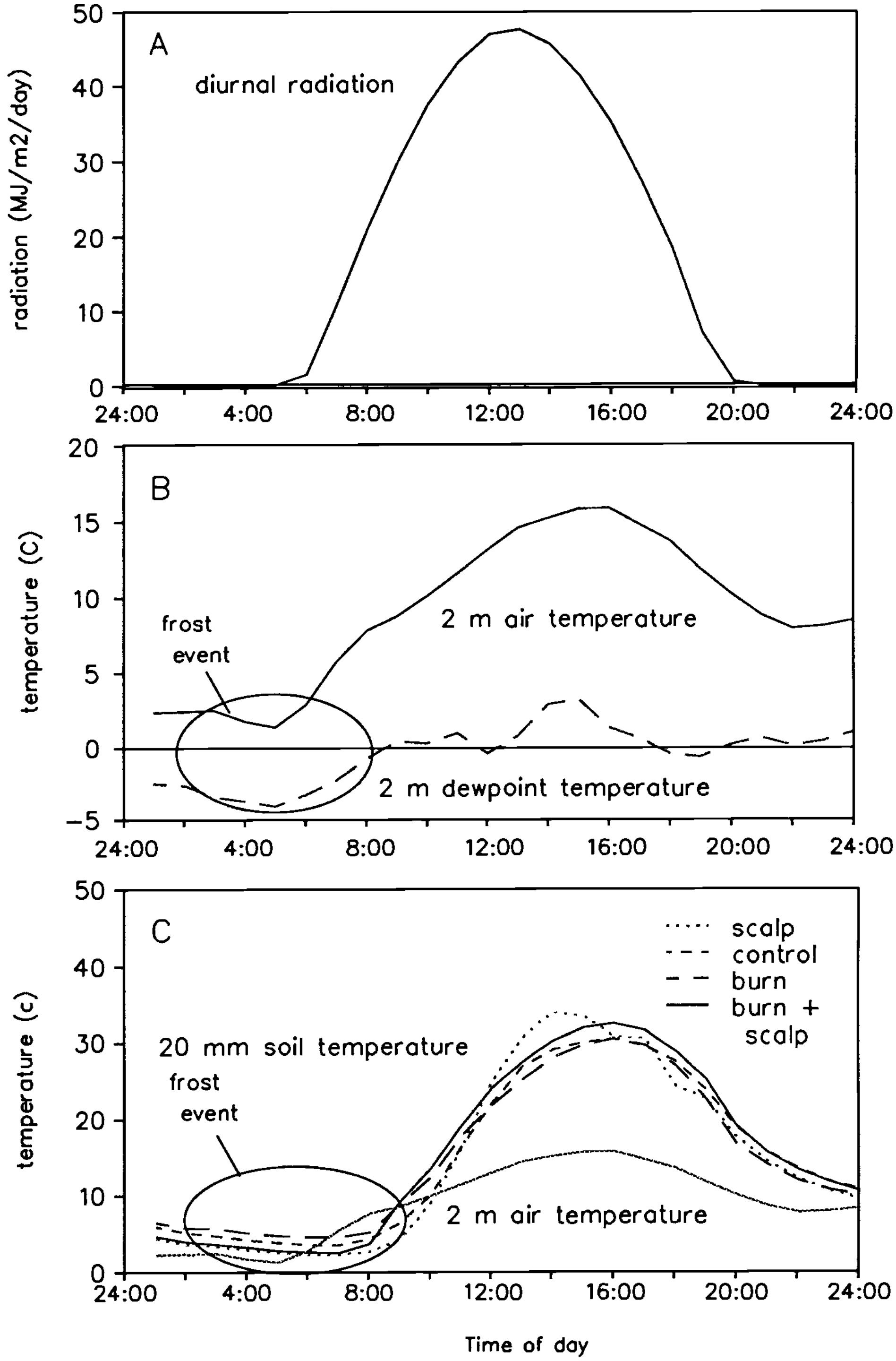

Figure 9. July 4 frost event soil and air climate variables.

all treatments never dropped below air temperature on June 6, but on July 4, soil temperature on all treatments was below air temperature for some period of time. Predawn soil temperatures under the burn and the burn+scalp treatments were below air temperature for page approximately 2 hours, the control treatment for 3 hours, and the scalp treatment for five hours. The rate at which the soil loses and gains heat and changes temperature is a function of soil heat capacity. As the air began to warm from the early morning sun, the soil surfaces with the greater ability to absorb heat energy were gaining heat from the air. Frost damage on the seedlings was first noted on July 5; damage was most severe for seedlings growing on the scalp treatment, least for seedlings growing on the burn treatment.

At 200mm depth, the diurnal temperature range for all four treatments was wider in July than in June (Figure 10). Soil temperature under the scalp treatment on June 6 and July 4 reached the lowest minimum of the four treatments (11°C). On July 4, the burn+scalp treatment recorded the second coldest diurnal soil temperature at that depth (12°C), but over the course of the day, increased in temperature in response to surface radiative input until it was the warmest treatment by 3:00 P.M. (16.5°C) while the scalp treatment remained the coldest (15°C). Deep soil warming is a function of the capacity of the soil to conduct heat from the surface down. As soil water content decreases, the depth of change in soil

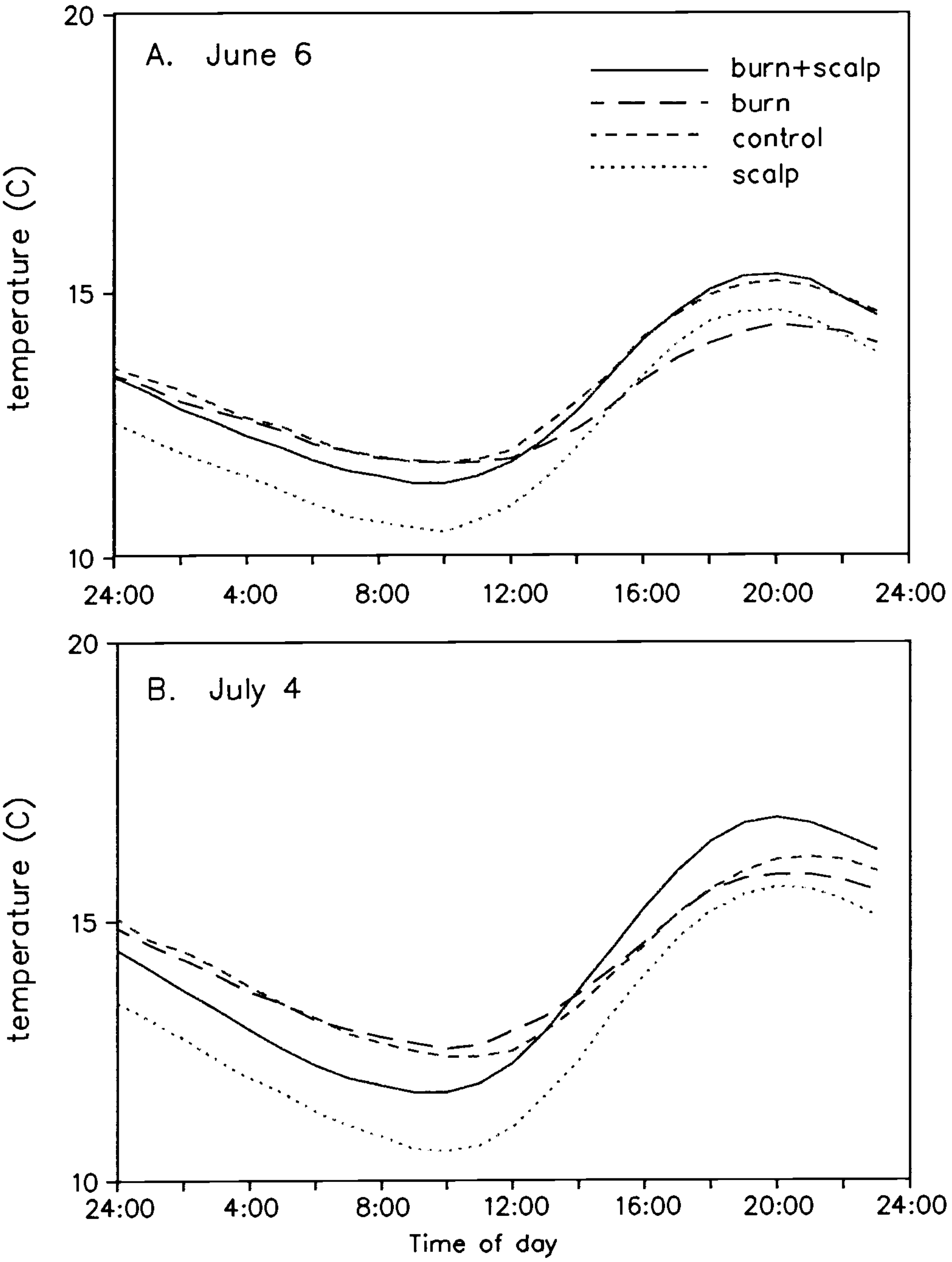

Figure 10. Soil temperature at 200 mm depth during two frost events.

temperature in response to surface conditions decreases as well. A dry soil has lower thermal conductivity than moist soil (Hillel, 1982).

Soil Water

Expected treatment effects Soil water is necessary for optimum seedling growth and also acts as an environmental buffer during periods of intense cold and heat due to combined effects of its high specific heat and thermal conductivity.

Table 1 shows the hypothetical relationship between evaporation, transpiration, and soil heat characteristics for the four treatments. Treatments that control vegetation will have the lowest transpiration rates. Burning is an effective vegetation control treatment. Existing vegetation is killed or set back, and seeds in the surface duff layer are damaged by burning. The burn treatments, burn+scalp and burn, are expected to have lower transpiration rates than the unburned treatments, scalp and control. Scalping provides some control of vegetation, but is less effective than burning. Treatments that are scalped, whether burned or unburned, are expected to have lower transpiration rates.

Removal of the surface duff layer causes increased evaporation rates. The duff layer is a poor conductor of heat and water. It protects the soil surface from incident solar radiation, keeping surface soil temperatures down. It also isolates water near the soil surface

Table 1. Effect of treatments on soil water loss and soil heat properties. Plus signs (+) indicate the relative enhancement of the listed factor by each treatment. T is transpiration; E is evaporation.

Treatment	Water Loss Enhancement		Relative Water Loss	Heat Capacity	Surface Heat Exchange
	T	E			
Burn+scalp	+	++	low	++	+++
Burn	++	+	low	++	++
Scalp	+++	++	high	+	+++
Control	++++	+	high	+	+

from the effects of water vapor potential gradients in the air, increasing resistance to evaporation. Therefore, evaporation rates will be greater for the scalped treatments than the unscalped treatments. When the effects of surface treatment on transpiration and evaporation are combined, the burned treatments, burn+scalp and burn, are expected to conserve more water than the unburned treatments, scalp and control.

Water content also has an effect on soil heat capacity. Treatments that conserve water have greater heat capacities than those that do not. The two burn treatments, burn+scalp and burn, should therefore have enhanced abilities to absorb and store heat energy relative to the two unburned treatments, scalp and control.

Treatment effect on surface heat exchange is controlled by the thickness of the litter layer. Decreasing litter layer thickness generally enhances heat exchange between the soil and the atmosphere. Therefore, the two scalped treatments have the greatest heat exchange capabilities. Burning tends to decrease the thickness of the litter, so improves the surface heat exchange capabilities of an unscalped soil.

Interactive effects of heat storage and heat exchange capabilities indicate that the capacities of the two burn treatments to store heat were increased by their high surface heat exchange. Net heat energy exchange for the scalp treatment, with enhanced surface heat exchange capabilities, but only a limited ability to store heat due to excessive water loss, has a high potential to be negative.

Data analysis Soil water data were collected on eight occasions over the summer season. Since frost during periods of active growth was found to be the major factor controlling seedling survival, analysis was completed for treatment water loss between May 16 and July 30 to clarify the role soil moisture played in seedling response to frost stresses. Analysis of whole profile water loss was done to reveal overall trends in water loss. Then, various depth increments near to the soil surface were analyzed to reveal treatment effects in the seedling root zone. The change in soil heat capacity that occurred as a function of changes in water content was also calculated for each treatment.

Whole profile water loss There were significant differences in whole profile water loss between burned and unburned treatments by June 4 (Figure 11a). That trend continued until late July when short term water loss (defined as water loss since last sample or non-cumulative) for the control treatment dropped below all other treatments (Figure 12a). By June 24, whole profile water loss for the scalp and the control treatments was approximately 35% greater than for the burn treatment and 73% greater than for the burn+scalp treatment (Figure 11a). By the end of July, cumulative water loss was

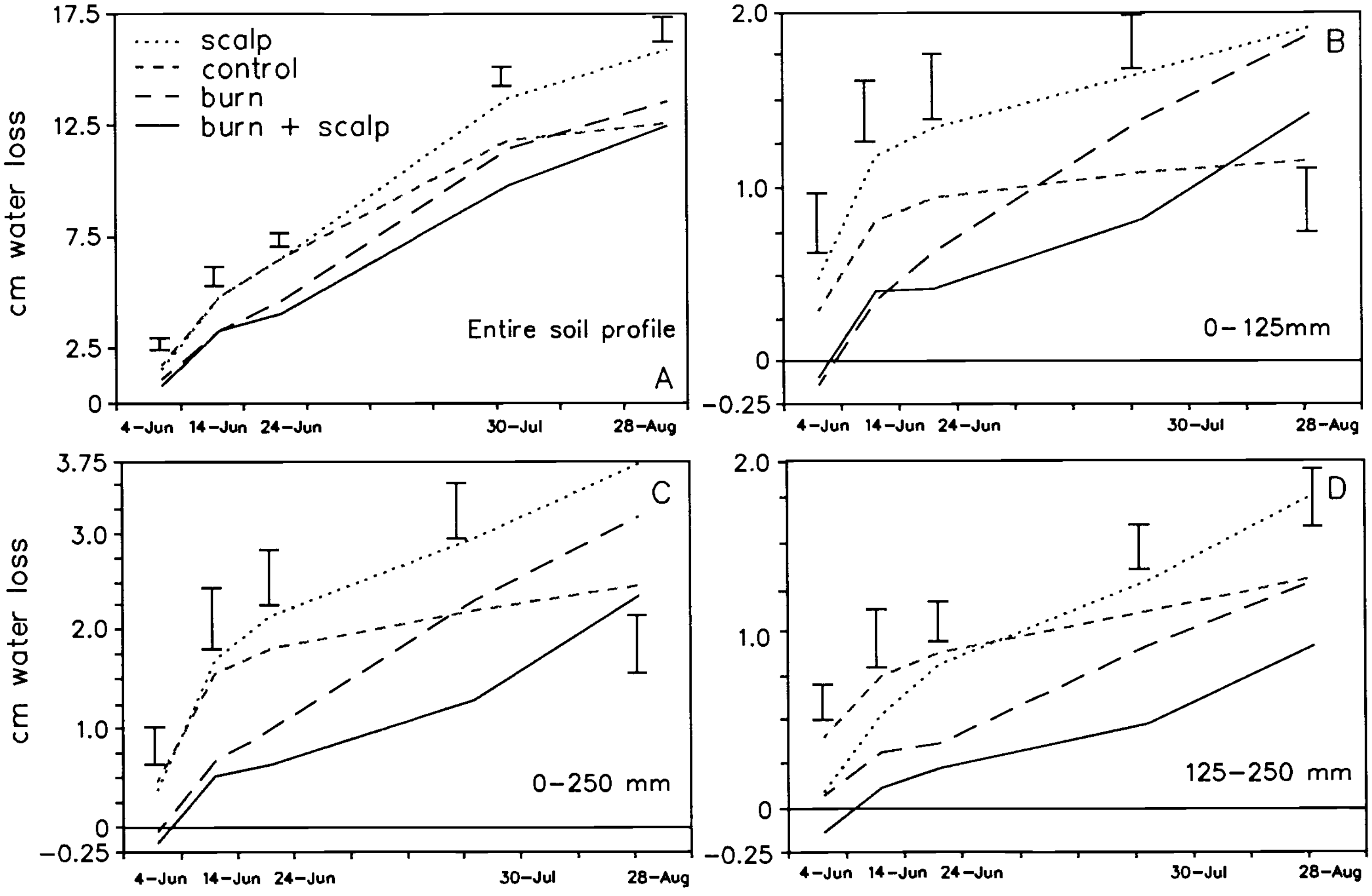

Figure 11. Cumulative soil water loss by treatments at different depths.
(Bars show Least Significant Difference at 90% confidence level.)

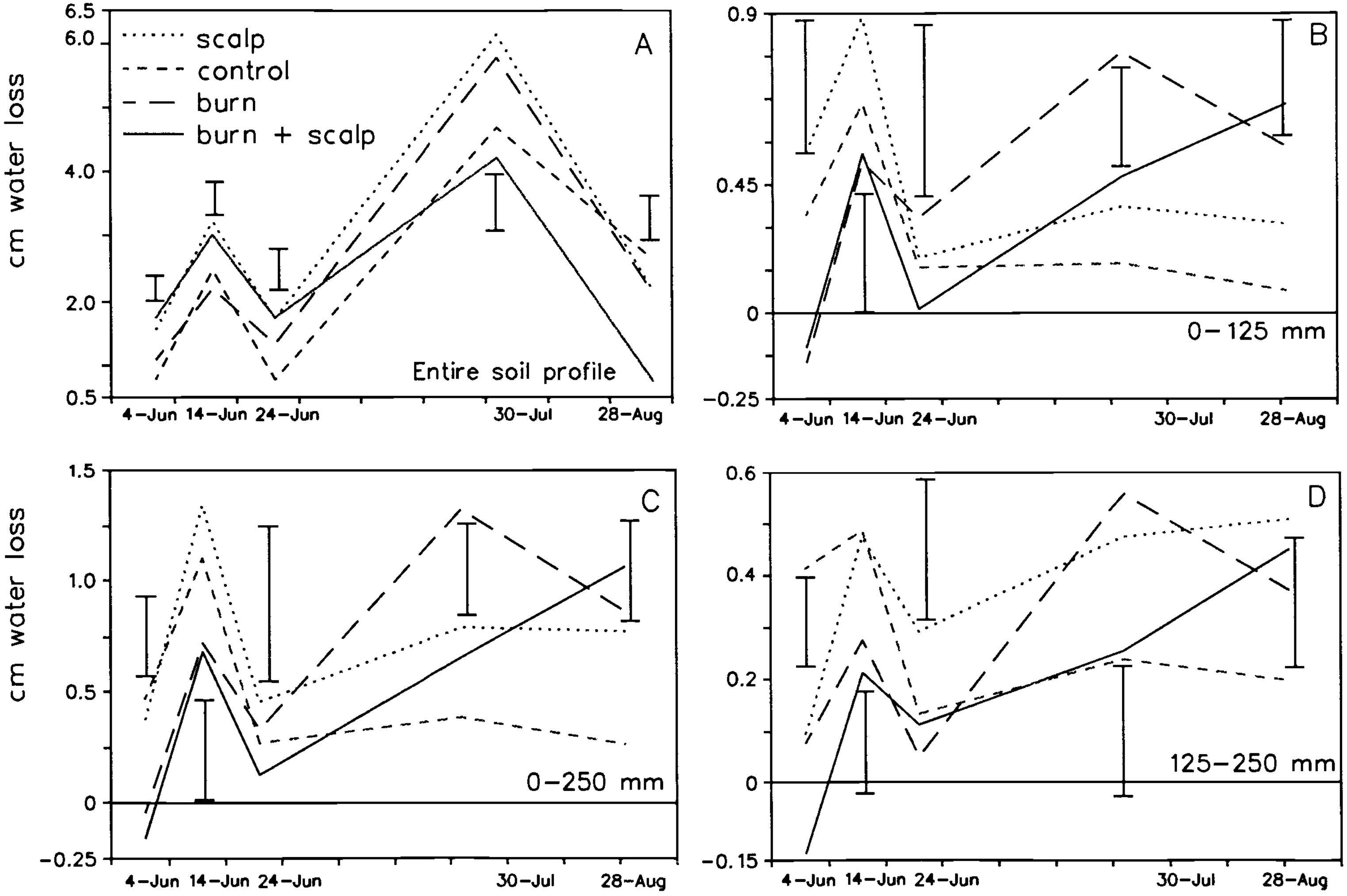

Figure 12. Short term (noncumulative) water loss at different depths.
(Bars show Least Significant Differences at the 90% confidence level.)

greatest for the scalp treatment and least for the burn+scalp treatment. It should be noted that ranking for water loss on the treatments by late June was identical to ranking for frost damage.

Seedling root zone water loss Breaking the soil water profiles into smaller depth increments near the surface allows a more detailed evaluation of water loss. Water loss from the 0-250mm depth was evaluated for trends in near surface water loss. Then two increments, one from 0-125mm and one from 125-250mm were analyzed to separate surface from subsurface treatment effects. By June 4, there were significant differences in 0-250mm depth water loss between treatments (Figure 11c). On that date, as a result of precipitation between May 16 and June 4, water content actually increased and was significantly higher for the burn and the burn+scalp treatments. Conversely, water content decreased and was significantly lower for the scalp and the control treatments. All four treatments had received the same amount of precipitation, but water loss on the two unburned treatments was high enough that the moisture input from the rain was used in addition to stored soil water reserves.

Significant differences in water loss at the 0-250mm depth show that the burned treatments conserved more water than the unburned treatments during the early seedling growth period, approximately from early May until the end of July.

A comparison of near-surface water loss (0-125mm) to subsurface water loss (125-250mm) reveals some treatment effects on transpiration. The control treatment used significantly more subsurface water than all other treatments by June 4 (Figure 11b). The burn treatment also used more early season subsurface water than the burn+scalp treatment. The increase in water content on June 4 discussed above occurred for both the burn treatments near the surface (0-125mm), but only for the burn+scalp treatment between 125mm and 250mm depth. Since evaporation rates would have been relatively low for a mulched surface with cool early season temperatures, those results can be attributed to vegetative water loss.

Changes in soil heat capacity Soil water, due to its high heat capacity, can buffer the effects of frost on outplanted seedlings by increasing the amount of heat stored during the day to balance night time heat loss. Water has a heat capacity of 4.19 MJ/m^3 K. Childs et al. (1985) found that fine fraction soil minerals from several locations in the study site region had an average heat capacity of 1.2 MJ/m^3 K (ranging from 0.92 to 1.47 MJ/m^3 K). Assuming initial volumetric water contents of 30% (soil tests results gave a range of 29-36% water content at field capacity), it is possible to calculate changes in soil heat capacity as water content decreased (Figure 13).

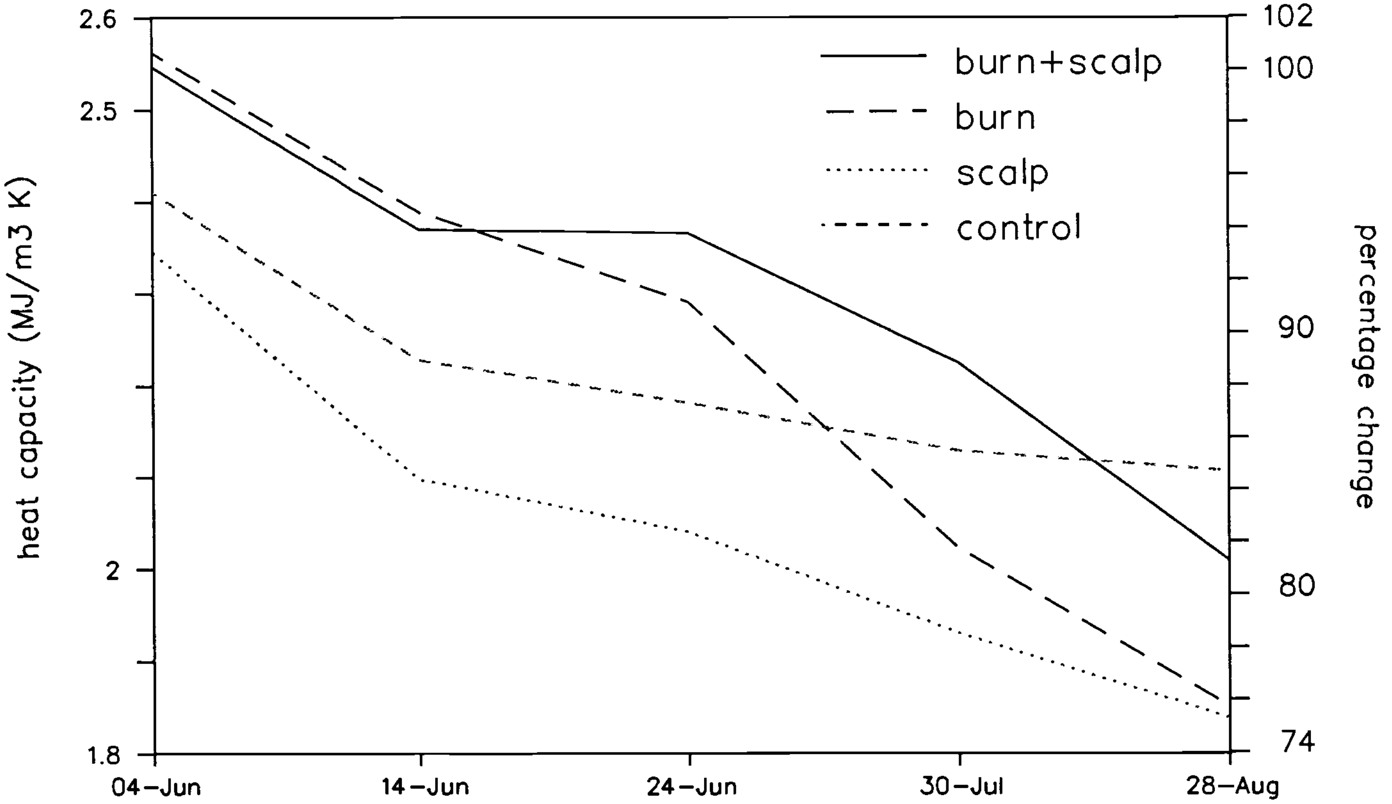

Figure 13. Change in total soil heat capacity as a function of temporal changes in water content.

Between June 24 and July 30, seedlings on all four treatments showed varying degrees of frost damage. Seedlings growing on the scalp treatment showed significantly more damage on July 5 (45%) than either of the burn treatments. The scalp treatment heat capacity had decreased 18% by June 24 as compared to a decrease of 6% and 9% under the burn+scalp and the burn treatments.

During the July 4 frost event, soil temperature dropped below air temperature for the first time in the season and caused seedling damage on all four treatments. It is possible that it was a more extreme event than those recorded earlier in the summer, but on treatments with higher heat capacities, the duration of soil temperature extremes was decreased and seedlings were better able to resist damage.

SUMMARY AND CONCLUSIONS

Frost and low temperatures reduce seedling survival on high elevation sites in southwest Oregon. Soil surface treatments that conserve water can decrease the incidence of Douglas-fir seedling frost damage and frost death due to effects of soil water on soil heat capacity and temperature.

Early in the growing season, five potentially damaging frost events were identified (in June and July). No seedling frost damage was recorded on any treatment until July 5 (from a frost event on July 4), even though at least three frost events occurred prior to that during periods of rapid seedling growth. At that time, seedlings on all treatments showed some frost damage. Seedlings growing on treatments that were most moisture conservative suffered significantly less frost damage and frost induced death throughout the season. The ranking of water loss on the treatments by late July was identical to the ranking of frost damage - scalp, control, burn and burn+scalp.

Seedling condition and damage, soil water loss, soil heat capacity (calculated from soil water loss) and changes in soil temperature were compared between a frost event on June 6, when no seedling damage was observed, and the July 4 frost event, which caused visible seedling damage. By June 6, water loss in the surface 250mm of soil was significantly greater under the scalp treatment than under either burn treatment. The two burn treatments (burn and burn+scalp) logged the least seedling frost damage following the July 4 event; seedlings growing on the scalp treatment showed the most.

Diurnal curves showed that 20mm depth soil temperature dropped below 2m height air temperature during the July 4 frost event, but not during the June 6 frost event, even though air temperature was similar on both dates, indicating a change in soil heat capacity between June 6 and July 4. By June 24, due to changes in soil water content, soil heat capacity under the burn+scalp treatment had decreased 6% since the beginning of the season while that under the scalp treatment had decreased by 18%. As long as soil temperature remained above air temperature during frost events, no seedling damage was evident. Heat capacity was thought distinguish the degree of frost damage observed on seedlings in the four treatments. The treatments with the lowest water loss had the largest heat capacities and suffered the least frost damage during the first damaging frost event on July 4 and throughout the season.

Stored soil water is lost through either evaporation or transpiration. Water loss for the scalp treatment can be attributed to both transpiration (roots from adjacent plants use water from under the scalp) and surface evaporation. Water loss for the control treatment can be attributed primarily to transpiration rather than evaporation due to the effects of surface litter. The significantly greater early season water losses in the unburned areas indicate that water loss through transpiration was of greater importance than evaporative water loss during the seedling growth period.

Control of surface vegetation was found to have the greatest effect on water conservation; burning for vegetation control was found to be a more effective water conservation treatment than scalping, but combining the two treatments resulted in the lowest soil water loss. The burn+scalp treatment had the lowest early season water loss of all four treatments except in the top 125mm where the burn treatment used slightly less (but not significantly less) water in early June.

The significantly greater water loss near the soil surface in the unburned treatments continued until after the fourth sampling date, June 24. High early season water loss from the unburned treatments were followed by decreases on later dates when water stores were becoming severely depleted. At that time, water loss trends in the burn and burn+scalp treatments began to increase relative to the scalp and control treatments.

Midsummer demand for moisture can only be met if there is still water stored in the soil profile. The scalp and the control treatments had used significantly more water at all depths early in the season than the burn or the burn+scalp treatments (see Figure 11a). By June 24, the scalp treatment had lost almost 2.3cm of water in the surface 250mm of soil. At field capacity, 7.5cm of water are held in that layer (assuming 30% from lab data); available water can be approximated at 3.75cm. So, the scalp treatment had lost almost 63% of its available water by June 24, over 100% more than the burn treatment (1.0cm) and over 200% more than the burn+scalp treatment (0.6cm) (See Figure 11b). The burn treatment did not reach that level of cumulative water loss until late July, the burn+scalp until late August. Treatments that controlled vegetative water loss had significantly lower water loss overall. Early season transpiration appeared to be a more significant water loss mechanism than evaporation.

The burn+scalp treatment was most water conservative during early season periods of rapid seedling growth and development. The burn treatment ranked second in early season water conservation. These two treatments had significantly higher rates of seedling survival rates and suffered less frost damage, so it is apparent that early season water conservation is important to seedling development. Conservation of soil water on high elevation sites with frost damage potential can have a positive effect on seedling survival.

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APPENDIX

APPENDIX A: Weekly soil temperature statistical results

A.1 AVERAGE WEEKLY SOIL TEMPERATURE[5]

date	Treatment	Average Temp.at 2cm.	Signif. Diffs.	Average Temp.at 20cm.	Signif. Diffs.
May 17	Burn+scalp	11.4	B	8.7	B
	Burn	9.8	C	8.9	B
	Control	11.8	A	10.3	A
	Scalp	12.0	A	8.6	B
May 24	Burn+scalp	19.0	A	13.0	B
	Burn	16.0	B	12.7	B
	Control	18.8	A	14.3	A
	Scalp	19.1	A	12.8	B
May 31	Burn+scalp	18.6	A	15.4	A
	Burn	16.4	B	15.8	A
	Control	18.2	A	15.9	A
	Scalp	18.4	A	14.7	A
June 7	Burn+scalp	21.1	A	15.6	A
	Burn	18.2	C	14.8	B
	Control	20.3	B	15.5	A
	Scalp	20.4	AB	14.6	AB
June 14	Burn+scalp	15.5	A	13.8	AB
	Burn	13.9	B	13.5	B
	Control	15.3	A	13.9	A
	Scalp	15.1	A	12.9	AB
June 21	Burn+scalp	23.6	A	16.9	A
	Burn	21.2	C	16.2	B
	Control	23.3	A	17.1	A
	Scalp	22.7	B	15.8	AB
June 28	Burn+scalp	20.9	A	17.0	AB
	Burn	19.5	B	16.6	B
	Control	20.6	A	17.3	A
	Scalp	19.9	B	15.8	B
July 5	Burn+scalp	19.0	A	15.7	AB
	Burn	18.2	B	15.3	C
	Control	18.9	A	15.9	A
	Scalp	18.2	B	14.6	BC
July 12	Burn+scalp	18.9	A	15.9	B
	Burn	18.2	B	15.6	B
	Control	19.1	A	16.5	A

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[5] All temperatures are in °C. Reported significant differences are from ranked data. This method was used to reduce variability and minimize the effect of outliers on analysis results.

	Scalp	18.3	B	15.2	B
July 19	Burn+scalp	22.2	A	17.4	B
	Burn	21.3	B	16.7	B
	Control	22.6	A	18.2	A
	Scalp	21.3	B	16.6	B
July 26	Burn+scalp	22.8	A	17.5	B
	Burn	22.1	B	17.3	B
	Control	23.1	A	18.7	A
	Scalp	21.7	B	16.8	B
August 2	Burn+scalp	24.7	B	19.0	B
	Burn	24.3	B	19.3	B
	Control	25.6	A	20.7	A
	Scalp	24.1	B	18.4	B
August 9	Burn+scalp	25.7	B	19.3	B
	Burn	26.1	B	19.6	B
	Control	27.4	A	21.3	A
	Scalp	25.2	B	19.0	B
August 16	Burn+scalp	24.3	B	19.1	B
	Burn	24.3	B	19.3	B
	Control	25.4	A	21.3	A
	Scalp	23.9	B	19.0	B
August 23	Burn+scalp	22.5	B	17.9	B
	Burn	22.6	B	18.2	B
	Control	24.1	A	20.1	A
	Scalp	22.2	B	17.8	B
Sept. 8	Burn+scalp	10.7	B	13.1	BC
	Burn	10.4	B	13.8	AB
	Control	11.3	A	14.6	A
	Scalp	10.5	B	12.6	C
Sept. 12	Burn+scalp	5.4	B	7.1	B
	Burn	5.2	B	8.4	A
	Control	6.0	A	8.3	A
	Scalp	6.0	A	7.3	B
Sept.19	Burn+scalp	3.8	B	5.2	C
	Burn	3.5	B	5.8	B
	Control	4.7	A	6.8	A
	Scalp	4.8	A	5.7	B
Sept. 26	Burn+scalp	10.0	C	8.2	C
	Burn	12.1	AB	8.9	C
	Control	11.5	B	10.1	A
	Scalp	11.9	A	9.0	B

A.2 WEEKLY MAXIMUM SOIL TEMPERATURES

date	Treatment	Maximum Temp.at 2cm.	Signif. Diffs.	Maximum Temp.at 20cm.	Signif. Diffs.
May 17	Burn+scalp	23.2	A	10.4	BC
	Burn	16.5	B	9.7	C
	Control	22.8	A	12.1	A
	Scalp	23.9	A	10.5	B
May 24	Burn+scalp	33.7	A	15.1	A
	Burn	25.7	B	14.1	B
	Control	31.7	A	16.1	A
	Scalp	33.4	A	14.9	A
May 31	Burn+scalp	33.1	A	17.0	A
	Burn	25.3	C	17.4	A
	Control	30.2	B	17.9	A
	Scalp	32.4	A	16.2	A
June 7	Burn+scalp	39.3	AB	17.9	A
	Burn	31.0	C	16.4	B
	Control	37.4	B	17.3	A
	Scalp	40.2	A	16.9	A
June 14	Burn+scalp	28.1	AB	15.4	A
	Burn	22.9	C	14.7	B
	Control	27.5	B	15.3	A
	Scalp	29.3	A	14.4	AB
June 21	Burn+scalp	42.2	A	18.8	A
	Burn	35.9	B	17.7	B
	Control	40.6	A	18.7	A
	Scalp	42.4	A	17.8	A
June 28	Burn+scalp	38.3	A	18.7	A
	Burn	34.5	B	18.0	B
	Control	36.8	A	18.8	A
	Scalp	38.9	A	17.5	AB
July 5	Burn+scalp	34.3	A	17.6	A
	Burn	33.3	A	16.6	B
	Control	34.1	A	17.4	A
	Scalp	35.1	A	16.4	A
July 12	Burn+scalp	37.2	B	17.7	A
	Burn	36.3	B	16.9	B
	Control	37.5	AB	18.0	A
	Scalp	39.3	A	17.0	A
July 19	Burn+scalp	40.1	B	19.6	A
	Burn	40.5	B	18.3	B
	Control	40.8	AB	20.0	A
	Scalp	41.9	A	18.7	A
July 26	Burn+scalp	41.7	A	19.4	B
	Burn	42.3	A	18.9	B

	Control	42.1	A	20.4	A
	Scalp	42.9	A	18.7	AB
August 2	Burn+scalp	44.1	B	22.4	B
	Burn	47.4	A	20.7	B
	Control	44.9	B	22.3	A
	Scalp	46.0	AB	20.0	B
August 9	Burn+scalp	44.6	C	22.1	B
	Burn	51.6	A	21.1	B
	Control	46.6	BC	23.1	A
	Scalp	47.2	B	22.3	B
August 16	Burn+scalp	42.6	B	20.6	B
	Burn	49.1	A	20.4	B
	Control	43.7	B	22.9	A
	Scalp	44.6	B	20.5	B
August 23	Burn+scalp	39.3	B	19.5	B
	Burn	45.6	A	19.5	B
	Control	40.7	B	21.9	A
	Scalp	41.6	B	19.5	B
Sept. 8	Burn+scalp	21.0	A	14.3	B
	Burn	23.5	A	14.9	B
	Control	21.9	A	16.1	A
	Scalp	22.9	A	13.9	B
Sept. 12	Burn+scalp	13.6	A	8.6	B
	Burn	15.1	A	10.7	A
	Control	13.7	A	10.8	A
	Scalp	14.7	A	8.7	B
Sept.19	Burn+scalp	8.7	B	6.2	C
	Burn	10.6	A	7.0	B
	Control	10.2	A	8.0	A
	Scalp	11.0	A	6.8	CB
Sept.26	Burn+scalp	20.3	D	9.7	C
	Burn	28.2	A	9.8	BC
	Control	22.5	C	11.8	A
	Scalp	25.3	B	10.7	AB

A.3 WEEKLY MINIMUM SOIL TEMPERATURE

date	Treatment	Minimum Temp.at 2cm.	Signif. Diffs.	Minimum Temp.at 20cm.	Signif. Diffs.
May 17	Burn+scalp	3.8	B	7.4	B
	Burn	5.1	A	7.8	B
	Control	4.8	A	9.1	A
	Scalp	4.8	A	7.2	B
May 24	Burn+scalp	9.4	C	11.4	B
	Burn	9.8	BC	11.5	B
	Control	10.4	A	12.8	A
	Scalp	10.1	B	11.1	B
May 31	Burn+scalp	10.5	C	14.1	A
	Burn	11.1	AB	14.4	A
	Control	11.4	A	14.6	A
	Scalp	10.8	BC	13.3	A
June 7	Burn+scalp	9.0	B	13.7	AB
	Burn	9.8	A	13.5	B
	Control	9.9	A	13.9	A
	Scalp	8.9	C	12.6	B
June 14	Burn+scalp	6.8	AB	12.7	AB
	Burn	7.7	A	12.7	AB
	Control	7.3	A	12.9	A
	Scalp	6.2	B	11.7	B
June 21	Burn+scalp	11.9	B	15.2	B
	Burn	12.1	B	15.0	B
	Control	12.7	A	15.8	A
	Scalp	11.4	B	14.1	B
June 28	Burn+scalp	9.7	BC	15.5	B
	Burn	10.3	B	15.4	B
	Control	10.9	A	16.1	A
	Scalp	9.3	C	14.2	B
July 5	Burn+scalp	8.9	BC	14.1	B
	Burn	9.2	B	14.1	B
	Control	9.7	A	14.6	A
	Scalp	8.4	C	12.9	B
July 12	Burn+scalp	7.5	B	14.2	B
	Burn	7.7	BC	14.3	B
	Control	8.5	A	15.1	A
	Scalp	6.8	C	13.4	B
July 19	Burn+scalp	10.3	B	15.5	B
	Burn	9.9	B	15.3	B
	Control	11.3	A	16.6	A
	Scalp	9.6	B	14.7	B
July 26	Burn+scalp	10.2	B	15.7	B
	Burn	10.1	B	15.9	B

	Control	11.3	A	17.2	A
	Scalp	9.6	B	15.1	B
August 2	Burn+scalp	12.8	B	17.4	B
	Burn	12.8	B	18.1	AB
	Control	14.6	A	18.6	A
	Scalp	12.8	B	16.8	B
August 9	Burn+scalp	12.4	B	16.6	AB
	Burn	12.0	B	18.0	AB
	Control	14.5	A	17.4	A
	Scalp	12.7	B	16.1	B
August 16	Burn+scalp	12.8	B	17.8	B
	Burn	11.9	C	18.1	B
	Control	14.3	A	19.6	A
	Scalp	12.7	B	17.5	B
August 23	Burn+scalp	10.6	B	16.6	B
	Burn	10.6	B	17.1	B
	Control	12.5	A	18.6	A
	Scalp	10.5	B	16.3	B
Sept. 8	Burn+scalp	4.0	B	12.2	B
	Burn	3.2	C	13.1	A
	Control	5.1	A	13.6	A
	Scalp	3.4	BC	11.5	B
Sept. 12	Burn+scalp	1.4	BC	5.9	C
	Burn	1.1	C	7.5	A
	Control	2.1	A	6.9	AB
	Scalp	1.9	AB	6.3	BC
Sept. 19	Burn+scalp	1.3	B	4.3	C
	Burn	0.9	B	5.2	AB
	Control	1.9	A	5.8	A
	Scalp	1.9	A	5.0	BC
Sept. 26	Burn+scalp	3.6	B	7.0	B
	Burn	3.8	B	7.8	B
	Control	4.4	A	8.1	A
	Scalp	5.2	A	8.1	B

A.4 WEEKLY RANGE OF SOIL TEMPERATURES (Max-Min)

date	Treatment	Range of Temp.at 2cm.	Signif. Diffs.	Range of Temp.at 20cm.	Signif. Diffs.
May 17	Burn+scalp	19.5	A	3.0	A
	Burn	11.4	B	2.2	B
	Control	18.0	A	3.0	A
	Scalp	19.1	A	3.2	A
May 24	Burn+scalp	24.3	A	3.7	A
	Burn	15.9	C	2.6	C
	Control	21.3	A	3.3	AB
	Scalp	23.8	B	3.8	B
May 31	Burn+scalp	22.7	A	2.9	A
	Burn	14.1	C	3.4	C
	Control	18.8	A	3.3	A
	Scalp	21.6	B	2.9	BC
June 7	Burn+scalp	30.2	B	4.2	A
	Burn	21.2	D	2.9	C
	Control	27.6	A	3.4	A
	Scalp	31.3	C	4.2	B
June 14	Burn+scalp	21.3	B	2.7	A
	Burn	15.4	C	2.0	C
	Control	20.2	A	2.4	AB
	Scalp	23.2	B	2.8	B
June 21	Burn+scalp	30.3	AB	3.6	A
	Burn	22.4	C	2.7	B
	Control	27.9	A	3.0	A
	Scalp	31.0	B	3.7	B
June 28	Burn+scalp	28.6	B	3.2	A
	Burn	24.3	C	2.5	C
	Control	25.9	A	2.7	B
	Scalp	29.6	BC	3.2	C
July 5	Burn+scalp	25.4	B	3.5	A
	Burn	24.2	B	2.5	C
	Control	24.4	A	2.7	B
	Scalp	26.7	AB	3.5	C
July 12	Burn+scalp	29.7	B	3.5	A
	Burn	26.8	B	2.6	C
	Control	29.0	A	2.9	A
	Scalp	32.5	B	3.6	B
July 19	Burn+scalp	29.8	B	4.1	A
	Burn	30.6	B	3.0	C
	Control	29.4	A	3.4	B
	Scalp	32.3	B	4.0	B
July 26	Burn+scalp	31.6	B	3.6	A
	Burn	32.2	AB	2.9	B

	Control	30.9	A	3.2	AB
	Scalp	33.3	B	3.6	B
Aug. 2	Burn+scalp	31.3	B	3.2	A
	Burn	32.9	A	2.6	C
	Control	30.3	AB	2.9	B
	Scalp	33.2	B	3.3	B
Aug. 9	Burn+scalp	32.2	BC	4.5	A
	Burn	39.5	A	3.1	B
	Control	32.0	B	5.8	A
	Scalp	34.5	C	6.2	A
Aug. 16	Burn+scalp	29.8	B	2.8	A
	Burn	37.2	A	2.3	B
	Control	29.4	B	3.3	A
	Scalp	31.9	B	3.0	A
Aug. 23	Burn+scalp	28.7	B	2.9	AB
	Burn	33.3	A	2.4	B
	Control	28.2	AB	3.3	A
	Scalp	31.0	B	3.3	A
Sept. 8	Burn+scalp	16.9	B	2.2	B
	Burn	10.3	AB	1.9	B
	Control	16.8	A	2.4	A
	Scalp	19.5	B	2.4	A
Sept. 12	Burn+scalp	12.1	A	2.7	A
	Burn	14.0	A	3.2	B
	Control	11.6	A	4.0	B
	Scalp	12.8	A	2.3	A
Sept. 19	Burn+scalp	7.5	A	1.9	AB
	Burn	9.6	A	1.8	B
	Control	8.3	A	2.2	B
	Scalp	9.1	A	1.8	A
Sept. 26	Burn+scalp	16.7	C	2.8	AB
	Burn	14.6	A	2.6	B
	Control	17.7	B	2.8	A
	Scalp	20.7	C	3.1	AB