# FROST EVENTS, FROST DAMAGE, AND POTENTIAL FROST RING FORMATION IN WOODY SPECIES OF NORTHERN ARIZONA

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**ABSTRACT**

FROST EVENTS, FROST DAMAGE, AND POTENTIAL FROST RING FORMATION IN WOODY SPECIES OF NORTHERN ARIZONA

David B. K. Pedersen

The impacts of frost events and frost damage can be significant and affect nearly all vegetation in a forest. In some cases, the frost damage can be great enough to lead to mortality. However, in lesser cases where tree mortality is not observed, frost rings, an internal cellular deformation signature of cells occurring in an annual growth ring, can form as a result of severe external damage. These frost rings are helpful in reconstructing past climate and frost damage. Research into frost rings seems to be primarily limited to higher elevations (treeline) or higher latitudes (primarily the arctic or subartic), or from the early part of the twentieth century. A case study was established in the Inner Basin of the San Francisco Peaks, which examined the severity of the June 1999 frost and snow event. This frost event was reported as leading to significant defoliation and external damage of quaking aspen (*Populus tremuloides* Michx.). The study examined whether frost rings were formed in aspen and included two other frost susceptible species Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and corkbark fir (*Abies lasiocarpa* (Hook.) Nutt. *var. arizonica* (Merriam) Lemmon) in the analysis. Though the frost event was reported to have extensive external foliage damage, there were no indications of internal damage, such as frost rings, found in the 48 tree cores samples that were taken from the Inner Basin of the San Francisco Peaks.

KEYWORDS: *frost ring, frost damage, frost event, Populus tremuloides, Picea engelmannii, Abies lasiocarpa var. arizonica, Inner Basin, San Francisco Peaks, climate change*

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## Introduction and Objectives

Frost is the formation of ice crystals on surfaces of plants, soil, objects when these surfaces are cooled to the dew point of the adjacent air and below the freezing point of water (Inouye 2000). Below freezing temperatures and frost events can occur during any time of the year in temperate latitudes. However, below freezing temperatures in the spring can cause physical damage (frost damage) to plants as ice crystals form within cells followed by rapid thawing of newly developing and frost susceptible buds, shoots, leaves, and flowers (Zon 1904; Phillips 1907; Strain 1966; Prozherina et al. 2003). Frost events are short-term, but the economical and ecological impacts can have long-term implications on vegetation, wildlife, timber, and tourism. The effects of below freezing temperatures on crop plants are well known, but the short- and long-term ecological effects of frost damage to native plants are less well known and rarely studied (Inouye 2000; Augspurger 2009). Climate change predictions include an increase in mean spring temperatures in temperate latitudes, which would bring earlier bud break and a greater risk of frost damage in the future (Augspurger 2009).

Freezing temperatures during the growing season can be detrimental to tree growth and may cause mortality. This is not to say that all tree growth will suffer desiccation and/or mortality at 0ºC, but rather to introduce two critical factors of the freezing temperatures: severity and longevity. Temperatures below -3º or -4ºC have significantly greater effects upon trees than temperatures of -1 to -2ºC (Glock 1951). Likewise, one hour of 0ºC temperatures is far less damaging than 24 hours of sustained temperatures below 0ºC (Sinclair and Lyon 2005). The vast majority of trees in the temperate regions of the world have the ability to tolerate ambient temperatures of -1º to

-2ºC and suffer no damage externally or internally (Sinclair and Lyon 2005). This tolerance is due to solutes in the internal water solution of trees, which lower the freezing point thereby delaying ice nucleation and expansion (Prozherina et al. 2003). These frost events, or times of recorded temperatures lower than climatological average temperatures, are quite dynamic and occur at various times throughout the year.

Frost events are most common during the spring and fall seasons in the temperate regions throughout the world. Numerous boreal regions and areas at higher altitudes can experience freezing temperatures throughout the growing season, especially in topographically frost-prone areas, e.g., cold air-draining basins. The focus of this paper will be on the spring frost events, a period when frost events tend to be most damaging (Zon 1904; Bannister et al. 2005). In the spring, especially during bud burst, growing parts of leaves are small, succulent, and most susceptible to freezing. As the leaves develop the tolerance to freezing increases and the likelihood of frost damage to plants typically decreases as photoperiod and temperature increase.

In early June 1999, northern and eastern Arizona experienced a damaging frost event which was accompanied with snow. This event coupled with the defoliating insect large aspen tortix (*Choristoneura conflictana*), was significant in that approximately 2428 hectares of aspen (*Populus tremuloides* Michx.) were defoliated (Fairweather 1999). The aspen trees that leafed out early in the spring 1999 were hardened off and more tolerant of the snow and cold temperatures than those that were in the early stages of bud burst. However, damage from the large aspen tortix resulted in green leaves dropping off the aspen; whereas, leaves which were affected by the frost were primarily brown to black (Fairweather 1999). This 1999 frost event was thought to be a significant inciting factor in sudden aspen decline disease (Fairweather et al. 2008; Worrall et al. 2008) in northern Arizona.

The objectives of this project and paper were to: 1) conduct a literature review of studies that examined frost events, frost damage, and frost rings in environmental and climatological conditions similar to northern Arizona; 2) determine if any weather stations across northern and eastern Arizona recorded the frost event of June 1999; and finally, 3) if any weather station did record this frost event, determine if the trees were damaged severely enough to record this event as deformed annual tree rings (i.e., frost rings). These data will help determine if frost damage is an inciting factor in sudden aspen decline disease.

**Impacts on Vegetation**

Damage to trees resulting from frost has impacts both to the external and internal structure and processes of the tree. The degree of frost damage is linked to the severity and exposure of the tree to the freezing conditions. Intuitively, the external impacts on vegetation are usually visible and more consistent with frost events. Internal impacts are harder to decipher, typically relying on cross sectional samples to ascertain cellular signatures of frost damage.

External vegetative frost damage is fairly apparent and readily identified. First, after thaw has occurred, the damaged vegetation appears water-logged and becomes limp, unable to maintain the rigidity and upright nature of its normal branching structure. Following this water-logged stage, the damaged vegetative growth will shrivel and dry out, commonly changing to a bronze, dark brown, or black coloration (USDA Forest Service 2003; USDA Forest Service 2006). After the growth has dried, shoots and leaves typically abscise from the living parts of the tree after a couple of weeks. New growth will typically commence soon after deceased growth abscises from the tree. This new growth takes place from the surviving adventitious or dormant buds, sometimes located as much as a meter or more back from the frost damaged vegetation (Harris 1934), this is known as frost-induced dieback (Frey et al. 2004). New growth is dependent upon on the severity of the frost event, the plant species involved, and the growing season remaining after the frost event. For example, during a post-frost event trip to the White Mountains of eastern Arizona, I observed frost damage to a corkbark fir that had killed roughly half an inch of new growth (Fig. 1) from the previous growing season. Due to the shortened growing season of this high elevation stand (2815 m) and the relatively minute shoot growth, no additional growth took place after the frost event.

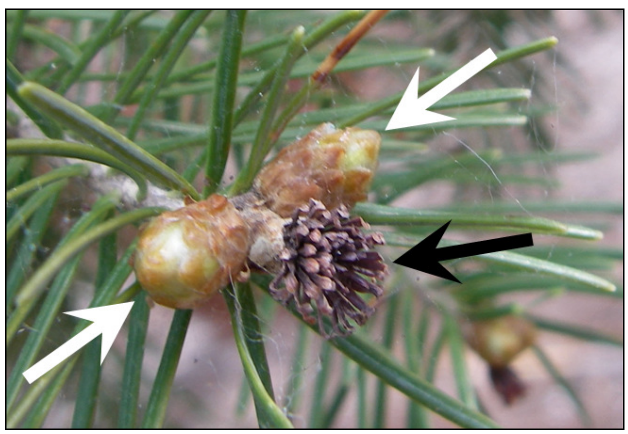

**Figure 1**. Frost damaged corkbark fir buds from the 2008 growing season (black arrow) and the new buds preparing to break for the 2009 growing season (white arrows). Picture taken 4 April 2009 (D. Pedersen).

Internal frost damage is more difficult to determine because trees subjected to frost might not form a frost ring, an internal cellular deformation signature of cells occurring in an annual growth ring (Fig.2). Additionally light-rings, or rings which have weakly lignified latewood cells and are typically formed by cooler than average growing season temperatures (Filion et al. 1986; Gindl 1999; Gurskaya and Shiyatov 2006), can also form. There is a limited amount of literature available on the balance of external damage related to internal damage. For example, if a deciduous tree was to be completely defoliated, would frost ring formation be likely, or is the formation of a frost ring more dependent on certain temperature criteria being satisfied? Interaction between cold air and the tree surface is not homogenous across the entire circumference and can be affected by numerous variables such as topography, basal area, and exposure; therefore, frost ring presence is a function of how the cold air affected the different sides of the frost-damaged tree surface. In fact, Rhoads (1923) noted that frost rings were commonly called “moon rings” since they were frequently lacking in total circumference of the annual growth ring.

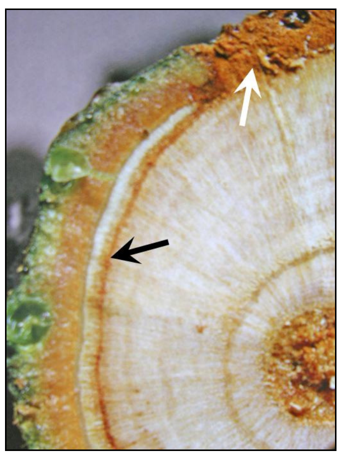

**Figure 2**. Photograph of frost ring (black arrow) and corresponding phloem, cambium, and sapwood mortality (white arrow). (Sinclair and Lyon 2005)

**Role of Climate Change**

Climate change is likely to have an effect upon frost events and corresponding frost damage. Though the facets of climate change are complex and often intertwined, this paper will, in part, investigate several factors that seem to be well researched and applicable to frost events.

Perhaps the most prominent effect of climate change is the increasing temperatures that have been observed in the twentieth and twenty-first centuries. Several predictions, chiefly made by forecasting models, have placed the warming temperatures between 3º to 6ºC during this century in the high and temperate latitudes of the globe (Saxe et al. 2001; Weltzin et al. 2003; IPCC 2007). These temperature changes will have direct effects upon vegetation and upon the processes of the ecosystem. These temperature changes are expected to have some indirect consequences on the water cycle, air circulation patterns, and precipitation regimes though precipitation models are less certain than climate change temperature models (Christensen and Lettenmaier 2007).

Villalba et al. (1994) showed that Engelmann spruce growth at mesic sites at treeline in Colorado was strongly correlated to summer temperatures. As warmer summers were recorded, growth resulted in wider annual rings. However, at more xeric treeline sites, the spruce growth was favored by cooler and wetter summers. Another study by Elliott and Baker (2004) showed that aspen establishment in Colorado flourished near treeline during the warming of the twentieth century, in large part due to the coincidence of the second wettest period in the past 1000 years (1905-1928). This Colorado study showed that establishment of aspen during this warm and moist period was primarily via seed germination; whereas, establishment later in the twentieth century as precipitation decreased and temperatures continued to rise was mainly through vegetative reproduction. Aspen is an adaptable tree species and though temperature and precipitation may fluctuate, the result may not always be mortality or decreased growth

(Elliott and Baker 2004) and due to tree adaptations accurate predictions of climate change and its effect on biological processes are difficult to model or foresee.

The timing of the temperature increase is important. In southwestern Colorado, average temperatures have increased 1.1ºC in the past 115 years, with the vast majority of the warming occurring between 1990 and 2005 (Rangwala and Miller 2010). Furthermore, this increase has largely been the result of increased maximum temperatures during the spring and summer seasons. With much of the observed warming occurring in the spring season (Cayan et al. 2001, Ault et al., in preparation), there are numerous factors influencing this critical time in a tree's development. Warming spring temperatures in southern Utah, northern Arizona, and western Colorado, has led to significant changes in the timing of snowpack melt and runoff on snow events throughout Colorado (Nydick 2009; Rhoades 2010). Changes in snowpack melt are significant as soil moisture would decrease when a tree's phenology is relying on moisture to reallocate nutrients back to the crown. The link of soil moisture to temperature is indisputable; with warming temperatures, precipitation would likely have to increase to maintain today's soil moisture levels in what might be a warmer future (Nydick 2009). Soil moisture has been modeled for southwestern Colorado by Christensen and Lettenmaier (2007) as being a 10-25% decrease in the lower elevations (below 2500 m above mean sea level (AMSL)) and up to a 30-50% decrease in the higher elevations by the year 2050. This decreased moisture availability is also likely to affect the timing of bud burst for many tree species.

Spring bud burst has occurred on average 2-5 days earlier in the last 50 years and current models are showing this trend is likely to follow a one to three day earlier spring bud burst, per decade, in the future (Cayan et al. 2001; Badeck et al. 2004; Schwartz et al.

2006; Ault et al., in preparation). Even with the average earlier onset of bud burst, it is important to realize there is an interannual variability of a tree's bud burst date of days to over a month (Gu et al. 2008). Even though a shift in several days may not cross critical thresholds, these phenological changes over large spatial and temporal extents may be significant. A warming climate could increase the likelihood of frost events in temperate regions (Cannell and Smith 1986). Though temperatures may increase and warm at an earlier date during the spring season, polar fronts and extreme weather events, such as the 2007 spring freeze in the eastern United States (Gu et al. 2008) would likely increase the leaf and bud damage of trees with earlier bud burst and leaf out (Augspurger 2009).

When freezing temperatures are recorded, frost events appear to be most damaging, especially when they are preceded by warmer than climatologically average, or abnormal temperatures, such as record-setting events for the corresponding location (Korstian 1921; Hemenway 1926; Harris 1934; Gu et al. 2008). These above average temperatures initiate a dehardening process in trees (Scarth and Levitt 1937). These events led to internal and external damage of the affected tree species.

An important factor in frost hardiness of trees is the synchronization between cooling overnight minimum temperatures along with decreasing photoperiod. This process is likely to be altered by climate change and warming temperatures. Warming autumn temperatures may result in frost hardening due to night length rather than the synergistic cooler temperatures and decreasing daylight hours; therefore, an overall decrease in frost hardiness as compared to present-day levels would be expected (Saxe et al. 2001; Bannister et al. 2005). Additionally, these warmer temperatures are likely to delay severe frosts further reducing the onset of frost hardiness and possibly the overall frost hardiness of the tree. Although, the impact of warming autumn temperatures seems to lengthen the trees' growing season, the tree's growth is still limited by the decreasing photoperiod.

Anthropogenic alterations to the environment are expected to compound the effect of climate change. Increased carbon dioxide ($CO_2$) and ozone ($O_3$) concentrations will almost certainly change biological processes. Though the results of these changes are not known, one study by Cole et al. (2010) showed that elevated $CO_2$ levels coupled with increased moisture over the past several decades in Wisconsin have resulted in increased annual ring widths and subsequent increased growth. Additionally, increased growth in low moisture environments may be the result of more efficient water use with elevated $CO_2$ concentrations. One study in Finland by Prozherina et al. (2003) showed the significance of genotype to frost and ozone damage. Those genotypes of birch (*Betula pendula*) that broke bud early were susceptible to frost; however, those genotypes which broke bud later were more vulnerable to ozone damage. The study showed that the birch compensate for the frost damage by increasing leaf production; however, simultaneous ozone damage may retard the frost damage recovery process. Anthropogenic effects of climate change will likely impact frost hardiness of tree species to varying degrees depending on location and species (Inouye 2000).

**Frost Rings**

Frost rings are identified by the characteristic presence of damaged cells and are visibly different from normal cells (Fig. 3). The resulting damage is from intercellular ice that permanently alters the densification of the secondary cell walls and lignification of partially matured xylem cells (LaMarche and Hirschboeck 1984; Brunstein 1995; Brunstein 1996). These collapsed cells become compacted as a result of the ice formation

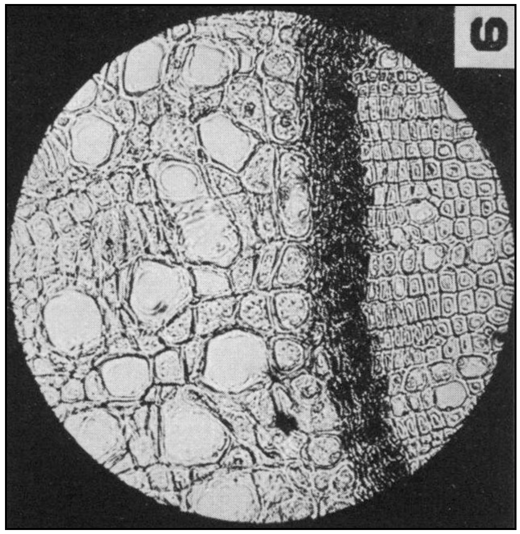

**Figure 3**. Picture of frost ring (dark line right of center) and corresponding non-linearity and compaction of cells (left of dark line). (Harris 1934)

in the intercellular space. Therefore, the presence of darkened cells (collapsed xylem tissue) and often erratic linear patterns becomes more apparent than in non-frost damaged tree tissue (Harris 1934). Furthermore, the normally uniseriate ray structure of *Populus* trees upon damage from frost switched from the typical uniseriate structure to a biseriate ray structure producing a widening of the xylem rays (Harris 1934). An important note, as mentioned earlier, is the frost ring may only be present in a partial circumference of a tree's cross-section and not present throughout the entire annual ring growth.

Frost rings can be classified into two categories: formation in the earlywood (spring) and formation in the latewood (autumn) - (Fig. 4), which will identify the season when the frost event took place. In the higher elevations of northern Arizona the earlywood formation of annual growth rings takes place in the beginning of the growing season, typically in mid-May to mid-June and is characterized by a period of rapid growth (Stokes and Smiley 1968). Unlike earlywood, latewood formation is found toward the end of the growing season during slowing cambial activity. The latewood growth leads to the formation of thicker cell walls and darker visual appearance, which typically form in mid-September to mid-October.

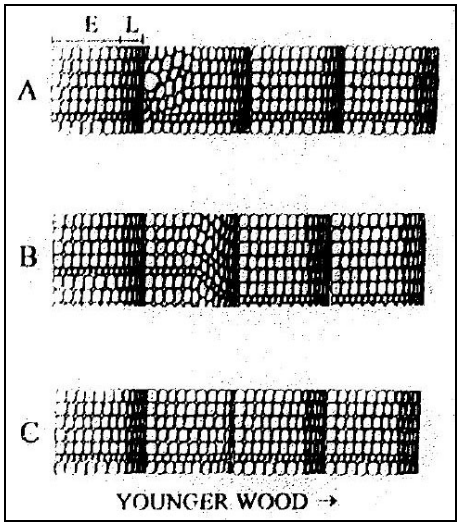


**Figure 4**. Drawings depicting frost ring formations in Rocky Mountain bristlecone pine. Non-linear cell pattern deformation formation is in the second annual ring from the left. (A) Earlywood frost ring formed (cell deformation only) when the frost event happens in the beginning of the growing season, (B) latewood frost ring (deformation and darkening) that occurs during a late growing season frost event, and (C) light ring showing less latewood due to cool summer temperatures. (Brunstein 1995)

Simon (1984) stated that it is possible to ascertain a date for a frost event to within a couple days of occurrence for bristlecone pine (*Pinus aristata* Engelm.) growing at treeline due to the abbreviated nature of the growing season at higher elevations of the southern Rocky Mountains. However, in the ecotone of mixed-conifer and aspen located in northern Arizona, the time period for identifying the occurrence of a frost event is likely only if the frost event occurred over a larger temporal scale (e.g., several weeks), due to the nature of the longer growing season. Moreover, it is possible to record two or three frost events during one growing season. This occurrence is visible via multiple frost rings appearing in one annual growth ring (Rhoads 1923; Gurskaya and Shiyatov 2006). Most studies use conifer species for dendrochronological frost ring studies due to the longevity, persistence, abundant distribution, and 'easy to read' tree cores.

There is a strong correlation between tree age, frost ring formations, and frost damage, or frost-related mortality (Korstian 1921; Rhoads 1923; Bailey 1925; Gurskaya and Shiyatov 2006). Bailey (1925) reported damage in trees of age six to eight years; whereas, older adjacent trees recorded little if any frost damage. Similarly, Rhoads (1923) showed a relationship of age to frost damage in spruce (15 years and younger) and larch (4 years and younger). In addition, Brunstein (1995) found that the vast majority of earlywood frost rings were within 100 years of the pith, and therefore a younger age especially when dealing with several thousand year-old bristlecone pines. In these studies the younger trees experienced more damage, or higher mortality rates due to the thinner bark and younger foliage. Unlike conifers, aspen have a relatively short lifespan, spatial extent, and limited homogeneity throughout the majority of northern Arizona. But little is known about whether aspen record frost rings.

The frequency and occurrence of these freezing events have specific criteria for frost related damage to occur in plant tissue. First, frost rings are most common during the growing season of that particular tree species and corresponding site. Though damage to trees does occur at other times of the year, for example xylem embolisms, frost cracks, wind burn, and red belts (Sakai and Weiser 1973; Sperry et al. 1994; Oliver and Larson 1996), in this paper I focus on frost damage during the growing season, particularly late spring. Secondly, the timing of specific temperatures appears to be most effective in formation of a frost ring. The most cited temperature criterion is two consecutive nighttime minimum temperatures of -5°C or lower, with an intervening daytime maximum temperature of 0°C or lower (Hemenway 1926; LaMarche and Hirschboeck 1984; Simon 1984; Brunstein 1995). Though few, if any, studies discuss a minimum threshold for frost damage and frost ring formation, it seems there may be a minimum temperature threshold that could overrule the intervening maximum temperature of 0ºC.

Major frost-damaging events, those commonly leading to earlywood or latewood frost- rings, are site-dependent. Gurskaya and Shiyatov (2006) reported the presence of frost rings in spruce and larch trees at least every other year in Siberia and found most frost-related damage took place in the earlywood of these species. This study revealed that late spring and early summer frosts (earlywood) take place at a higher frequency than late summer and early autumn frosts (latewood). Nevertheless, Brunstein (1995) noted that the frequency of latewood frost rings was three times greater than earlywood frost rings in bristlecone pine, thereby showing a greater significance to late summer and early autumn frost events at treeline in the southern Colorado Rocky Mountains. In this region the Rocky Mountain bristlecone pine was found to have a frost ring on average every 10-12 years versus the more frequent frost events found in Siberia. All bristlecone pine sample sites utilized in the Brunstein (1995) study reported having aspen on or near each sample site and most likely these aspen were also damaged from the corresponding frost events. Interestingly, although frost events are relatively frequent in other areas, they are not as frequent in the higher elevations of northern Arizona (Brunstein 1995; Gurskaya and Shiyatov 2006).

An alternative approach to direct frost ring detection is inference through readily available meteorological data recorded during frost events. Modern-day weather instrumentation is real-time, fairly reliable, and accurate. This equipment is pivotal in recording temperatures throughout the year and can be used to study the potential for frost events, especially in non-urbanized areas. In the past 20 to 25 years the western United States has seen a large increase in the establishment of instrumentation in remote locations. Several federal agencies monitor weather and have successfully located weather stations in remote locations, two of which are the National Weather Service (NWS) and the National Resource Conservation Service (NRCS). One such program by the NRCS is the SNOTEL, or snow telemetry program, which was established primarily to monitor snowpack and make projections about spring melt-water. Conversely, the NWS has established a myriad of weather station sites to ground truth forecasts and more accurately represent climatological data.

Though few studies have used this indirect approach to frost events and potential frost ring formation, there is circumstantial evidence to conclude a potential frost event from accurately collected climate data. These data could be used to record not only the frost event and corresponding temperatures but also the preceding weather conditions, such as warmer than average temperatures. Weather conditions prior to frost events can play a crucial role in the severity and extent of frost damage in tree species (Korstian 1921; Hemenway 1926; Harris 1934; Cannell and Smith. 1986; Gu et al. 2008). Therefore, the likelihood one could infer a frost event from collected weather data seems feasible. One must also take into account the topography and location of the weather stations when extrapolating climate data to a corresponding frost event. For instance, if the temperatures conducive to a frost ring formation are recorded at a weather station in a valley bottom, surrounding slopes or elevated terrain likely experienced different temperature regimes, especially minimum temperatures.

**Growing Season Freezing Temperatures**

Freezing temperatures during the growing season are not an uncommon occurrence throughout the higher elevations of the western United States; however, many trees are well-adapted to the variety of microclimates present in northern Arizona. For example, aspen at higher elevations or northerly aspects commonly leaf out after aspen in lower or southerly aspects, often due to ambient temperature. These later leaf out dates allow trees to avoid freezing temperature events. Furthermore, many of the overnight freezing temperatures occurring in northern Arizona are of short duration, usually only several hours, and the threshold of an intervening daytime maximum temperature of freezing or lower is often not met (Western Region Climate Center 2010).

One species particularly affected by frost events are aspen. Spring frost damage appears to be more detrimental to aspen growth than autumn frost damage for several reasons. First, the growth of aspen trees and other diffuse-porous tree species is most accelerated during the beginning of the growing season (Boone et al. 2004), when the earlywood is being formed and succulent young growth is vulnerable to freezing temperatures. Fruiting and flowering of aspen closely follows a maximum temperature of 12°C sustained for six consecutive days (Burns and Honkala 1990), and it is common in northern Arizona to achieve these consecutive warm days early in the spring season. However, below freezing overnight minimum temperatures commonly occur into mid-June (NOAA 2007) for the 2134-meter elevation range of northern Arizona, an area of lower elevation than the vast majority of aspen populations in this region. Secondly, in the spring when aspen have reduced their frost resistance through the dehardening process, the trees are more susceptible to frost damage than in early to mid autumn when the aspen have begun to increase their frost resistance (frost hardening) due to decreasing photoperiod and to a lesser degree the cooling overnight minimum temperatures (Alden and Hermann 1971). The June 1999 snow and frost event in northern Arizona definitely caused external damage to quaking aspen including bud damage and defoliation (Fairweather 1999), but whether internal damage was caused is unknown.

**Conditions Leading To Frost Ring Formation**

Though frost rings are directly tied to climatologically colder than normal temperatures during the growing season, there are several possible driving factors, in addition to climate change, which can result in these below normal conditions. The majority of these events have continental or global-scale effects; however, others may be more localized in nature.

Volcanic eruptions have been linked to frost rings formation (LaMarche and Hirschboeck 1984; Simon 1984; Brunstein 1995; Brunstein 1996). Volcanic eruptions displace countless aerosols and particulate matter into the atmosphere resulting in 2º-4°C surface cooling, which can last up to three or four years following an eruption (LaMarche and Hirschboeck 1984). Moreover, these events have global implications, often affecting multiple locations simultaneously. This is shown by frost ring events recorded simultaneously in the bristlecone pine of the Colorado Rocky Mountains and the Great Basin bristlecone pine (*Pinus longaeva* D.K. Bailey) in the Great Basin of Nevada numerous times over the past two millennia. The two most recent events occurred in 1912 and 1965 following volcanic events in 1912 (Katmai, Alaska) and 1963 (Agung, Bali) (LaMarche and Hirschboeck 1984; Brunstein 1996). Not all volcanic events lead to frost rings. There are multiple factors that lead to the distribution of frost rings and global cooling; however, those factors are beyond the scope of this paper.

Another possible mechanism of frost ring formation is reduced sea surface temperatures. Kuivinen and Lawson (1982) found a direct link to colder than normal sea surface temperatures, reciprocated in below normal air temperatures leading to reduced annual growth of birch (*Betula pubescens* Ehrh.) in southern Greenland. Though this is likely to have a less direct impact in northern Arizona due to the significant distances from the ocean, sea surface temperatures are a large driving factor in El Niño and La Niña events. This is important as strong El Niño events have been shown to lead to frost ring formation (Brunstein 1996).

Extreme climatic events have the potential to lead to frost rings. There have been frequent frost rings observed during the Little Ice Age (1650-1850), as well as frost rings found in association with cold summers (1816, the “year without a summer”). Furthermore, years with above normal snowfall have also lead to decreased annual growth in bristlecone pine due to burial of new buds and reduced growing season length due to persistence of the snowpack (Brunstein 1996). Cold arctic air frequently travels south from Canada in September to the High Plains and affects the Front Range of the Rocky Mountains. However, these late summer and early autumn cold air outbreaks occur less frequently in northern Arizona because the cold, dense air over the Plains cannot rise over the Rockies to the Southwest region. In addition, the polar jet stream positioning over the more southerly latitude of northern Arizona during the late summer and early autumn is an infrequent event. However, extreme radiational cooling and low humidity are common throughout the northern Arizona and can lead to freezing temperatures throughout the growing season, especially in May and June.

**Frost Events, Frost Damage, and Tree Growth**

Due to the destructive nature of frost events and especially frost events in the spring, the cost of foliar damage to a tree can be immense. During this time, the tree is utilizing much of the carbohydrates and resources and translocating them upward from the roots into the crown. When a frost event occurs, the foliar damage can result not only in the loss of much of these nutrients, but also the loss of adventitious buds and sometimes branches and twigs, depending on the severity of the frost event. Additionally, if the frost event is accompanied with snow, there can be severe damage to the crowns in the form of crown breakage, particularly if the frost and snow event occurs after leaf out (Frey et al. 2004). This external dieback can lead to shrubby-looking or deformed statured trees.

Lui and Muller (1993) observed the severe damage of an early May frost event in a mixed deciduous forest in eastern Kentucky. Many of the trees suffered considerable defoliation. The frost event occurred on 4 May 1986 with a minimum temperature recorded of -2.2ºC. Ring widths were measured from the year prior to the frost event (1985) and the year following the frost event (1987) and used for comparison. The precipitation for 1985 and 1987 was nearly constant and found not to be significantly different from one another ($P>0.05$); ergo, the average was taken for the two years. They found for all trees (dominant, codominant, intermediate, and suppressed) that growth during the frost year was 14% below the average ring width growth of 1985 and 1987 ($P<0.001$). Furthermore, the greatest growth reduction was in the dominant trees (15%), followed by the codominant (9%), intermediate (5%), and suppressed (3%). Foliage growth did not return to normal until the end of June. The study also demonstrated the importance of the canopy to the atmospheric boundary layer which insolated trees in lower strata, somewhat protecting them from the lowest temperatures.

**Frost Events and Frost Damage Case Studies**

Few ecological studies have focused on frost events and frost damage (Inouye 2000; Augspurger 2009). Two of the earliest studies that examined the effects of frost upon forest vegetation in the Southwest were by Zon (1904) followed by Phillips (1907), who examined the effect of a late spring frost on trees. Phillips (1907) found a significant correlation between bud burst timing, elevation, and temperature. The study found lower elevation aspen that leafed out early were completely defoliated, while higher elevation Engelmann spruce, corkbark fir, and aspen were unaffected by the freezing temperatures due to delayed bud burst.

Korstian (1921) conducted a study that would closely resemble a frost event and related frost damage for northern Arizona. The study was conducted at a U.S. Forest Service nursery outside of Salt Lake City, in the Wasatch Mountains of northern Utah. This nursery was located at 2255 meters AMSL, which is a similar elevation to the lower aspen and mixed conifer forests of northern Arizona. Another advantage to this study is the data were collected on a variety of tree species, native, non-native, and even from the same species found at different locations due to the nature of the nursery setting and surrounding forest. Trees in this study were planted and are not in containers. Furthermore, the frost and snow event took place at the end of May 1919, following a several week period of significantly warmer than average temperatures.

May 1919 was an exceptionally warm month, recording temperatures as 2.5ºC above normal from 43 weather-observing stations across Utah (those having records for ten years or longer). Temperatures at the nursery were 2.9ºC above the May average, with a maximum temperature observed of 25.5ºC, just days before the frost and snow event. These temperatures are quite similar to what is observed in Flagstaff, Arizona (2135m) during the month of May. With the onset of these warm temperatures, bud burst was two to three weeks earlier than normal. On 30 May, a cold front moved through and 12.7 cm of snow fell and minimum temperature of -9.4ºC was recorded.

These large swings in temperature, accompanied with snowfall, had drastic effects upon the vegetation. Damage ranged from total tree mortality to minor external damage to branches and buds. Engelmann spruce was reported to have suffered significant damage. Four-year-old seedlings had much of the current year's growth killed and several trees were completely killed. Interestingly, those Engelmann spruce trees that were grown from seed stock from Gunnison National Forest (central Colorado) suffered only 10 percent terminal dieback, whereas native Engelmann spruce from the adjacent Wasatch National Forest had 50 percent terminal dieback. Four-year-old blue spruce (*Picea pungens* Engelm.) had only 10 percent terminal mortality. However, four-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) was reported to have complete mortality among the uncovered specimens, and even those that were insolated with hay succumbed to severe frost damage. Nearby planted 1.8-meter tall Douglas-fir had all of the previous year's growth killed along with a partial killing of the lower branches. Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) had no observable damage, while five-year-old western white pine (*Pinus monticola* Dougl. ex D. Don) had minor damage.

In most cases, in the forest adjacent to the nursery, white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) had more frost damage than the Engelmann spruce or blue spruce. The study reported neighboring subalpine fir trees as large as 45.7 cm in diameter were completely killed by the frost and snow event. This damage was largely due to the fact the subalpine fir trees had broken bud earlier than the spruce trees and were more developed. The highest concentration of injuries was between 2133m and 2438m AMSL (Korstian 1921).

In addition to the conifer damage reported in the May 1919 frost event, Korstian also reported frost damage to quaking aspen. Numerous aspen had broken bud and already had one to two-inch leaves on their branches. The current growing season's leaves were killed, and much of the previous year's growth was also killed. Observed aspen trees were completely defoliated and remained barren for over a month as new adventitious buds and surviving buds began to re-foliate parts of most aspen trees. However, the aspen leaves that were produced during the second leaf flush were as large as 21.6 cm by 25.4 cm, with most exceeding 15.2 cm. This by comparison is four to five times larger than an average aspen leaf which is roughly 5 cm (Fig. 5). Other hardwoods such as Gambel oak (*Quercus gambelii* Nutt.), Rocky Mountain maple (*Acer glabrum* Torr.), and mountain alder (*Alnus incana* (L.) Moench ssp. *tenuifolia* (Nutt.) Breitung) were also reported as suffering significant frost damage. Most of these species observed loss of the current and the previous year's growth.

The Korstian (1921) study had similar tree species and meteorological characteristics to the June 1999 frost event that occurred in northern Arizona. Extensive climatological records were not included in the Korstian (1921) study, however, the

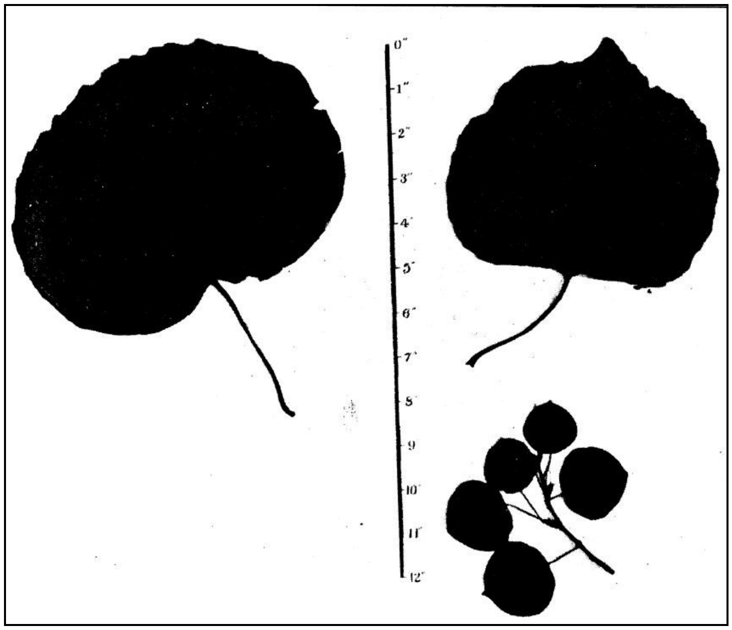


**Figure 5**. Aspen leaf size as a result of frost. The lower right shows typical range of aspen leaf sizes, the large leaves on the top of the picture are leaves produced post May 1919 event. Note the inches scale in the center of the image. (Korstian 1921)

12.7 cm of snow that fell melted off by noon the following day, with some snow remaining through the day on north-facing slopes. This observation is important as it may show that the ambient air temperature the day following the frost event was likely above 0ºC. Again, like the Lui and Muller (1993) study, the temperature criteria for frost ring formation were probably not achieved; however, the minimum temperature of -9.4ºC appeared to achieve some threshold, which led to major damage and mortality.

Conditions observed during the Korstian (1921) study reveal a climate scenario that would be quite feasible in northern Arizona. Flagstaff's average monthly May temperature is 10.4ºC, with the maximum high temperature of 31.6ºC and a minimum of -13.9ºC (NOAA 2007), which are well within the constraints noted by Korstian (1921). Moreover, Flagstaff averages 3 cm of snowfall in May, with as much as 38 cm being recorded (1904). As elevations increase in northern Arizona, the May snowfall averages and maximums increase appreciably and the likelihood of a frost and snow event exists.

The key is to ascertain a balance between tree phenology (bud burst) and freezing temperatures.

Another study by Harris (1934) showed the importance of weather in frost events with more of a focus on frost ring formation. Unlike the Korstian study this study took place in Champaign-Urbana, Illinois and involved privet (*Ligustrum*), elm (*Ulmus*), willow (*Salix*), and poplar (*Populus*); privet and elm are not native to northern Arizona. Temperatures in the winter of 1931-1932 were reported as the warmest since record keeping began in 1878. December, January, and February were all significantly warmer than average and the lowest temperatures of that winter were actually recorded during a long-term frost event during the first half of March (Table 1).

Like the Korstian (1921) study, the Harris (1934) study showed the importance of warm weather preceding a frost event. Prior to this frost event, minimum March temperatures were above freezing and maximum temperatures ranged from 6º to 10.5ºC. The Harris (1934) study does not discuss what the temperature regime was like in January and February 1934 other than it was warmer than usual and warmer than the frost event in March. Vegetative growth was underway and the frost event severely damaged new growth. Beginning on the night of 5 March the temperature dropped to -9.4ºC and was followed by seven days where the maximum temperature never rose above 0ºC.

**Table 1**. Daily maximum and minimum temperatures for March 1932. The frost event is highlighted in grey. Temperatures were recorded in Fahrenheit (ºF). (Harris 1934)

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day ................ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| Maximum .......... | 51 | 46 | 43 | 47 | 44 | 16 | 18 | 15 | 21 | 25 | 28 | 25 | 33 | 28 | 41 | 60 |
| Minimum ........... | 38 | 36 | 38 | 35 | 15 | 6 | 5 | 8 | 5 | 6 | 12 | 15 | 13 | 12 | 18 | 30 |
| Day ................ | | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| Maximum .......... | | 51 | 47 | 50 | 38 | 33 | 35 | 39 | 53 | 66 | 58 | 46 | 56 | 69 | 61 | 44 |
| Minimum ........... | | 33 | 24 | 31 | 24 | 30 | 24 | 25 | 25 | 42 | 40 | 33 | 33 | 35 | 40 | 30 |

In some cases daily maximum temperature never exceeded -9.4ºC and minimum temperatures were as low as -15ºC.

Frost damage from this March event caused dieback ranging from 8 cm to as much as 2 m along with complete loss of foliage. American elm (*Ulmus americana* L.) varied in damage from several killed twigs, to severe dieback. Foliage proceeded to develop below the frost damaged buds and was more dense than usual. Pussy willow (*Salix caprea* L.), another diffuse-porous species similar to aspen, suffered extreme dieback during the frost event and was reported as the first species in the vicinity to flower. Much of the damage took place on the tops of the shrubs; however, some lateral branches were also killed outright. Damage on the willows ranged from 7.6 cm to 1.2 m. Lombardy poplar (*Populus nigra* L. var. *italic* Du Roi), also a diffuse-porous species related to aspen, experienced extensive dieback to both terminal and lateral branches and were likely observed in high numbers due to the high urban cultivation of these trees.

One advantage of this Harris (1934) study is that frost rings were observed and taken into account. The privets were reported as having a narrow frost ring, indicated by the discoloration of the cells present in the annual growth ring (Fig. 6). Samples of elm, willow, and poplar also showed frost rings. Frost rings in the privet were reported as ranging from two to 10 or 12 cells in width. It was also noted that the frost rings in elms and poplars were smaller than those observed in the privets, and frost rings were completely undetectable in willows. Though this Harris (1934) study took place in Illinois and dealt with species not native to northern Arizona, it showed the significance of warm temperatures preceding a frost event for frost ring formation.

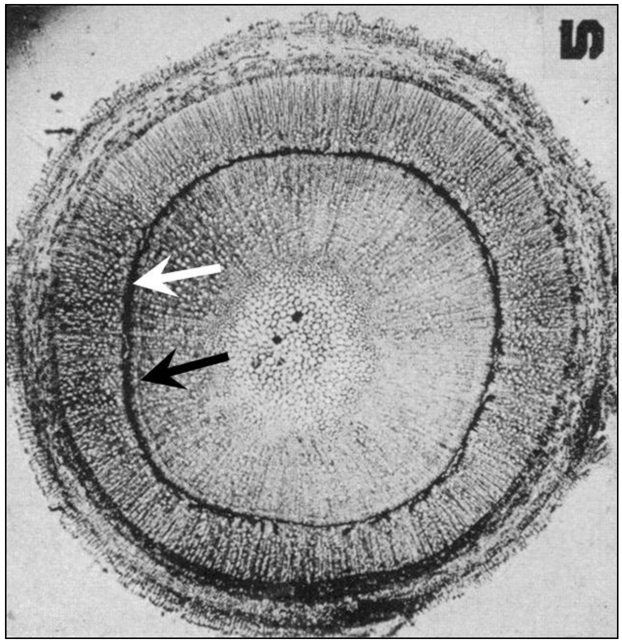

**Figure 6**. Frost ring formation in a two-year-old privet stem. The white arrow indicates the frost ring and the black arrow shows the annual growth ring boundary. (Harris 1934)

**Inner Basin Case Study**

Drawing from these early studies on frost events and frost damage, I conducted a case study in northern Arizona to investigate the potential for frost ring formation during the frost and snow event on 5-7 June 1999. The June 1999 event was a regional-scale event with freezing temperatures recorded throughout northern and eastern Arizona. Firstly, I examined the weather records from 35 weather stations across northern and eastern Arizona (Appendix A), which reveal the extent of this event. These stations ranged in elevation from 1496 m (Payson, Arizona) to 2966 m (Snowslide SNOTEL, San Francisco Peaks) and geographical extent ranged from the South Rim of the Grand Canyon to Hannagan Meadow in the White Mountains of eastern Arizona, a distance of nearly 400 km. Of the 35 stations included into the climate analysis, the coldest overnight minimum temperatures occurred on 5 or 6 June depending on the location. On the night of 5, 25 stations recorded a minimum temperature of ≤0ºC, six stations recording a minimum temperature >0ºC, and four stations reported missing data. Whereas, on 6 June, 23 stations recorded a minimum temperature of ≤0ºC, seven stations recorded a minimum >0ºC, and five stations reported missing data.

I then determined which station recorded climate data with the highest probability of resulting in frost ring formation. Only one station, Snowslide SNOTEL on the San Francisco Peaks in northern Arizona, observed a daily maximum temperature close to 0ºC, along with five consecutive nights below 0ºC equally distributed around the maximum temperature +0.6º on 5 June (Table 2). June 5 also had the coldest minimum, -5.6ºC.

**Table 2**. Recorded temperatures from Snowslide SNOTEL (2-7 June 1999).

| June 1999 | Max. Temp (ºC) | Min. Temp (ºC) |
|---|---|---|
| 02 | 14.8 | 3.2 |
| 03 | 4.2 | -0.1 |
| 04 | 7.5 | -0.2 |
| 05 | 0.6 | -5.6 |
| 06 | 8.3 | -3.3 |
| 07 | 14.7 | -2.5 |

A trace amount of snowfall was recorded during this storm at the Flagstaff Pulliam Airport (2135 m), where weather observations are taken. Greater amounts of snow were likely received at the higher elevations around Flagstaff. For example, the Snowslide SNOTEL site received 2.54 cm of snow water equivalent (SWE). Reasonable SWE conversions for winter snowfall are roughly 1 cm of liquid water equals roughly 10 cm of snowfall. However, this was a relatively warm snowfall event as compared with a mid-winter snowfall, meaning the water content of the snow was likely higher. A conservative estimation for the Snowslide SNOTEL site would probably be 5-8 cm of snowfall. Based on the temperature criteria, the Snowslide SNOTEL was the only station of the 35 analyzed where the trees would most likely record this frost event as a frost ring. Therefore, I conducted a more detailed study of tree rings from trees on the Snowslide site.

The Snowslide SNOTEL (35.3421ºN, 111.6509ºW), established in 1997, is located in the Inner Basin of the San Francisco Peaks (Fig. 7), north of Flagstaff. Terrain adjacent to the SNOTEL site can be described as a micro-valley. Just south and east of the weather site, a ridge, which is a remnant glacial moraine, rises roughly 20 m above the micro-valley floor. This ridge runs from the southwest to the northeast and therefore creates a nearly half-crescent, north to west-facing slope around the SNOTEL site. Directly to the west, the terrain gradually increases in elevation (Fig. 8), whereas to the north the terrain follows a small drainage and decreases in elevation.

The climate of the Snowslide site is typical of higher elevation regions throughout northern Arizona. The precipitation regime follows a bimodal distribution (Fig. 9), with one maximum occurring during the winter (December through April) and the other maximum during the summer rainy season, also called the summer monsoon season (July through September). Temperatures are mild in the summer months, with relatively cold winters. This temperature scheme is especially true for the higher elevation Snowslide site (2966 m). Though the minimum temperatures observed at Snowslide are usually within 1º to 2ºC of Flagstaff, the maximum temperatures are consistently 5º to 6ºC lower than the maximum temperatures observed in Flagstaff.

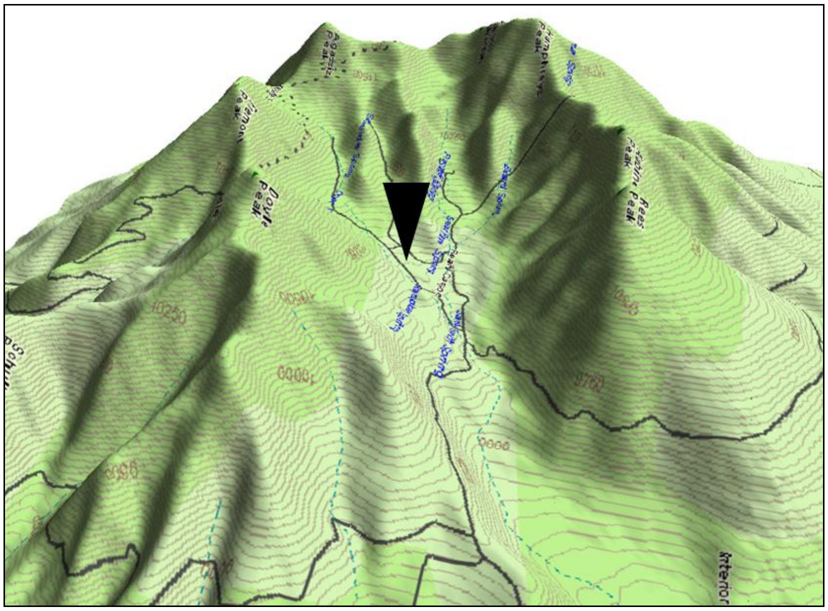

**Figure 7**. Topographical representation of the San Francisco Peaks; black pointer represents the location of study site.

**Figure 8**. Snowslide SNOTEL study site within the Inner Basin of the San Francisco Peaks, facing southwest. Note the meteorological equipment on the left side of the picture. Photo taken by D. Pedersen.

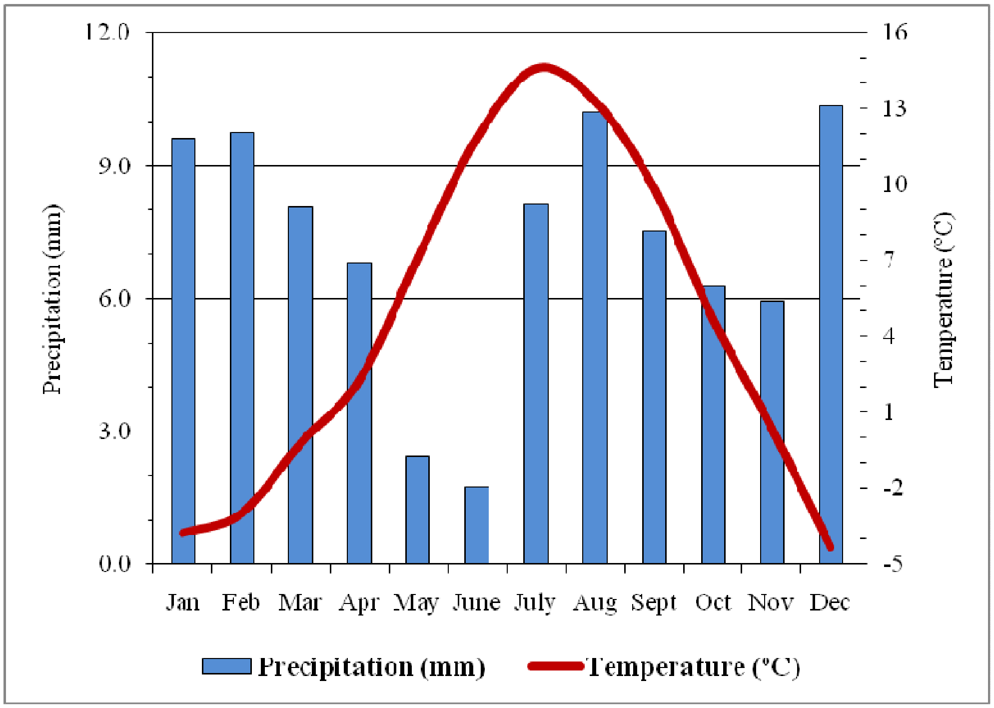


**Figure 9**. Climograph of Snowslide SNOTEL site; 1997-2009 (Data source: NRCS).

The tree composition at the Snowslide site consists primarily of Engelmann spruce, corkbark fir, and aspen. Colder, north-facing slopes are primarily Engelmann spruce with a small component of corkbark fir. Extending out from the site to the west, the forest composition changes to primarily aspen with sporadic Engelmann spruce and corkbark fir, predominantly in the understory (Fig. 8). Heading to the north and to the northeast, mature Engelmann spruce and corkbark fir form the vast majority of the dominant stratum, with a minor component of dominant and codominant aspen.

The study design consisted of taking 48 tree core samples from four transects, roughly 80 m in length, originating from the Snowslide SNOTEL weather instrumentation. Based on the research done by Korstian (1921), I included Engelmann spruce, corkbark fir, and aspen into the study as all three species had potential for frost ring formation. Moreover, I was trying to focus on younger trees that may have experienced more damage during the June 1999 frost and snow event. The four transects were established (northwest, northeast, southeast, and southwest). Along each of the four transects six trees were sampled with two cores per tree (Appendix B). On the southwest transect I included three Engelmann spruce due to lack of a second corkbark fir.

Tree cores were taken using a large diameter increment borer (13 mm width). Sampling height was taken at an average height of 53 cm due to the length of the borer handle and also the copious lower branches present on many trees. Two samples were taken per tree with the second same tree sample taken 90º from the first sample and offset in height to avoid coring the previous cavity. The 90º offset in sampling was primarily done to increase the chances of finding a frost ring due to the lack of circumferential completeness of most frost rings as mentioned by Rhoads (1923).

The 48 samples were taken to Ecological Research Institute at Northern Arizona University, where the samples were progressively sanded (120, 220, 320, and 400-grit sandpaper), mounted, and visually dated using standard dendrochronological procedures (Stokes and Smiley 1968), a microscope and accompanying Leica software (Fig. 10). The temperatures in May of 1999 were roughly 0.8ºC below normal for both maximum and minimum temperatures in Flagstaff; therefore, the significance of a warmer than normal temperature regime prior to the frost event is minuscule. Temperatures at the Snowslide site for the month of May 1999 had an average maximum temperature of 12.4ºC and an average minimum of -2.2ºC. The maximum temperature was 17.7ºC on 21 May and the minimum recorded was -12.4ºC on 1 May.

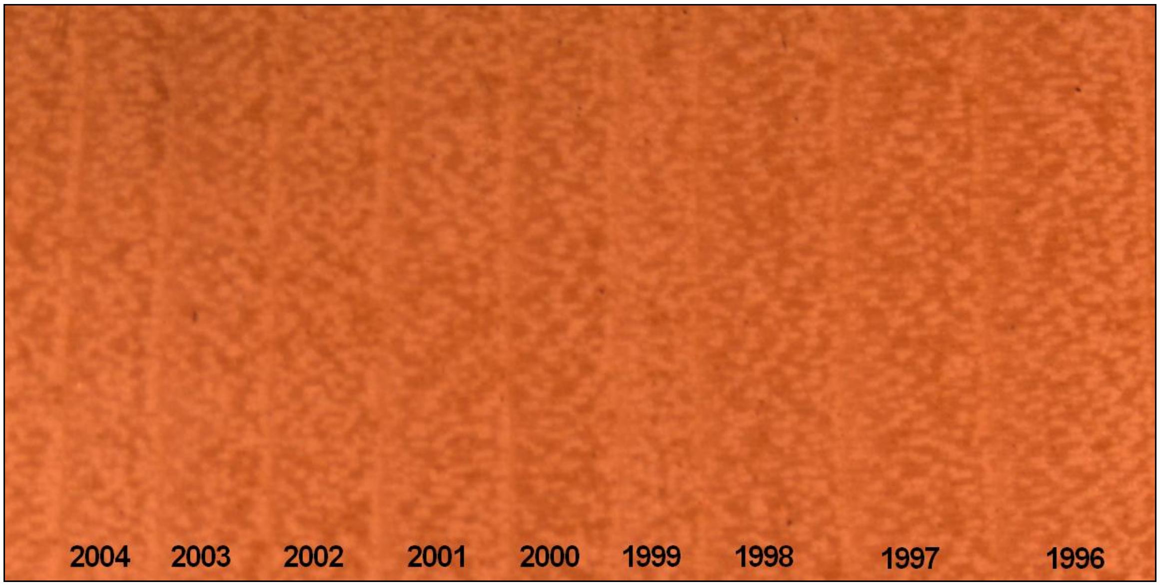


**Figure 10**. Aspen core sample showing the annual rings; picture taken using Leica. Years are marked in the corresponding year of growth.

All 48 tree core samples were visually inspected for the presence of frost rings in the earlywood of 1999. None of the 48 samples exhibited any of the frost ring characteristics, such as collapsed and darkened cells or non-linearity. The June 1999 event may not have been severe enough to cause internal damage to any of the tree species at this site. Another likely assessment from the lack of frost ring formations is the bud burst date. It is probable that the bud burst date for all three tree species around the Snowslide site is after the first week in June, especially following a nearly average temperature May. This scenario would have protected the trees from frost damage and significant crown breakage to the aspen from the high water content snowfall. Though aspen defoliation as a result of frost and large aspen tortix was reported on the west, east, and north sides of the San Francisco Peaks (Fairweather 1999), it appears as though this damage was more severe at the lower elevations (<2900 m) and to genotypes that likely broke bud earlier than those experienced at the Snowslide site. This conclusion is consistent with Phillips (1907) and Strain (1966) who found aspen at higher elevation sites that had not broke bud did not suffer any external damage as compared to lower elevation aspen that had all newly developing leaves killed. The balance of bud burst and freezing temperatures is important in locating potential areas susceptible to freeze damage in northern Arizona.

Frost events during the growing season in Arizona are rare and weather conditions conducive to frost ring formation are even rarer. Daily temperature ranges in the low-humidity atmosphere of northern Arizona are vast, typically changing 16º-20ºC between minimum and maximum. There are records, particularly in the month of June, where locations have recorded record minimums and record maximums in the same day, with ranges as great as 38ºC. This dichotomy of temperature leads to potential frost damage during the morning hours, or time of lowest temperature. However, with such rapid increases in afternoon temperatures, the chance of recording a maximum temperature ≤0ºC is minute. In fact, the coldest June maximum temperature for Flagstaff since weather records began in 1898, was 6.6ºC in 1899, well above the suggested 0ºC for frost ring formation and the coldest minimum (-5.6ºC) is also just below the minimum threshold. This is not to say that temperatures in and around drainages and higher elevations in northern Arizona cannot experience the recommended temperature thresholds but it seems difficult to achieve these specific temperature patterns with the polar jet stream characteristically well north of northern Arizona in June.

**Conclusions and Management Implications**

The impacts of frost events and frost damage can lead to significant external damage. In some cases, the frost damage can be great enough to lead to mortality. However, in lesser cases where tree mortality is not observed, frost rings can form as a result of severe external damage. These frost rings are helpful in reconstructing past climate and historic frost damage.

Climate change could alter the frequency or timing of frost events. Though results of climate change are not known and how frost event frequencies will respond accordingly is uncertain, there is research to suggest that warmer temperatures in winter, and especially in the spring, could increase frost events (Inouye 2000; Augspurger 2009). The likelihood of spring time temperatures increasing during the twenty-first century is strong. These increases in temperature are apt to initiate premature dehardening and will likely increase the risk of frost damage (Cannell and Smith 1986; Gu et al. 2008; Augspurger 2009). Earlier warm spring temperatures are still susceptible to cold-air outbreaks and freezing temperatures following these periods of warm weather. Trees trying to adapt to the earlier warmer temperatures, thereby breaking bud earlier, will be more susceptible to these late spring frosts.

Conditions leading to frost events and potential frost ring formation are variable in spatial and temporal scale. Local events such as the frost and snow event in northern Arizona in June 1999 were localized; whereas, volcanic eruptions or sea surface temperature alterations can have global consequences. Both of these phenomena are likely to continue, as they have in the past, and will likely lead to alterations in tree growth.

Research into frost rings seems to be primarily limited to higher elevations (treeline), higher latitudes (primarily the arctic or subartic), or from observations in the early part of the twentieth century. Further research should be undertaken to better understand frost rings and the temperature constraints to form them, especially in the numerous microclimates of northern Arizona. A minimum temperature threshold should be researched and tested and possibly a manual of thresholds for local species compiled. From these data, we can examine the relationships of changing temperatures, frost events and the direct impact on trees, and have better predictions for global climate change models.

Managing for frost events and frost damage is challenging. Little can be done in the days or weeks prior to a frost event across a landscape to protect vegetation from frost and potential snow events. However, forest managers can be more proactive by knowing the state of health of forest species and stands. A forest that is experiencing a drought, insect outbreak, or other disturbance is more stressed. A frost event that impacts a forest undergoing these disturbances will likely experience even greater impact from the frost event, than if the frost were the only agent of disturbance. Drought, insect outbreak, and a late spring frost were the multiple disturbance events that happened in 1999, which were inciting factors that lead to sudden aspen decline disease on the Coconino National Forest (Fairweather et al. 2008). A manager cannot control frost events or drought, but they can take more proactive measures such as planting frost or drought resistant tree seedlings, controlling competition (conifer encroachment into aspen stands), or controlling ungulate herbivory of aspen regeneration (e.g., reducing elk herds and exclosures).

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**Appendix A**. Temperatures are recorded in degrees Fahrenheit (ºF). Boxes with temperatures ≤32ºF are shaded.

## Minimum Temperatures for Arizona Weather Stations - June 1999

| Weather Station | Elevation (ft) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alpine | 8050 | 34 | 29 | 46 | 27 | 20 | 30 | 28 | 29 | MM | 30 | 29 | 31 | 33 | 32 | 35 | 41 | 45 | 41 | 40 | 38 | 47 | 38 | 43 | 44 | 45 | 43 | 45 | 47 | 50 | 48 |
| Alpine 18SW | 9160 | 36 | MM | MM | 42 | MM | 26 | 33 | 33 | 30 | 32 | 32 | 39 | 37 | 41 | MM | 49 | 54 | MM | MM | MM | MM | MM | MM | MM | MM | MM | 49 | 48 | 48 | 49 |
| Bellemont | 7152 | 27 | 36 | 37 | 31 | 29 | 27 | 27 | 29 | 27 | 25 | 29 | 33 | 35 | 42 | 49 | 43 | 40 | 39 | 37 | 40 | 43 | 33 | 32 | 41 | 40 | 41 | 44 | 43 | 42 | 42 |
| Baker Butte SNOTEL | 7300 | 45.1 | 44.4 | 39.2 | 39.9 | 32.5 | 30.7 | 41.4 | 44.6 | 45.5 | 45.0 | 44.8 | 46.8 | 49.5 | 52.0 | 53.2 | 50.5 | 55.2 | 52.7 | 50.9 | 55.2 | 58.5 | 55.4 | 51.3 | 55.2 | 55.8 | 56.1 | 56.7 | 59.2 | 61.0 | 57.6 |
| Baldy SNOTEL | 9125 | 34.7 | 28.8 | 38.1 | 40.3 | 31.6 | 23.9 | 22.1 | 30.2 | 30.7 | 28.8 | 32.4 | 29.5 | 30.7 | 34.7 | 42.6 | 38.1 | 39.6 | 41.2 | 37.2 | 40.1 | 38.5 | 41.0 | 40.5 | 38.3 | 38.7 | 41.4 | 51.1 | 46.0 | 43.2 | 46.0 |
| Beaver Head SNOTEL | 7990 | 34.0 | 28.6 | 34.7 | 32.0 | 24.4 | 22.3 | 20.7 | 27.0 | 28.8 | 28.8 | 28.2 | 27.7 | 30.7 | 35.4 | 38.8 | 38.3 | 40.8 | 46.2 | 41.0 | 40.6 | 40.1 | 38.3 | 36.3 | 39.6 | 38.7 | 40.1 | 43.2 | 43.3 | 44.4 | 43.7 |
| Blue Ridge Ranger Station | 6880 | 37 | 45 | 43 | 42 | MM | MM | 28 | 42 | 38 | 33 | 35 | MM | MM | 38 | 48 | 53 | 50 | 48 | MM | MM | 46 | 40 | 49 | 51 | 52 | MM | MM | 52 | 60 | MM |
| Coronado Trail SNOTEL | 8400 | 33.6 | 28.2 | 33.3 | 32.5 | 27.3 | 23.7 | 23.0 | 29.5 | 30.2 | 28.8 | 29.5 | 29.8 | 32.7 | 37.0 | 37.9 | 37.0 | 40.3 | 44.1 | 39.4 | 41.7 | 40.5 | 36.9 | 36.0 | 40.8 | 41.2 | 42.3 | 42.8 | 43.7 | 45.0 | 45.0 |
| Flagstaff Pulliam Airport | 7003 | 40 | 38 | 41 | 29 | 27 | 29 | 31 | 33 | 33 | 31 | 31 | 40 | 36 | 43 | 53 | 48 | 42 | 41 | 44 | 43 | 43 | 38 | 40 | 47 | 50 | 48 | 47 | 48 | 51 | 51 |
| Flagstaff 4SW | 7122 | 28 | 36 | 36 | 36 | 24 | 26 | 25 | 32 | 27 | 25 | 27 | 31 | 30 | 37 | 45 | 42 | 39 | 35 | 32 | 36 | 35 | 42 | 35 | 42 | 41 | 45 | 45 | 42 | 43 | 43 |
| Fort Valley | 7347 | 27 | MM | MM | 30 | 29 | 26 | 26 | 28 | 27 | 27 | 27 | 34 | 37 | 38 | 47 | 43 | 38 | 38 | 36 | 38 | 41 | 33 | 32 | 41 | 42 | 41 | 42 | 43 | 45 | 43 |
| Fry SNOTEL | 7200 | 32.7 | 36.0 | 39.2 | 37.6 | 25.5 | 27.3 | 28.6 | 27.5 | 32.2 | 31.1 | 30.6 | 29.8 | 35.8 | 37.6 | 44.2 | 48.6 | 47.5 | 43.0 | 41.9 | 39.2 | 42.8 | 43.5 | 35.1 | 36.3 | 43.9 | 48.6 | 45.9 | 46.8 | 45.5 | 48.6 |
| Grand Canyon | 6790 | 34 | 34 | 38 | 29 | 32 | 33 | 32 | 35 | 33 | 35 | 38 | 38 | 42 | 63 | 45 | 48 | 50 | 46 | 43 | 47 | 55 | 42 | 40 | 46 | 45 | 47 | 45 | 45 | 52 | 50 |
| Greer | 8275 | 34 | 39 | 44 | 44 | 27 | 30 | 35 | 36 | 36 | 34 | 34 | 41 | 42 | 45 | 46 | 46 | 42 | 47 | 40 | 44 | 42 | 42 | 43 | 44 | 45 | 50 | 51 | 49 | 51 | 51 |
| Hannagan Meadow SNOTEL | 9020 | 36.3 | 34.0 | 35.4 | 29.5 | 23.5 | 22.1 | 19.4 | 27.9 | 27.9 | 27.1 | 28.9 | 26.4 | 31.3 | 34.5 | 39.2 | 37.6 | 39.6 | 43.9 | 38.3 | 39.6 | 38.8 | 38.5 | 37.2 | 40.6 | 39.2 | 41.7 | 47.8 | 47.1 | 46.6 | 48.0 |
| Happy Jack | 7480 | 30 | 37 | 35 | 34 | 23 | MM | 26 | 33 | 29 | 28 | 31 | 37 | 38 | MM | MM | 41 | 46 | 41 | 43 | MM | 44 | 37 | 44 | 47 | 44 | 46 | MM | 51 | 49 | 50 |
| Heber | 6590 | 38 | 42 | 47 | 44 | MM | MM | 28 | 44 | 34 | 38 | 33 | MM | MM | 42 | 56 | 49 | 52 | 53 | MM | MM | 49 | 42 | 46 | 50 | 46 | MM | MM | 47 | 56 | 56 |
| Heber SNOTEL | 7640 | 48.4 | 48.0 | 44.6 | 43.9 | 28.8 | 39.4 | 48.4 | 50.0 | 49.5 | 49.6 | 46.9 | 48.4 | 47.3 | 52.0 | 51.8 | 52.2 | 50.5 | 50.0 | 49.6 | 52.2 | 54.0 | 52.9 | 52.7 | 53.8 | 53.8 | 56.1 | 60.1 | 57.6 | 58.6 | 58.8 |
| Maverick Fork SNOTEL | 9200 | 33.3 | 29.7 | 32.9 | 38.7 | 29.7 | 22.3 | 20.7 | 26.6 | 31.3 | 28.4 | 30.9 | 29.1 | 31.1 | 34.2 | 39.0 | 37.9 | 40.5 | 39.6 | 36.3 | 39.6 | 37.4 | 40.8 | 35.1 | 39.9 | 39.6 | 41.4 | 42.4 | 44.2 | 41.7 | 46.0 |
| McNary 2N | 7340 | 37 | 41 | 45 | 43 | 27 | 35 | 37 | 41 | 40 | 39 | 41 | 44 | 46 | 48 | 48 | 49 | 49 | 45 | 47 | 48 | 49 | 48 | 47 | 49 | 50 | 52 | 54 | 55 | 53 | 53 |
| Mormon Mountain SNOTEL | 7500 | 37.9 | 35.1 | 36.1 | 37.8 | 25.5 | 25.0 | 30.7 | 36.1 | 39.6 | 35.1 | 35.8 | 34.3 | 38.8 | 41.0 | 46.0 | 52.3 | 48.0 | 46.9 | 43.5 | 42.8 | 45.1 | 47.3 | 41.4 | 41.5 | 46.8 | 47.1 | 50.4 | 53.1 | 48.6 | 47.8 |
| Munds Park | 6470 | 31 | 38 | MM | MM | MM | MM | 25 | 31 | 30 | 30 | 31 | 35 | 36 | 42 | 45 | 48 | 42 | 42 | 41 | 42 | 45 | 36 | 37 | 43 | 43 | 47 | 47 | 47 | 45 | 44 |
| Payson | 4908 | 42 | 42 | 42 | 49 | 33 | 39 | 40 | 49 | 42 | 42 | 44 | 51 | 48 | 56 | 53 | 53 | 54 | 52 | 52 | 55 | 67 | 52 | 52 | 56 | 56 | 58 | 68 | 61 | 60 | 58 |
| Promontory SNOTEL | 7930 | 41.9 | 42.6 | 40.6 | 36.1 | 30.2 | 30.4 | 41.7 | 42.8 | 43.5 | 42.4 | 41.7 | 45.3 | 51.1 | 54.3 | 50.9 | 50.5 | 50.9 | 49.5 | 48.9 | 54.3 | 55.0 | 52.3 | 51.3 | 54.1 | 55.8 | 55.0 | 58.6 | 57.0 | 59.2 | 56.5 |
| Show Low | 6411 | 50 | 49 | 49 | 49 | 33 | 35 | 39 | 46 | 47 | 49 | 47 | 48 | 49 | 54 | 57 | 58 | 58 | 53 | 54 | 55 | 58 | 55 | 54 | 53 | 57 | 57 | 58 | 58 | 59 | 65 |
| Snowflake | 5640 | 44 | 43 | 50 | 52 | 35 | 38 | 41 | 39 | 41 | 38 | 41 | 45 | 46 | 50 | 57 | 56 | 58 | 53 | 52 | 57 | 60 | 50 | 52 | 57 | 51 | 56 | 59 | 60 | 61 | 59 |
| Snowslide Canyon SNOTEL | 9730 | 38.8 | 37.8 | 31.8 | 31.6 | 21.9 | 26.1 | 27.5 | 39.9 | 41.7 | 40.3 | 33.8 | 31.3 | 34.3 | 34.7 | 39.4 | 43.7 | 43.0 | 39.6 | 38.3 | 40.5 | 41.2 | 43.9 | 42.4 | 42.6 | 41.4 | 51.6 | 48.7 | 51.1 | 51.1 | 50.9 |
| Springerville | 6998 | 35 | 63 | 47 | 47 | 24 | 25 | 37 | 33 | 34 | 29 | 29 | 34 | 36 | 45 | 47 | 46 | 54 | 42 | 48 | 41 | 55 | 41 | 45 | 42 | 47 | 50 | 49 | 49 | 46 | 50 |
| Saint Johns | 5733 | 50 | 45 | 43 | 40 | 36 | MM | 42 | 44 | 48 | 45 | 43 | 45 | 48 | 53 | 56 | 52 | 57 | 50 | 47 | 52 | 56 | 54 | 53 | 57 | 58 | 58 | 62 | 62 | 60 | 66 |
| Sunrise Mountain | 9370 | 24 | 33 | 34 | 25 | 15 | 22 | 34 | 23 | 21 | MM | MM | 21 | 35 | 32 | 35 | 35 | 32 | 35 | 32 | 35 | 30 | 32 | 32 | 32 | 44 | 42 | 36 | 38 | 39 | 38 |
| Sunset Crater Nat'l Mon. | 6980 | 37 | 43 | 41 | 40 | 26 | 28 | 27 | 46 | 34 | 48 | 29 | 35 | 32 | 40 | 50 | 46 | 43 | 38 | 42 | 39 | 50 | 45 | 34 | 41 | 52 | 65 | 64 | 51 | 45 | 48 |
| Williams | 6750 | 47 | 41 | 42 | 37 | 32 | 37 | 37 | 47 | 41 | 44 | 40 | 47 | 47 | 48 | 55 | 58 | 53 | 50 | 50 | 50 | 58 | 45 | 48 | 52 | 59 | 59 | 64 | 59 | 53 | 59 |
| White Horse Lake SNOTEL | 7180 | 39.6 | 39.6 | 38.3 | 37.9 | 29.5 | 29.7 | 32.2 | 34.2 | 41.0 | 34.9 | 36.3 | 35.4 | 43.5 | 43.3 | 49.8 | 50.5 | 51.1 | 46.0 | 42.8 | 45.9 | 51.3 | 48.0 | 39.9 | 44.4 | 47.3 | 50.9 | 51.1 | 50.9 | 52.5 | 50.2 |
| Wildcat SNOTEL | 7850 | 33.1 | 27.5 | 32.0 | 30.6 | 24.1 | 21.2 | 20.8 | 27.5 | 28.9 | 28.6 | 28.2 | 27.7 | 30.0 | 34.7 | 38.8 | 36.9 | 42.1 | 45.9 | 40.5 | 42.6 | 40.6 | 39.6 | 37.4 | 41.5 | 37.2 | 40.1 | 43.0 | 45.1 | 43.9 | 44.8 |
| Workman Creek SNOTEL | 6900 | 46.8 | 43.5 | 44.2 | 41.4 | 32.5 | 31.5 | 40.1 | 46.4 | 47.5 | 44.6 | 45.1 | 46.8 | 48.7 | 52.7 | 53.1 | 53.6 | 54.7 | 54.7 | 47.5 | 55.6 | 52.5 | 52.9 | 51.6 | 54 | 57 | 57.7 | 57.4 | 58.3 | 58.8 | 58.1 |
| **AVG** | | 37.1 | 38.7 | 40.0 | 37.6 | 27.7 | 28.7 | 31.3 | 36.1 | 35.6 | 35.2 | 34.8 | 36.9 | 39.0 | 43.2 | 47.0 | 46.6 | 46.9 | 45.1 | 43.0 | 44.8 | 47.3 | 43.4 | 42.5 | 45.8 | 47.2 | 49.2 | 50.9 | 50.2 | 50.5 | 50.7 |
| **MIN** | | 24.0 | 27.5 | 31.8 | 25.0 | 15.0 | 21.2 | 19.4 | 23.0 | 21.0 | 25.0 | 27.0 | 21.0 | 30.0 | 32.0 | 35.0 | 35.0 | 32.0 | 35.0 | 32.0 | 35.0 | 30.0 | 32.0 | 32.0 | 32.0 | 37.2 | 40.1 | 36.0 | 38.0 | 39.0 | 38.0 |
| **MAX** | | 50.0 | 63.0 | 50.0 | 52.0 | 36.0 | 39.4 | 48.4 | 50.0 | 49.5 | 49.6 | 47.0 | 51.0 | 51.1 | 63.0 | 57.0 | 58.0 | 58.0 | 54.7 | 54.0 | 57.0 | 67.0 | 55.4 | 54.0 | 57.0 | 59.0 | 65.0 | 68.0 | 62.0 | 61.0 | 66.0 |
| **STDEV** | | 6.62 | 7.35 | 5.12 | 6.81 | 4.67 | 5.35 | 7.48 | 7.66 | 7.35 | 7.43 | 6.32 | 7.78 | 6.91 | 7.99 | 6.53 | 6.38 | 6.72 | 5.47 | 5.82 | 6.67 | 8.32 | 6.69 | 7.04 | 6.55 | 6.54 | 6.92 | 7.82 | 6.31 | 6.62 | 6.66 |

MM – Indicates missing records

Source: NRCS, NCDC, WRCC, NWS

**Appendix B**. Field sampling record from Snowslide SNOTEL site.
POTR = Aspen; PIEN = Engelmann spruce; ALBA = Corkbark fir

| FIELD DATA FOR FROST RING SAMPLING | | | | | | |
|---|---|---|---|---|---|---|
| DATE | ID | TREE TYPE | TRANS | CIRCUM (CM) | DIA (CM) | CORE HGT (CM) |
| 7-Sep-10 | 01 | POTR | NW | 114.3 | 36.4 | 86.4 |
| 7-Sep-10 | 02 | POTR | NW | 114.3 | 36.4 | 58.4 |
| 7-Sep-10 | 03 | POTR | NW | 104.1 | 33.1 | 55.9 |
| 7-Sep-10 | 04 | POTR | NW | 104.1 | 33.1 | 63.5 |
| 7-Sep-10 | 05 | PIEN | NW | 111.8 | 35.6 | 55.9 |
| 7-Sep-10 | 06 | PIEN | NW | 111.8 | 35.6 | 27.9 |
| 7-Sep-10 | 07 | PIEN | NW | 53.3 | 17.0 | 27.9 |
| 7-Sep-10 | 08 | PIEN | NW | 53.3 | 17.0 | 58.4 |
| 7-Sep-10 | 09 | ABLA | NW | 129.5 | 41.2 | 55.9 |
| 7-Sep-10 | 10 | ABLA | NW | 129.5 | 41.2 | 38.1 |
| 7-Sep-10 | 11 | ABLA | NW | 101.6 | 32.3 | 38.1 |
| 7-Sep-10 | 12 | ABLA | NW | 101.6 | 32.3 | 55.9 |
| 7-Sep-10 | 13 | PIEN | NE | 66.0 | 21.0 | 88.9 |
| 7-Sep-10 | 14 | PIEN | NE | 66.0 | 21.0 | 38.1 |
| 7-Sep-10 | 15 | POTR | NE | 127.0 | 40.4 | 55.9 |
| 7-Sep-10 | 16 | POTR | NE | 127.0 | 40.4 | 76.2 |
| 7-Sep-10 | 17 | POTR | NE | 106.7 | 34.0 | 50.8 |
| 7-Sep-10 | 18 | POTR | NE | 106.7 | 34.0 | 33.0 |
| 7-Sep-10 | 19 | PIEN | NE | 129.5 | 41.2 | 58.4 |
| 7-Sep-10 | 20 | PIEN | NE | 129.5 | 41.2 | 45.7 |
| 7-Sep-10 | 21 | ABLA | NE | 132.1 | 42.0 | 81.3 |
| 7-Sep-10 | 22 | ABLA | NE | 132.1 | 42.0 | 59.7 |
| 7-Sep-10 | 23 | ABLA | NE | 116.8 | 37.2 | 71.1 |
| 7-Sep-10 | 24 | ABLA | NE | 116.8 | 37.2 | 66.0 |
| 7-Sep-10 | 25 | PIEN | SW | 39.4 | 12.5 | 40.6 |
| 7-Sep-10 | 26 | PIEN | SW | 39.4 | 12.5 | 27.9 |
| 7-Sep-10 | 27 | PIEN | SW | 73.7 | 23.4 | 50.8 |
| 7-Sep-10 | 28 | PIEN | SW | 73.7 | 23.4 | 38.1 |
| 7-Sep-10 | 29 | ABLA | SW | 115.6 | 36.8 | 53.3 |
| 7-Sep-10 | 30 | ABLA | SW | 115.6 | 36.8 | 27.9 |
| 7-Sep-10 | 31 | PIEN | SW | 45.7 | 14.6 | 61.0 |
| 7-Sep-10 | 32 | PIEN | SW | 45.7 | 14.6 | 43.2 |
| 7-Sep-10 | 33 | POTR | SW | 115.6 | 36.8 | 63.5 |
| 7-Sep-10 | 34 | POTR | SW | 115.6 | 36.8 | 55.9 |
| 7-Sep-10 | 35 | POTR | SW | 76.2 | 24.3 | 66.0 |
| 7-Sep-10 | 36 | POTR | SW | 76.2 | 24.3 | 88.9 |
| 7-Sep-10 | 37 | PIEN | SE | 67.3 | 21.4 | 30.5 |
| 7-Sep-10 | 38 | PIEN | SE | 67.3 | 21.4 | 48.3 |
| 7-Sep-10 | 39 | PIEN | SE | 66.0 | 21.0 | 30.5 |
| 7-Sep-10 | 40 | PIEN | SE | 66.0 | 21.0 | 30.5 |
| 7-Sep-10 | 41 | POTR | SE | 88.9 | 28.3 | 78.7 |
| 7-Sep-10 | 42 | POTR | SE | 88.9 | 28.3 | 38.1 |
| 7-Sep-10 | 43 | POTR | SE | 76.2 | 24.3 | 50.8 |
| 7-Sep-10 | 44 | POTR | SE | 76.2 | 24.3 | 36.8 |
| 7-Sep-10 | 45 | ABLA | SE | 177.8 | 56.6 | 61.0 |
| 7-Sep-10 | 46 | ABLA | SE | 177.8 | 56.6 | 76.2 |
| 7-Sep-10 | 47 | ABLA | SE | 154.9 | 49.3 | 48.3 |
| 7-Sep-10 | 48 | ABLA | SE | 154.9 | 49.3 | 61.0 |

| | | | |
|---|---|---|---|
| **MAX** | **177.8** | **56.6** | **88.9** |
| **MIN** | **39.4** | **12.5** | **27.9** |
| **AVG** | **100.6** | **32.0** | **53.2** |
| **STDEV** | **37.6** | **12.0** | **17.7** |