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Utah State University

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SNOW AVALANCHE DISTURBANCE IN INTERMOUNTAIN SPRUCE-FIR
FORESTS AND IMPLICATIONS FOR THE SPRUCE BARK BEETLE
(COLEOPTERA: SCOLYTIDAE)

by

Elizabeth G. Hebertson

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Ecology

Approved:

David W. Roberts
Major Professor

Barbara J. Bentz
Committee Member

John A. Bissonette
Committee Member

Jesse A. Logan
Committee Member

Richard J. Mueller
Committee Member

Thomas Kent
Dean of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2004

ABSTRACT

Snow Avalanche Disturbance in Intermontane Spruce-Fir Forests and Implications
for the Spruce Bark Beetle (*Conoepinus*, Scolytidae)

by

Elizabeth G. Hebertson, Doctor of Philosophy

Utah State University, 2004

Major Professor: Dr. David W. Roberts
Department: Forest, Range, and Wildlife Resources

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Spruce beetle outbreaks are the primary biotic disturbance affecting forests in the Intermontane spruce-fir zone. Major snow avalanches can produce large quantities of host material for spruce beetle colonization; however, few studies have examined the influence of avalanche disturbance on spruce beetle initiation. The purpose of my research was to investigate potential relationships between these two disturbance agents. In the first study, I used dendro-ecological analyses to date major avalanche years on the Wasatch Plateau in south-central Utah, and then determined what climate factors were associated with avalanche occurrence. The results indicated that mean January snowfall was significantly related to the probability of major avalanche years, although model correlations were extremely low. Potential dating errors, the lack of complete historical climate data, and the absence of snow pack information may have prohibited obtaining higher model correlations. In the second study, I investigated how the seasonal availability of host material influenced spruce beetle brood production. I found that

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significantly fewer mean numbers of spruce beetles were produced in downed spruce felled during August 1997 than from trees felled in April of 1998. More brood adults also were present in, or emerged from the bottom surfaces of sample trees than either unexposed (North, East) or exposed (South, West) bole aspects. These results provided evidence that with greater potential for spruce beetle populations to build in host material produced in the spring, snow avalanche disturbance could contribute to the risk of outbreaks. I constructed snow avalanche and spruce beetle outbreak chronologies from historic documents in the third study, and used classification tree analysis to predict historic spruce beetle outbreaks from major avalanche years and historic climate data. Major snow avalanche years were not identified in this analysis as important for the occurrence of spruce beetle outbreaks. Historic spruce beetle outbreaks, however, were significantly related to generally warm fall and winter temperatures and to drought. These results indicate that climate and other factors not considered in this analysis have a greater influence on spruce beetle epidemiology than the production of host material by snow avalanches.

(171 pages)

DEDICATION

I was inspired to take on this research during the summer of 1992 on a visit to the Wasatch Plateau in south-central Utah. My motivation didn't really arise from a deep desire to understand the tale of my unusual surroundings, the white limestone peaks awash with alpine glow, the battling hummingbirds, or an ill-fated forest. It blossomed as an excited curiosity fed by the incredible passion of my companion on that trip, Mike Jenkins. Mike absolutely loves forces of nature, including wildfires, insect outbreaks, thunderstorms, but especially snow avalanches. He delighted in describing the unpredictability, power, and beauty of these phenomena, the calm before the storm, the precarious balance of stress verses strength, or stability versus volatility. The fever struck me one balmy August afternoon after scrambling up a steep avalanche path to sample trees damaged by large slides. Upon determining the age of scar samples we had collected, answers to questions, more questions and countless stories began to unfold. Feelings of elation, satisfaction, accomplishment, and possibility suddenly replaced thoughts of burning lungs, sweat, hunger, and fatigue. These moments are the simple but real reward of any scientific endeavor and I knew a new road of exciting discoveries lay ahead of me. Garnering the full breadth of Mike's knowledge through the years would require trailing him up into the steeps, through thickets, over rock and ash, across wind blown ridges, wherever questions and answers could be found, during summer and winter, in rain, snow or shine. And so, this work evolved from numerous discussions while hiking through spruce beetle infested forests, coring trees high in avalanche starting zones, examining layers deep within a snow pit, fixing instruments at the Beaver

Mountain weather station, creating fuel breaks, or tracking up a powder slope. Although the road was rough at times and answers never came easy, the educational experience was well worth the ride. Mike has been a great teacher, mentor, and friend. This work belongs to him.

Dr. Michael Jenkins provided the expertise, inspiration, and support for this research. He fostered an environment that not only gave me the necessary academic countless opportunities that greatly served to enrich and broaden our education.

Dr. Michael Jenkins, Dr. James Kennedy, Dr. Charles Day, Superior College Natural Resources professors, staff members, and students gave me the opportunity to serve as a teaching assistant for the Summer Camp program from 1992-1998. This was truly a wonderful time. I was privileged to share in the rich history of the Camp, work with such inspiring people, and be a part of many memorable lessons.

Leon LaMadeleine, John Anhalt, Alan Dymerski, John Guyon, Lee Peterson, Valerie DeBhader, Lata Dunning, and most notably Steve Munson of the USDA Forest Service, Forest Health Protection, Oyster Field Office stood by me through perhaps the most trying phases of this work. Their undying patience and faith gave me the strength and resolve to keep pushing ahead in spite of the many difficulties I encountered.

I am indebted to Steve and Diane Cote of the San Pete Ranger District, Manti-LaSal National Forest for their heroic efforts in getting me through several field seasons away from home. They willingly offered me their help, friendship, and hospitality.

Karlton Moss, San Pete Ranger District, and Robert Sanchez, Richfield Ranger District, Fishlake National Forest offered their brawn and sawyer expertise in the field on several occasions.

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Completing this research would not have been possible without the support, assistance, patience, and encouragement of a phenomenal group of individuals to whom I will be forever thankful. Dr. Michael Jenkins provided the expertise, inspiration, and motivation for this research. He fostered an environment that not only gave me, but his other students countless opportunities that greatly served to enrich and broaden our educations.

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David Turner, USDA Forest Service, Rocky Mountain Research Station, and Susan Durham patiently guided me through the statistical rigors of this research. I would have been lost in a world of frustration without their assistance, explanations, interpretations, and understanding smiles.

Others deserving recognition and thanks include Sam Satterwhite, Satterwhite Log Homes, Gunnison, UT, who provided spruce logs used in this research; and my good friend Wanda Lindquist who provided encouragement, laughs, and much needed computer and graphics assistance. Graphics were also created by Jeanne Zschnecker, USDA Forest, Intermountain Region, Engineering Staff.

I deeply appreciate the members of my committee including David Roberts, Jesse Logan, Barbara Bentz, John Bissonette, and Richard Mueller for their patience, advice, and understanding in the final hours of this work. They are an exemplary group of colleagues and friends.

I have been blessed to share my life with Wayne and Joan Hebertson, John and Julie Hebertson, Andrea and John Luddington, Peter Hebertson and Shelly Jensen, and Aaron, Kalie, Scott, Jesse, Ashlee, Justin, Hannah, Ryan, and Nicholas, my family. I cannot express in words how you make me feel. Because of you, my life has meaning.

Elizabeth G. Hebertson

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CHAPTER 1

INTRODUCTION AND REVIEW OF THE LITERATURE

Introduction

Snow avalanches naturally occur in mountainous terrain of the Intermountain region. Like other disturbances, snow avalanches vary in kind, frequency, magnitude, intensity, and severity (Pickett and White 1985). Interactions between the local topography, weather, and the existing snow pack structure largely influence these parameters (Fredston and Fesler 1999). Rarely, unique combinations of terrain, weather, and the mountain snow pack result in major avalanches and/or widespread avalanche cycles (Roch 1949; Armstrong and Armstrong 1987; Birkeland and Mock 2001; Hebertson and Jenkins, Chapter 2). Because winters in the Intermountain region often embody characteristics of both maritime and continental climates, understanding the mechanisms of major avalanche occurrence in the Intermountain region is particularly difficult (Roch 1949; LaChapelle 1966; Schaerer 1986; Armstrong and Armstrong 1987; Changnon 1993; Mock and Birkeland 2000). The lack of remote weather stations, complete and reliable climate records, available snow pack data, and historical documentation have also limited investigations of major avalanche occurrence (Mock and Kay 1992; Mock and Birkeland 2000).

Major avalanches have great human and ecological significance. The direct impacts of major avalanches include the destruction of property, structural damage, forest restoration, interruption of transportation corridors, and the loss of human life (Leaf and Martinelli 1977; Bowles and Sandahl 1987; Voight 1990; Mears 1992; McClung and Schaerer 1993; Giraud 1994; Atkins and Williams 2000; Jöhanesson and Arnalds 2002).

Comprehensive analyses of the direct economic impacts associated with avalanches in the United States has not been conducted; however, losses in Canada were approximated at C\$40M per year in the 1990's (Jamieson 2003). Estimates of total economic impacts would be far greater with the inclusion of indirect costs such as reduced real estate values, decreased productivity, limited recreational access, mitigation, litigation, and forest damage (Voight 1990; Kattelmann 1996; Jöhanncsson and Arnald 2002).

Snow avalanches are a dominant influence on the assemblage and distribution of plant species within affected locations and create a fragmented vegetation mosaic (Smith 1974; Cushman 1976; Butler 1979; Malanson and Butler 1984; Patten and Knight 1994). Avalanche damage may predispose injured trees to insects and disease (Miller et al. 1979; Gregory et al. 1991; Jenkins et al. 1998). Avalanche paths create natural firebreaks altering the spread of fire (Veblen et al. 1994). Woody avalanche debris increases fuel loads resulting in local fire hazards, and provides habitat for sensitive and endangered wildlife species (Dueser and Shugart 1978; Miller et al. 1979; Bartels et al. 1985; Taylor and Fonda 1990; Hecnar 1994; Veblen et al. 1994; Butts 1997; Ruggiero et al. 1998). Debris deposited in streams can also improve or adversely impact fisheries (Bilby and Likens 1980; Dudley and Anderson 1982; Sedell et al. 1988).

Another consequence of major avalanches in the Intermountain region is the production of suitable host material for the Engelmann spruce beetle (*Dendroctonus rufipennis* Kirby (Coleoptera: Scolytidae)). The spruce beetle is a native insect of spruce-fir forests in the Intermountain Rocky Mountains. Endemic populations of spruce beetles typically inhabit downed spruce, but they will also attack overmature and stressed trees (Dyer and Taylor 1971; Schmid and Frye 1977; Schmid 1981). Although mechanisms

responsible for triggering spruce beetle outbreaks are not well understood, epidemic populations can cause extensive mortality of larger diameter spruce. Since the mid 1980's, spruce beetle outbreaks in south-central and southern Utah have resulted in deaths of over 1 million trees (Matthews et al. 2002). The mortality of canopy trees modifies stand structure and species composition in affected forests (Baker and Veblen 1990; Veblen et al. 1991*b*; Veblen et al. 1994; Jenkins et al. 1998). Spruce beetle mortality also increases fuel loads and stand-replacing fires are possible with appropriate fire weather conditions (Bessie and Johnson 1995; Jenkins et al. 1998).

Most documented spruce beetle outbreaks have followed extensive blow down and logging disturbances that created large amounts of downed spruce (Miller 1970; Schmid and Hinds 1974; Schmid and Frye 1977; Werner et al. 1977; Schmid 1981). Not all disturbance events, however, result in the eruption of spruce beetle populations. Stand conditions, host vigor and climate are all known to influence the success of spruce beetle attack and rates of spread through living stands (Schmid and Frye 1976; Hard 1985; Holsten et al. 1999; Hansen et al. 2001). The suitability of available down host material may also limit the ability for spruce beetle populations to build.

In contrast to other disturbances, snow avalanches may produce host material at a time and in an environment optimal for brood production. Major avalanches create woody debris by uprooting trees or breaking their main stems and branches (Burrow and Burrows 1976). This woody debris might provide a local source of host material for spruce beetle habitation. Widespread avalanche cycles, such as those that occurred throughout the Intermountain region during the early to mid 1980's (Birkeland and Mock 2001; Hebertson and Jenkins, Chapter 2) result in a significant amount of downed host

material across the landscape (Figure 1.1). As avalanches lose momentum, they deposit snow and woody debris in the lower portion of the runout zone (McClung and Schaerer 1993). Snowmelt exposes the host material just prior to, or coincident with the onset of the spruce beetle flight in the spring. Shade and moisture provided by piled debris and snow tends to keep the condition of host material favorable for colonization and brood production. These conditions may also deter competing organisms from initially colonizing the resource. Additionally, stands near avalanche paths are often dense and comprised of a high percentage (> 50%) of large diameter spruce (> 40 cm diameter at breast height) (Alexander 1987; Long and Barrett 1994) making them conducive to spruce beetle attack and population spread. Stress associated with avalanche damage and subsequent infection by diseases further increases the susceptibility of living trees to spruce beetle attack (Wargo and Harrington 1991).

As a result, major avalanches might have a role equal to wind and other disturbances known to influence the intensification and spread of spruce beetle populations. Few studies, however, have examined the influence of snow avalanche disturbance on spruce beetle population dynamics. More importantly, understanding the role of each agent within a disturbance regime has become vital to maintaining forest ecosystems within a desired range of proper functioning condition and consequently to overall forest health.

The primary objective of this research was to investigate historic climate factors associated with major avalanche years in the Intermountain region and explore links between major avalanches and the development of spruce beetle outbreaks. The specific objectives were to:

- 1) Utilize dendro-ecological methods to date major avalanche years in several paths located on the Wasatch Plateau in south-central Utah, and examine historic climate factors that contributed to major avalanche years.
- 2) Determine if the seasonal availability of downed host material significantly affected its suitability for spruce beetle production.
- 3) Explore the relationship between major avalanche years and historic spruce beetle outbreaks in northern and south-central Utah and western Colorado.



Figure 1.1. Snow avalanche debris containing downed host material

Literature Review

The Role of Disturbances in Intermountain Spruce-Fir Forests

The spruce-fir zone is widely distributed throughout the central and southern Rocky Mountains, generally occurring at elevations above 2800 m (Habeck and Mutch 1973; Alexander 1987; Long and Barrett 1994). A cool, humid climate characterizes this zone with temperature extremes ranging from - 46° C to above 32° C with a relatively short frost-free period. The spruce-fir zone receives on average 60 cm of precipitation annually, falling primarily in the form of snow.

Engelmann spruce (*Picea engelmannii* Parry ex Engel.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) primarily comprise forests of the Rocky Mountain spruce-fir zone (Habeck and Mutch 1973; Whipple and Dix 1979; Alexander 1987; Long and Barrett 1994). These two species coexist as dominants in climax communities forming extensive stands on all but the most extreme sites (Whipple and Dix 1979; Alexander 1987; Peet et al. 1988; Long and Barrett 1994). Lodgepole pine (*Pinus contorta* Dougl. ex Loud.) and aspen (*Populus tremuloides* Michx) (Alexander 1987) may occur with Englemann spruce and subalpine fir at higher elevations, or in pure stands on more exposed, dry sites at mid-slope positions (Whipple and Dix 1979). Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is a minor component of subalpine forests.

Climatic factors, topography, aspect, and moisture availability greatly influence the distribution of tree species within the spruce-fir zone (Habeck and Mutch 1973; Shea 1985; Long and Barrett 1994). Both Engelmann spruce and subalpine fir have low tolerance to high temperatures and deficient moisture at low elevations, which tends to

limit their distribution to the cool, humid environments that characterize high elevation sites (Alexander 1987). At the upper-elevational limits of spruce and subalpine fir, forests become discontinuous, and these two species often grow in clumps, or small patches within subalpine meadows (Shea 1985; Alexander 1987; Long and Barrett 1994). On exposed sites at timberline, they may form krummholz (Harlow et al. 1979; Long and Barrett 1994). Spruce-fir stands may also occur at lower elevations on north-facing slopes, in cold pockets along streams, and valley bottoms (Alexander 1987).

Natural disturbances also have an important role in contributing to the structure and composition of vegetation in the spruce-fir zone (Habeck and Mutch 1973; Oliver 1981; Peet et al. 1988; Veblen et al. 1991a; Takahashi 1994). Disturbances are often catastrophic events that originate in the physical environment and cause abrupt changes in plant communities (White 1979). Within given landscapes, however, disturbances may vary in kind, as well as in frequency, predictability, and magnitude resulting in a broad range of vegetative responses (White 1979). For example, major disturbances such as crown fires, control the availability of sites for the initiation of new stands by killing the majority of living tree stems and exposing mineral soil (White 1979; Oliver 1981). Similar-scale canopy disturbances including insect outbreaks and blowdown are selective mortality agents that do not consume biomass or result in as much soil exposure (Veblen et al. 1991a). These kinds of disturbances serve to reduce competition and increase nutrient availability resulting in the accelerated growth of understory plants and subcanopy trees (Levin and Paine 1974; Veblen et al. 1991a). Although seed sources may be available, seedling establishment may not be successful unless an additional disturbance such as fire follows (Aplet et al. 1988; Veblen et al. 1991a; Lertzman 1992).

Relatively large landslides, mudflows, severe soil erosion, and snow avalanches may also remove, or uproot mature trees creating sites for the establishment of new seedlings (Oliver 1981; Romme 1982; Veblen et al. 1991a). Minor disturbances commonly occur in subalpine forests and result in partial removal of the overstory, or the death of individual trees (Oliver 1981; White et al. 1984). Examples of minor disturbances include surface fires, lightning strikes, snow avalanches, insects, and diseases that create gaps in the canopy allowing the recruitment of subcanopy trees into the main canopy (Oliver 1981; White et al. 1984; Aplet et al. 1988; Veblen et al. 1991a). Disturbances of any scale may eliminate seed sources of species thus determining the species availability for establishment (Veblen et al. 1991a).

Another key concept to understanding the role of natural disturbances in forest ecosystems is that vegetative patterns and plant dynamics are primarily a function of the entire disturbance regime operating in a given landscape, as well as topography, soil, and other site characteristics (White 1979). Additionally, the nature of disturbances in a given landscape is governed by endogenous factors in the plant community (White 1979). Thus, explanations of vegetative patterns and plant dynamics in forest ecosystems should include the effects of multiple disturbances, the inter-relationship between these disturbances, and how the state of the vegetation influences and is influenced by natural disturbances.

Important Agents of Disturbance

In the spruce-fir zone of the Intermountain and southern Rocky Mountains, fire, the spruce beetle (*Dendroctonus rufipennis* Kirby (Coleoptera: Scolytidae), windfall, and

snow avalanches are reportedly the most important agents of disturbance (Baker and Veblen 1990; Veblen et al. 1991*b*; Veblen et al. 1994; Jenkins et al. 1998; Bebi et al. 2003). The effect of each agent on stand development has been studied intensively (Habeck and Mutch 1973; Werner et al. 1977; Romme and Knight 1981; Alexander 1987; Peet et al. 1988; Aplet et al. 1988; Baker and Veblen 1990; Veblen et al. 1991*b*). Less is known about potential interactions among these agents and their combined effect on forest vegetation.

Fire. Traditionally, fire is regarded as the most important mechanism that drives vegetation dynamics in western forest ecosystems (Heinselman 1973). Following a stand replacing fire in spruce-fir forests, the early successional communities that dominate burned sites include grasses, shrubs, and forbs, lodgepole pine, aspen, and Douglas-fir depending upon the habitat type and the species availability (Romme 1982; Veblen et al. 1991*a*; Long and Barrett 1994). With the presence of adequate moisture and an abundant seed source, Engelmann spruce may germinate heavily on burned sites becoming a dominant pioneer species (Habeck and Mutch 1973; Rebertus et al. 1992). Subalpine fir may also regenerate successfully, although it has low initial colonization rates (Loope and Gruell 1973; Veblen et al. 1991*a*). In the absence of further catastrophic disturbance, the more shade tolerant spruce and fir gradually replace seral communities (Parker and Peet 1984; Veblen et al. 1991*a*; Long and Barrett 1994). As the canopy begins to thin, the growth of fir accelerates, while remnants of the initial colonizing populations of spruce and lodgepole pine typically do not show accelerated growth rates (Veblen et al. 1991*a*). Seral species often persist within spruce-fir forests due to slow rates of succession and recurring fires (Habeck and Mutch 1973; Long and Barrett 1994). In mature stands, subalpine fir experiences a higher

rate of windthrow, which is consistent with its shorter life span and its susceptibility to root disease (Veblen 1986a; Veblen et al. 1989). However, because subalpine fir regeneration comprises a larger portion of the replacement trees, it is more likely to be recruited into the tree canopy (Veblen 1986b; Veblen et al. 1991a). On exceptionally harsh sites, seral pines or aspen may form self-replacing stands (Veblen et al. 1989).

Subalpine forests have low frequencies of stand replacing fires resulting from the rarity of extreme fire weather conditions (Bessie and Johnson 1995; Jenkins et al. 1998). During the approximately 300 years that may elapse between large-scale fire events, stands begin to deteriorate (Alexander 1987). The slow rates of decomposition at high elevations cause fuels to accumulate (Habeck and Mutch 1973; Bradley et al. 1992). These conditions result in the infrequent occurrence of severe, high-intensity fires, especially during drought (Habeck and Mutch 1973). Several other factors contribute to stand-replacing fires. Abundant regeneration in the understory, low tree crowns, and persistent dead branches create fuel ladders that are conducive to crown fires (Bradley et al. 1992). Both Engelmann spruce and subalpine fir have thin bark and shallow root systems making them highly susceptible to damage by fire (Alexander 1987).

Spruce Beetle. The most serious biotic disturbance agent affecting spruce-fir forests is the spruce beetle (Schmid and Frye 1977; Baker and Veblen 1990; Veblen et al. 1994; Holsten et al. 1999). The principal host of the spruce beetle in the Intermountain Rocky Mountains is Engelmann spruce (Schmid and Frye 1977). Spruce beetles infrequently attack blue spruce (*Picea pungens* Engelm.), and during epidemics may kill lodgepole pine (Schmid and Frye 1977) and subalpine fir (Miller 1970). In the Rocky Mountains, large-scale outbreaks cause extensive spruce mortality. However, the death

of individual spruce and small groups of trees also accounts for much loss of timber annually (Schmid and Frye 1977).

Endemic populations of spruce beetles typically inhabit the well-shaded surfaces of downed trees (Schmid and Frye 1977). Beetles may select downed material because snow acts as insulation preventing low temperatures from killing the brood during the winter (McCambridge and Knight 1972; Frye et al. 1974; Schmid 1981). Snow also protects the brood from predation by woodpeckers and squirrels (Knight 1958; Schmid 1981; Werner and Holsten 1985). Most major spruce beetle outbreaks are thought to have originated from timber harvesting or blowdown (Schmid and Frye 1977). Spruce beetle populations can rapidly increase to outbreak levels in downed trees following large wind events, or in logging slash (Miller 1970; Schmid and Hinds 1974; Werner et al. 1977; Schmid 1981). Adult emergence usually begins in May, and with the depletion of available resources spruce beetles may attack live spruce (Schmid and Frye 1977; Furniss and Carolin 1980; Hard 1989).

Female spruce beetles initiate attacks on living spruce, typically selecting stressed, large-diameter trees (Schmid and Frye 1977; Hard 1985). Following successful entry into the host tree, females produce aggregation pheromones that attract males and other females to the host and nearby trees (Schmid and Frye 1977; Hard 1989). Some trees have the ability to resist attack by pitching the beetles out. Mass attacks of beetles, however, can overwhelm even the most resistant trees resulting in mortality (Hard 1989). During prolonged outbreaks, spruce beetles also attack smaller diameter trees (Holsten et al. 1999; Dymerski et al. 2001). In the Rocky Mountains, stands comprised of more than 65% spruce, with basal areas greater than 35 m²/ha, and average stand diameters

exceeding 40 cm are most susceptible to spruce beetle attack (Schmid and Frye 1976). Spruce beetles also appear to favor trees growing in creek bottoms on well-drained sites (Schmid and Frye 1976).

Research examining the physiological defense mechanisms of host trees and forest ecology has provided greater insight into bark beetle, host and drought relationships. Water stress adversely affects tree tissues by compromising or inhibiting important physiological processes including photosynthesis, the movement of gases, the flow of latex and oleoresins and the absorption of water and ions (Kozlowski 1982). In response to drought stress, trees may accumulate solutes such as sugars, amino acids, organic acids and inorganic ions in leaves, inner bark tissues and roots (Raffa et al. 1993). This osmotic adjustment helps maintain turgor pressure allowing for continued, but reduced growth. The increased nutritive value of plant tissues, however, may also facilitate attacks by insects and disease agents (Sharpe et al. 1986). Trees initially respond to bark beetle attack with copious amounts of resin. Resin repels the attacks, interferes with pheromones, impedes gallery construction and suffocates colonizing beetles (Paine et al. 1997). Resin flow, however, depends upon the water condition of the host and the amount of available soil nutrients (Furniss and Orr 1978). Weakened trees may also emit volatile substances that attract beetles (Rudinsky 1966; Nebeker et al. 1993). Furniss and others (1981) also found that the alpha-pinene content in resin varied with the amount oleoresin present in trees depending on their level of water stress. They suggested that bark beetles might use this to sense a tree's moisture condition. Competition for water, light and nutrients with other plants also limits the photosynthetic capacity of trees with more resources allocated for recovery rather than defense against

insects (Christiansen et al. 1987). Overstocked stands, as a consequence, generally experience greater water stress and are more predisposed to bark beetle attack (Edmonds et al. 2000). Water stress will also affect trees in contiguous stands of one species all at once resulting in favorable conditions for the development and spread of bark beetle populations (McMullen and Atkins 1962; Edmonds et al. 2000). Longer periods of atypically warm and dry weather associated with drought often result in prolonged bark beetle flight periods (McMullen and Atkins 1962). Spruce beetle larvae may mature in one year rather than two during exceptionally long, warm periods following peak flight (Dyer 1969; Schmid and Frye 1977; Hansen et al. 2001).

Spruce beetle outbreaks act as the most important disturbance agent in the development of post-fire stands (Baker and Veblen 1990; Veblen et al. 1994; Jenkins et al. 1998). Intense spruce beetle mortality generally modifies stand structure and species composition by removing large, overstory spruce (Schmid and Frye 1977; Romme et al. 1986; Veblen et al. 1991*b*; Jenkins et al. 1998; Eisenhart 1999). Spruce beetles may kill trees individually, or in small groups creating canopy gaps and resulting in a reduction of average spruce age, diameter, and height (Veblen et al. 1991*b*). Stands affected by past beetle outbreak generally have a scarcity of spruce older than 140 years and non-host species are typically stand dominants (Veblen et al. 1994; Jenkins et al. 1998). The lack of bare, mineral soil following beetle disturbance deters the establishment of seedlings (Aplet et al. 1988; Veblen et al. 1991*b*; Lertzman 1992). Advanced subalpine fir and spruce regeneration releases, utilizing available growing space until one or more environmental factors becomes limiting (Peet et al. 1988). High levels of release increases the density of post-outbreak stands (Baker and Veblen 1990) and often results

in the uneven-aged, multi-storied stands (Miller 1970; Long and Barrett 1994).

Mortality caused by spruce beetles also increases fuel loads, and while long fire return intervals characterize the spruce-fir zone, the accumulation of dead woody material over time results in a high fire hazard (Schmid and Frye 1977; Jenkins et al. 1998). Conversely, fire may increase the resistance of spruce-fir forests to spruce beetle attack by eliminating downed spruce debris and by maintaining smaller, younger cohorts of spruce (Veblen et al. 1994; Bebi et al. 2003). Analysis of historic photographs taken between 1873 and 1915 of widespread mortality resulting from both fire and spruce beetle outbreaks in Colorado subalpine forests served to document the interaction between these two disturbance agents (Baker and Veblen 1990). The sequence of disturbance events revealed in these photographs indicated that spruce beetles killed individual spruce, or small patches of trees. Fire subsequently burned part of the beetle-disturbed forest. Following beetle attack and fire, trees may have been more susceptible to windthrow (Baker and Veblen 1990).

Wind. Mature and old growth spruce-fir stands commonly experience wind damage that ranges from individual tree falls to widespread blowdown (White 1979; Veblen 1986a; Alexander 1987). Topography, shallow root system development, and disease all increase a stands' susceptibility to damage by wind (Alexander 1987; Veblen et al. 1994). Ridgetops have the highest risk of wind exposure (Alexander 1987). Other locations at high risk include steep, mid- to upper-slope positions with windward exposures, and unprotected by nearby ridges (Alexander 1987). Wind damage also occurs where winds are funneled through saddles in ridges, and valley bottoms, and along forest edges where exposed trees are particularly prone to windthrow (Alexander 1987).

Windfall can occur during winter months as a result of heavy snowfall combined with high wind speeds (Veblen et al. 1989).

Trees growing on shallow, poorly drained soils, or in dense stands develop shallow root systems. Following any kind of partial cutting, these trees tend to blow over with sudden exposure to wind (Alexander 1987; Long and Barrett 1994). Diseases caused by root rotting and decay fungi predispose both spruce and fir to windthrow (Alexander 1987). Rust diseases including spruce broom rust (*Chrysomyxa arctostaphyli* Diet.) and fir broom rust (*Melampsorella caryophyllacearum* Schroet.) also deform boles increasing an infected trees' susceptibility to windsnap (Alexander 1987).

Windfall generally becomes an important disturbance agent as spruce-fir stands mature (Oliver 1981). The effect of wind disturbance ranges from the simple pruning of branches, to the widespread damage of trees (White 1979). The crowns of larger trees have greater exposure to wind increasing their susceptibility to windthrow (Oliver 1981). Subalpine fir also has a high likelihood of windthrow because of its shallow root system and susceptibility to root disease (Alexander 1987; Veblen et al. 1989).

Like other canopy disturbances, the primary response of vegetation to windthrow is the release of understory vegetation, thus blowdown generally serves to accelerate the rate of successional change from early successional to late successional communities (Veblen et al. 1989). The accumulation of large windthrown trees in the understory and the presence of advanced regeneration make stands susceptible to fire (Heinselman 1973). In stands older than 300 years, the likelihood of a stand-replacing fire increases, as does the probability of an extensive spruce beetle outbreak (Schmid and Frye 1977; Veblen et al. 1991b; Jenkins et al. 1998). Windthrown trees mix the soil and result in pit-

and-mound relief important for seedling establishment (Veblen 1986a; Veblen et al. 1989). They also provide rooting sites for seedlings (White 1979).

Snow Avalanches. Snow avalanches frequently occur in the Intermountain Rocky Mountains. Storms move into the Rocky Mountains from the Pacific Ocean during winter and early spring, carrying large amounts of moisture (Jensen et al. 1990; Barry 1992; Whiteman 2000). As air masses rise over the mountains, moisture within the mass condenses and falls in the form of rain or snow (Jensen et al. 1990; Barry 1992; Whiteman 2000). Snowfall can exceed 800 cm annually with greater snowfall occurring on western, windward slopes (Barry 1992; Whiteman 2000). Avalanche paths are typically concentrated in locations that receive heavy snowfall, and on slope inclines and aspects that will allow an avalanche to release and accelerate (McClung and Schaerer 1993). Wind and local terrain features also influence the probability of avalanching in certain locations (McClung and Schaerer 1993). Snow blown from ridgetops loads lee slopes. Rock outcrops, gullies, notches and trees alter both wind speed and wind direction and subsequently patterns of snow accumulation (McClung and Schaerer 1993).

In winter months, vegetation growing along the flanks and within the runout zone of avalanche paths may experience damage resulting from the impact of snow and debris (Smith 1974; Butler 1979; Malanson and Butler 1984). The type and extent of damage may vary depending upon the geomorphic situation, the size of the avalanche, and the type of snow (Burrows and Burrows 1976). Avalanches are responsible for breaking the main stems and branches of trees, uprooting or tilting trees, and causing severe wounds on the uphill sides of trees (Burrows and Burrows 1976). Fallen and scarred trees within forests surrounding avalanche paths provide evidence of the occurrence of catastrophic

avalanches. Early successional forests or young forests are also indicative of the occurrence of large, infrequent avalanches (Burrows and Burrows 1976; Malanson and Butler 1984; Veblen et al. 1994).

The breakage threshold of woody vegetation primarily depends on plant size (Johnson 1987). Deciduous shrub species, and small trees bend upon impact by snow and debris returning upright when the weight of the snow has been removed (Oliver et al. 1984). Larger-stemmed trees break losing their height advantage over smaller vegetation in locations that experience frequent avalanching (Johnson 1987). In locations with longer avalanche return periods, trees can grow to greater heights shading out smaller woody vegetation (Johnson 1987). Thus, vegetative species present on avalanche paths frequently exhibit elevational zonation with large conifers growing near the lower extent of the runout zone, and with deciduous shrubs and smaller trees occurring further up slope (Butler 1979; Malanson and Butler 1984). Within the starting zone of avalanche paths, frequent avalanche activity often results in matted vegetation (Butler 1985). Large, infrequent avalanche events typically remove overstory trees, but do not destroy advanced regeneration or sprouting vegetative species such as aspen (Oliver et al. 1984). Initially, aspen and other early successional species dominate disturbed paths. However, as the length of time between major avalanche events increases, more shade-tolerant coniferous species gradually invade these stands (Smith 1974; Butler 1979; Malanson and Butler 1984; McClung and Schaerer 1993).

Much research on snow avalanche disturbance has focused on vegetative damage and the response of the plant community (Smith 1974; Cushman 1976; Butler 1979; Butler 1986; Malanson and Butler 1984). Although snow avalanches occur in many

locations with a high degree of certainty and predictability, few studies have attempted to define the role of snow avalanches within the subalpine disturbance regime. In a study of historic disturbances in Colorado, Veblen and others (1994) concluded that severe avalanches may have reduced the ability of forests to carry fire by retarding the growth of sufficient biomass and creating fuel breaks. Veblen and others (1994) investigated spatial relationships between historic spruce beetle outbreaks, fire and snow avalanches in Colorado and concluded that outbreaks were not related to snow avalanche disturbance because spruce growing within avalanche paths were generally too small to support beetle populations. Their study, however, failed to consider the importance of available host material to the population dynamics of the insect. Major avalanches and/or widespread avalanche cycles can result in an extraordinary amount of woody host material. The season when host material becomes available may relate to its suitability for spruce beetle colonization and brood survival. The host material may also be produced in an environment optimal for spruce beetle production. Additionally, stands near avalanche paths are often dense and comprised of a high percentage (> 50%) of large diameter spruce (> 40 cm diameter at breast height) (Alexander 1987; Long and Barrett 1994) making them conducive to spruce beetle attack and population spread. Finally, stress associated with avalanche damage and subsequent infection by diseases may further increase the susceptibility of living trees to spruce beetle attack (Cobb 1989; Redfern and Filip 1991).

Major snow avalanches, for example, may have contributed to the recent spruce beetle outbreak on the Wasatch Plateau in Utah that was first detected in 1987. Maps of the initial outbreak area indicated that spruce beetle mortality centers commonly

coincided with topography prone to snow avalanches. Winters in the early to mid 1980's were also characterized by heavy snowfall and rain (Birkeland and Mock 2001; Hebertson and Jenkins, Chapter 2), and examination of forest vegetation revealed that major snow avalanches occurred during that time. Spruce beetle populations could have colonized host material in woody avalanche debris and subsequently spread into living trees.

Jenkins and others (1998) developed a diagrammatic model summarizing the potential interactions between important variables of disturbance regime in the spruce-fir zone (Appendix A.1). Through the creation of woody host material, snow avalanche, wind, and other disturbances may increase the likelihood of spruce beetle outbreaks. Secondary insects and diseases may also attack damaged trees predisposing them to spruce beetle infestation. The mortality of canopy trees caused by these agents can result in an increase of available resources for understory vegetation and undamaged trees (Veblen et al. 1994). The response of residual vegetation is growth release (Veblen et al. 1991a). If subalpine fir dominates the understory regeneration, it will be recruited into the forest canopy as the forest matures (Day 1972; Shea 1985; Aplet et al. 1988; Veblen et al. 1991a). Stands comprised of a greater subalpine fir component may be less attractive to spruce beetle attack (Schmid and Hinds 1974). Reduced competition may also enhance the vigor of remnant Engelmann spruce, thus increasing their resistance to infestation (Hard 1985). As mature subalpine fir begin to die after 125-175 years, the canopy opens. The greater longevity of spruce allows trees to gain dominance in the overstory (Day 1972; Alexander 1987; Aplet et al. 1988). Open canopy conditions and exposed mineral soil from uprooted trees may also encourage the establishment and

growth of spruce regeneration creating a greater spruce component. Fallen logs also provide important microsites for the establishment of spruce seedlings (Takahashi 1994). Stands with increasing spruce basal area and average spruce diameter eventually become more susceptible to spruce beetle outbreak (Schmid and Hinds 1974).

Spruce beetle outbreaks, blowdown and snow avalanche disturbances may also alter fuels complexes influencing fire behavior, and subsequently, the nature of vegetation patterns and dynamics. The accumulation of dead woody fuels resulting from extensive spruce beetle mortality increases the hazard of extreme wildfire. Intense, high-severity fires may expose mineral soil allowing for the initiation of new stands (Romme 1982). A mosaic of vegetation across the landscape may result from low intensity fires that burn through patchy mortality created by endemic populations of spruce beetle, scattered blowdown and snow avalanche debris (Bebi et al. 2003). Following stand replacing fires, the return to climax spruce-fir forests may require several hundred years (Jenkins et al. 1998).

Disturbances have important implications for both local ecosystems and larger landscapes by influencing the dynamics and distribution of plant communities, nutrient cycling, habitat for threatened and endangered species and the establishment of invasive non-native species. Understanding the role and interactions of agents within a disturbance regime has become vital to maintaining forest ecosystems with desired ranges of variability and proper functioning condition and restoring forest health. The information gained from this research may allow forest managers to recognize adverse impacts associated with snow avalanche disturbances and devise strategies that best achieve management goals while at the same time sustaining ecosystem integrity.

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CHAPTER 2

HISTORIC CLIMATE FACTORS ASSOCIATED WITH MAJOR AVALANCHE
YEARS ON THE WASATCH PLATEAU, UTAH¹**Abstract**

This study examined climate factors associated with major avalanche years on the Wasatch Plateau in south-central Utah. Dendro-ecological methods were used to date the occurrence of avalanche events in 16 avalanche paths during the period of 1928-1996. From this information, the probability of avalanche occurrence in each path for each year was calculated, and used to distinguish major avalanche years. The resulting avalanche chronologies indicated that 14 major avalanche years occurred on the Wasatch Plateau between 1928-1996. Logistic regression and classification tree analyses were used to examine relationships between climate variables and the probability of major avalanche years. The results of logistic regression analysis showed that mean January snowfall was significantly related ($p < 0.0001$) to the probability of major avalanche years, although model correlations were extremely low. Variability in the data resulting from path differences, potential dating errors, the lack of complete historic climate records, and the absence of snow pack information may have prohibited obtaining higher model correlations. The model, however, may help substantiate explanations of avalanche formation and initiation in the Intermountain region, or serve to generate alternative hypotheses for predicting major avalanche events. Avalanche professionals and land managers can use this to augment conventional strategies for protection, forecasting, land

¹ Coauthored by Elizabeth G. Hebertson and Michael J. Jenkins

use planning and management. This information also has broad ecological implications increasing our understanding of major avalanches as important disturbances of Intermountain alpine and subalpine ecosystems.

2.1. Introduction

Snow avalanches commonly occur in mountainous terrain of the Intermountain region in the western United States. Like other disturbances, snow avalanches vary in kind, frequency, magnitude, intensity, and severity. Interactions between local topography, weather, and the existing snow pack structure largely influence these parameters (Fredston and Fesler, 1999). The complexity of these interactions inherently makes understanding avalanche occurrence difficult, especially for major avalanches that occur infrequently and/or over large spatial scales.

In the Intermountain region, the determination of major avalanches is especially difficult because winters often embody characteristics of both maritime and continental climate classes. Avalanche formation and initiation can, therefore, resemble either climate class (Roch, 1949; LaChapelle, 1966; Armstrong and Armstrong, 1987; Changnon, 1993; Mock and Birkeland, 2000). When continental-like climate patterns prevail, for example, snowfall events are often interspersed with prolonged periods of dry, cold weather resulting in the formation of shallow, weak snow covers (Armstrong and Armstrong, 1987). Strong zonal southwesterly flows over the region are characteristic of maritime climate patterns with relatively warm temperatures and precipitation that may fall in the form of dense snow or rain (Mock and Birkeland, 2000). Large-scale trough patterns with a west to north flow usually produce heavy winter

precipitation with below-average temperatures (Jensen et al., 1990). Consequently, infrequent, major avalanches may result from unique climate patterns that create atypically unstable snow packs, or unusual weather, including extremes in precipitation, air temperature, and wind (Armstrong and Armstrong, 1987).

Investigations of factors contributing to major avalanches in the Intermountain region have typically been limited in scope. Studies have either examined one event that occurred during an exceptional season, or several events that occurred in one locality (Mock and Kay, 1992; Birkeland and Mock, 2001). Many avalanche events selected for study were also triggered artificially, or occurred in paths that experienced regular avalanche control. Control measures within ski areas or transportation corridors influences the frequency and magnitude of avalanche events in affected paths (Jenkins and Hebertson, 1994). Data collection is often contingent upon ski areas openings resulting in the lack of complete early season records. The quality of control work may also affect the accuracy of documentation and the reliability of data collected (Mock and Birkeland, 2000).

Few studies have attempted to understand factors associated with major avalanche events that occurred naturally within a certain geographic area over a relatively long temporal scale. Problems limiting this research are the lack of remote sites with long-term, contiguous weather records, corresponding snow pack data, and historical documentation of major avalanche events. Various numerical techniques and computer models may be used to rectify weather records, estimate missing values for precipitation and temperature, or infer values for high elevation sites from existing weather data (Danard, 1971; Cramer, 1972; Hanson, 1982; Running et al., 1987; Glassy and Running,

1994; Thorton, 2002). Barry (1992) provides a comprehensive overview of many of these methods. A number of snow pack prediction models have been developed and used primarily for hydrologic purposes, although some do address snow pack properties and processes (Jordan, 1991; Woodmencey, 1996). In the absence of historical records, few methods provide a reliable means for deriving chronologies of naturally occurring avalanches.

Dendro-ecology is one method that has proven useful for constructing avalanche chronologies of undocumented paths (Smith, 1974; Burrows and Burrows, 1976; Cushman, 1976; Carrara, 1979; Bryant et al., 1989; Jenkins and Hebertson, 1994; Jenkins and Hebertson, 1998; Rayback, 1998). Trees growing in avalanche paths respond to damage in several ways, thus providing a record of avalanche events. Dendro-ecological methods utilize tree ring analyses along with the examination of scars, reaction-wood formation, suppressed growth, and other indicators of avalanche damage to date avalanche events. Scars result from wounds to the inner bark of trees caused by snow and debris. In response to wounding, trees produce annual rings of callous tissue to seal the injured tissues. By counting the number of callous rings to the scar surface, one can derive a reliable date for the avalanche event. Severe avalanche damage also results in atypical growth responses that are reflected in tree ring patterns. Severe root system disruption for example can result in the formation of relatively narrow growth rings. Trees tilted by avalanches produce a special tissue called reaction wood in an effort to regain upright growth. Years connoting the initiation of these atypical growth patterns provide another means to date avalanche events. Aging new vertical stems or sprouts can provide additional evidence of avalanche occurrence during a specific period of time

(Burrows and Burrows, 1976). The ability to date avalanche events allows a calculation of avalanche frequencies, return intervals, and maximum runout distances.

The purpose of our research was to construct chronologies of natural avalanche events for paths on the Wasatch Plateau in south-central Utah using dendro-ecological methods. These avalanche chronologies were used to identify and date the occurrence of major avalanche events across the Plateau between 1928-1996. We next examined associations between the occurrence of major avalanche events and historic climate data for the area including temperature, precipitation, snowfall and discharge variables. Potential associations derived from these analyses could enhance existing explanations of climate factors and patterns that contribute to major avalanche events in the Intermountain region, or serve to generate alternative hypotheses. Avalanche professionals and land managers can use this information to augment conventional strategies for protection, forecasting and land use planning and management. This information also has broad ecological implications for increasing our understanding of major avalanches as important disturbances of Intermountain alpine and subalpine ecosystems.

2.2. Methods

2.2.1. The Study Site

The study site encompassed the southern portion of Wasatch Plateau located in south-central Utah (Figure 2.1). The Wasatch Plateau is a north-south high plateau

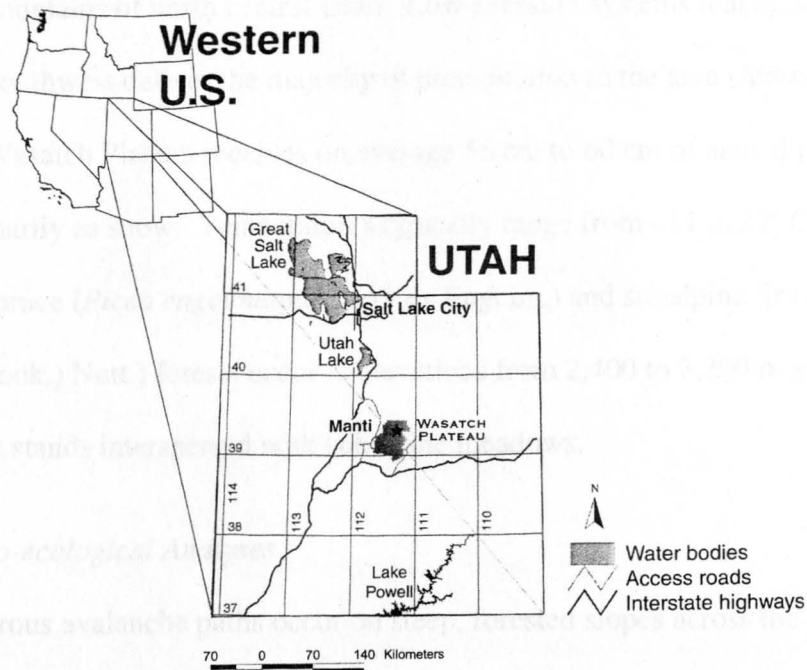


Figure 2.1. Location of the study site on the Wasatch Plateau in south-central Utah

bounded by Castle Valley to the east and Sanpete Valley to the west. The topography varies from rolling plateaus to steeper, east-west oriented drainages and associated canyons with the highest elevations exceeding 3,300 m. The climate is semi-arid. Although winter and spring storm fronts pass over the high plateaus of south central Utah on a regular basis, they receive significantly less precipitation than the northern mountain ranges and mountains of north central Utah. Low-pressure systems that approach from the south or southwest deliver the majority of precipitation to the area (Jensen et al. 1990). The Wasatch Plateau receives on average 56 cm to 60 cm of annual precipitation that falls primarily as snow. Temperatures typically range from -11 to 27° C. Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) forests occur at elevations from 2,400 to 3,300 m growing in discontinuous stands interspersed with subalpine meadows.

2.2.2. Dendro-ecological Analyses

Numerous avalanche paths occur on steep, forested slopes across the Wasatch Plateau (Figure 2.2). These paths were most likely created as a result of natural activity since no records of human-triggered avalanches for the area exist. The occurrence of large-scale avalanche events on the Plateau was determined using dendro-ecological techniques. Using topographic maps and aerial photographs, over 50 avalanche paths in spruce-fir stands area were identified. Of these, 16 paths were selected for sampling based on accessibility and the apparent absence of other disturbances, e.g., landslides, rock avalanches, fire, and timber harvesting. The expected maximum extent of avalanche runout was delimited on topographic maps and aerial photographs for each sample path.



Figure 2.2. The Bald Mountain avalanche path, Wasatch Plateau, Utah

Transects were run through the flanks and terminal portions of each path perpendicular to the fall line to the maximum extent of the runout zone. Along each transect, Engelmann spruce and subalpine fir greater than 13 cm diameter at breast height (1.37 m) were sampled by extracting increment cores from similar heights on four sides of the tree. Since atypical growth responses can occur in different radii of the tree, up to four cores were taken from each sample tree for the purpose of cross replicating events within the tree. The cores were placed in straws, labeled, and taken to the laboratory for analysis. Trees with avalanche scars and new vertical stems were sampled as they were encountered along each transect. Avalanche scars were sampled by cutting a wedge from the scar, or by taking a core sample using the technique described by Arno and Barrett

(1988). An increment core, or disk was removed from the base of new vertical stems to determine their age. In each avalanche path, a minimum of 20 trees was sampled. Trees exhibiting evidence of damage or stress induced by agents other than snow avalanches were not sampled.

Increment core and scar samples were prepared and analyzed according to the basic principles described extensively in other literature (Fritts, 1966; Stokes and Smiley, 1968; Burrows and Burrows, 1976; Swetnam et al., 1985). Briefly, increment cores were mounted on grooved boards. All core and scar samples were then sanded using consecutively finer-grained paper to reveal the annual growth rings. Cores extracted from different radii of each sample tree were examined for years of atypical growth responses including reaction-wood formation, narrow ring series, and scars. Years of potential avalanche events were determined by counting the annual rings, beginning with the outermost ring, inward to rings exhibiting the initiation of atypical growth responses or scars. Scars were dated by examining tree rings along one to several radii extending from the bark, through callous tissue and to the pith of the sample. The age of new vertical stems was determined by counting the annual rings inward to the pith. Years determined from all samples collected from each avalanche path were graphed on a modified skeleton plot after Schroder (1978).

Several factors can contribute to dating error using dendro-ecological analyses in spite of care taken during sample collection (Schroder, 1978). In this study, growth suppression, possibly resulting from either unfavorable climate conditions or miscellaneous external biologic and environmental factors was the primary factor. False and missing rings were also common in the callous margins of scar samples, particularly

when the injury had been substantial. To minimize these sources of dating errors, measures to cross-date all skeleton plots were employed. Cross-dating involved comparing common tree-ring patterns and atypical growth responses among sample trees with a master climate plot. The master climate plot was constructed from increment cores extracted from damage-free conifers growing on climatically sensitive sites in forests adjacent to avalanche paths. Preparation of the increment cores and the plotting of tree-ring sequences were done following the procedures described by Stokes and Smiley (1968). These comparisons helped determine if wide and narrow ring series and atypical growth responses might be attributed to climate. Growth responses resulting from climate were disregarded as possible avalanche events.

Methods of cross replication were also used to validate potential avalanche events for both within-tree samples and samples collected from each path. For example, an avalanche event was considered valid if scar dates and/or the initiation of atypical growth responses matched along the different radii of a sample. Samples that did not have sufficient event replication, or were too difficult to decipher were eliminated from further analyses. Replicated avalanche events were summed across all samples collected from a path to date avalanche years.

Because few old trees had survived to record earlier avalanche events, the number of event responses decreased back in time making the verification of early avalanches difficult. To reduce this problem, an avalanche probability (I) for a path at year t was calculated after Schroder (1978) to weigh the number of event responses according to the

number of trees providing the record for that year. The formula is given as:

$$I_{pt} = \left(\sum_{i=1}^{A_{pt}} R_{pit} \right) / A_{pt}$$

where A_{pt} is the number of trees sampled in path p in year t and R_{pit} is 1 if an event response was evident in the i -th tree in path p in year t (not more than one event per tree per year). Otherwise R_{pit} is 0.

To illustrate how the dates of avalanche events were derived using these methods, event responses from samples collected from 13 trees in the North Black Mountain path were plotted producing the modified skeleton plot in Figure 2.3. The chronology extends from 1880 (the earliest event response initiated) to 1996², the year when samples were collected. Although the majority of samples had either datable scars or definitive growth responses, many show little within-tree replication, especially in earlier years. Within-sample replication, however, increased the confidence of dating several avalanche events. In 1988, for example, trees 3 and 6 have evidence of a scar only along one radii of each sample. The initiation of a narrow ring series is also evident along the right radius of tree 10. Samples collected from trees 1, 7, and 8, however, have replicating scars along two radii examined providing good evidence that those trees incurred avalanche damage during 1988, and that the event responses observed in other samples likely resulted from an avalanche as well.

² Only the portion of the chronology from 1916 is shown

Figure 2.3. The modified skeleton plot showing event responses from tree samples collected in the North Black Mountain avalanche path. S = scar; R = reaction wood; N = narrow ring series; C = corrosion; A = locally absent ring; P = rupture; / = continued response.

Year	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Sample 11	Sample 12	Sample 13
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Year	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Sample 11	Sample 12	Sample 13
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Years that also show good within-sample replication of various responses include 1985, 1978 and 1968. The occurrence of fewer avalanches, or decreasing sample depth might account for the lack of replicating event responses plotted after 1965. Weighted avalanche probabilities helped to substantiate earlier dates including 1938, 1926, 1924, 1922, 1912 and 1901. The few samples that existed for years prior to 1920 made the calculation of meaningful probabilities difficult. As a consequence, these dates were noted but not considered for further analyses. Narrow ringseries observed in 1995, 1977, 1975, and 1934 corresponded with similar series in the master climate chronology indicating that drought probably accounted for this response. This procedure was used to date avalanches from chronologies constructed for each of the sixteen paths sampled.

2.2.3. Distinguishing Major Avalanche Years

The distinction between major avalanche events and those of less magnitude was based upon two assumptions. First, extensive tree damage caused by major avalanches would result in a proportionately greater number of event responses recorded in each path during a given year. Second, major avalanche cycles would most likely affect a larger number of paths across the Plateau. To distinguish major avalanche years, the avalanche probabilities calculated for each path were averaged over the total number of paths in a given year. Using these values, years from 1928-1996 were ranked from the highest to lowest (Table 2.1).

2.2.4. Climate Data

Historic weather data were acquired from the Western Regional Climate Center for stations in closest proximity to study sites on Wasatch Plateau. Of those stations

Table 2.1. Years from 1928-1996 and respective mean event response probabilities presented from highest to lowest

Year	P	Year	P	Year	P	Year	P	Year	P	Year	P	Year	P
1968	0.29	1985	0.18	1986	0.15	1959	0.12	1976	0.10	1940	0.07	1963	0.05
1982	0.26	1983	0.17	1933	0.14	1973	0.12	1994	0.10	1941	0.07	1991	0.05
1952	0.23	1989	0.17	1939	0.14	1981	0.12	1929	0.09	1955	0.07	1931	0.04
1957	0.23	1992	0.17	1962	0.14	1987	0.12	1945	0.09	1960	0.07	1943	0.04
1978	0.23	1938	0.16	1975	0.14	1988	0.12	1947	0.09	1971	0.07	1946	0.04
1954	0.22	1944	0.16	1932	0.13	1948	0.11	1966	0.09	1990	0.07	1953	0.04
1969	0.20	1980	0.16	1956	0.13	1949	0.11	1937	0.08	1942	0.06	1934	0.02
1936	0.19	1950	0.15	1964	0.13	1965	0.11	1951	0.08	1995	0.06	1928	0.00
1979	0.18	1961	0.15	1970	0.13	1972	0.11	1967	0.08	1996	0.06		
1984	0.18	1974	0.15	1993	0.13	1977	0.11	1935	0.07	1930	0.05		

reviewed, the Manti, Utah station (#425402) provided the longest, most contiguous and reliable data source for the area. The station had remained in the same location since the early 1920's with values for precipitation, temperature and snowfall dating from 1928 to the present. Variables from this data set selected for analyses included mean precipitation, snowfall, and temperature for the months of October through May, from 1928-1996. Precipitation and snowfall values were originally measured in inches, and temperatures in degrees Fahrenheit. These values were later converted to metric scales. Mean monthly values were thought to provide an appropriate level of resolution for analyses because dendro-ecological methods only date the year that an avalanche event occurred. These data were also used to derive seasonal values for temperature, precipitation and snowfall for the same period. Fall included the months of October and November, winter, the months of December, January, and February and spring, the months of March, April and May. Mean precipitation and snowfall values for each season were summed, while mean temperature values were averaged.

One drawback of the Manti station data was that weather variables were measured at an elevation of 1,750 meters. The starting zones of the avalanche paths sampled often

exceeded 3,000 meters in elevation. Methods to estimate weather values for upper elevations from lower elevation stations, however, were based on information that was unknown (for example, the moisture content of an air mass necessary for determining appropriate adiabatic lapse rates). Consequently, values derived from such extrapolations might prove more erroneous than using actual values from lower elevations. Although wind loading and slab formation often contribute to the initiation of avalanches, historic records for wind speed and direction were unavailable for analyses. Without snow depth data, calculations for snow pack characteristics such as temperature gradients were not possible. Measures of snow-water equivalent from SNOTEL (Natural Resources Conservation Service) data were not included in the analyses because no SNOTEL sites were located near the study area, and data available from distant SNOTEL sites lacked complete, long-term records. Instead, snowmelt reflected by stream discharge data (United States Geological Survey) measured in cubic feet per second was used to provide a surrogate for some measure of snow water content during the period of record (Gottfried et al., 2002). These data might also provide some insight into relative annual snow depths and seasonal freeze-thaw cycles. After examining records from several watersheds in the study area, streamflow data from the Sevier River gage (Hydrologic Unit Code 16030003) was selected for analyses. This data set provided a complete record of discharge values from 1917 to the present. Mean values for the months of October through May, from 1928–1996 were selected to correspond with the Manti climate data. Since snowmelt might occur through early summer, mean monthly values for June and July and total spring discharge were also analyzed.

2.2.5. Data Analyses

A classification tree analysis (CART) (Brieman et al., 1984; Steinberg and Colla, 1997) was used initially to predict major avalanche years from the set of historic climate data. Several CART models were analyzed, with years from 1928 to 1996 grouped into two response classes. Years with avalanche probabilities < 0.14 were class 0, and years with avalanche probabilities ≥ 0.14 were class 1. The CART procedure partitioned climate variables from the initial data using recursive binary splitting to produce trees of increasingly homogenous subsets. At each split, CART imposed a "goodness of split criterion", not unlike the method of least squares, to optimize splitting for each variable and ultimately minimize the overall probability of misclassifying the response variable. CART added variables until classification trees were grown to a maximum size and in the final step removed those variables that contributed no predictive power to the model. This allowed CART to select the best models adjusting for the number of variables used in the analysis.

The best CART model resulting from this analysis used only mean monthly January precipitation to optimize the splitting of major avalanche year probabilities. The splitting value for mean January precipitation was 4 cm. For this model, CART also selected closely associated surrogate variables that could be used in further analyses or discussion. These included mean monthly January snowfall and November precipitation with splitting values of 49 cm and 0.50 cm, respectively. Cross validation classification probabilities indicated that model correctly classified non-avalanche, or minor avalanche years 89% of the time. The likelihood of correctly classifying major avalanches years, however, was only 43%. Tests to assess model fit indicated that the model explained

only 44% of the variability in the data.

Logistic regression was used next to further explore this result. Logistic regression provides a more robust method for modeling probabilities than ordinary least squares regression (OLS) when the dependent variable takes on only two values (0, 1) (Everitt and Der, 1996; Whitehead 1998). This is primarily because the OLS linear probability model is heteroscedastic and may predict probability values beyond the (0, 1) range (Whitehead, 1998). In this analysis, the probability of major avalanche years was the dependent variable with major avalanche years (probabilities ≥ 0.14) equal to 1, and otherwise 0. The probability value of 0.14 was selected to provide a sufficient number of observations in each class for the analysis. Models were estimated to predict the logit of mean avalanche probability from the set of climate variables. The logit is simply the log odds ratio¹ of mean avalanche probability. Using the SAS procedure PROC GLIMMIX (Littell et al., 2001) an initial logistic regression model was fit with all climate variables and subsequently backward elimination was used to derive the most parsimonious model. This resulted in a final model with the general form of:

$$E(\ell) = \beta_0 + \beta_j (\text{January Snowfall});$$

where $E(\ell)$ is the predicted logit. The model gave parameter estimates of -2.4444 for β_0 and 0.0279 for β_j . The t statistics for β_0 and β_j were -23.11 and 5.60 , respectively, both highly significant with p values < 0.0001 . For the purpose of depicting results graphically, a back-transformation of predicted logits into the original scale was

¹ Logit = $\log_e [p/(1-p)]$; where p is the probability of a major avalanche year.

accomplished using the formula:

$$\hat{p} = 1/(1 + \exp(-\ell));$$

where \hat{p} is the probability of major avalanche year for given January snowfall. A graph of mean January snowfall values and predicted probabilities of major avalanche years for all avalanche paths is given in Figure 2.4. Although logistic regression analysis indicated that mean January snowfall was significantly associated with the probability of major avalanche years, the model gave a Pseudo- R^2 value of 0.056 indicating again that the strength of the relationship was extremely low. These results agreed with those of previous CART analyses. Examination of Figure 2.4 revealed considerable variability in the data that prohibited the ability to adequately detect general trends. Graphs of major avalanche year probabilities against mean January snowfall for individual paths on the Wasatch Plateau showed considerable variability between paths (Figures 2.5 and 2.6). For example, the spread of data points about predicted probabilities was much greater for the Ephraim Canyon avalanche path than for the Mount Baldy 2 avalanche path. This might suggest that avalanche behavior in the Ephraim Canyon avalanche path was more sensitive to a variety of influences, whereas mean January snowfall might typically have had a greater role in influencing avalanche behavior in the Mount Baldy 2 avalanche path. As a consequence, the LOESS procedure (SAS[®], 2001) was used to remove a large portion of the variation that might have been attributed to path differences and other potential sources including the serial or auto-correlation of sequential years. The LOESS procedure is a robust fitting method for nonparametric models, particularly when a

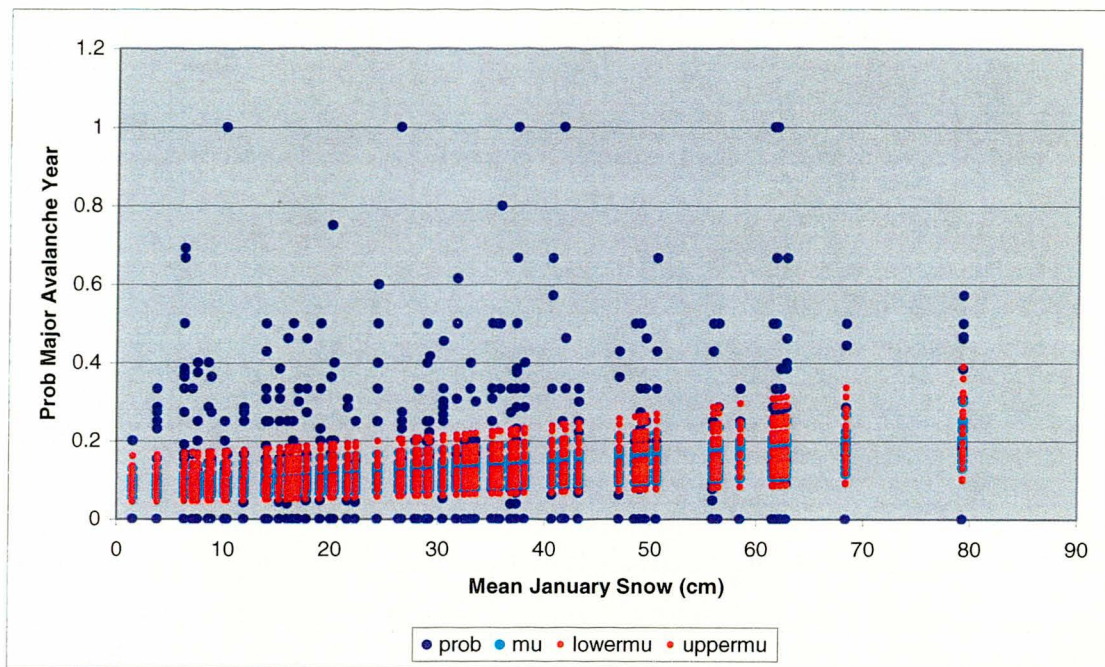


Figure 2.4. GLIMMIX plots of mean January snowfall values and predicted probabilities of major avalanche years for all paths sampled on the Wasatch Plateau

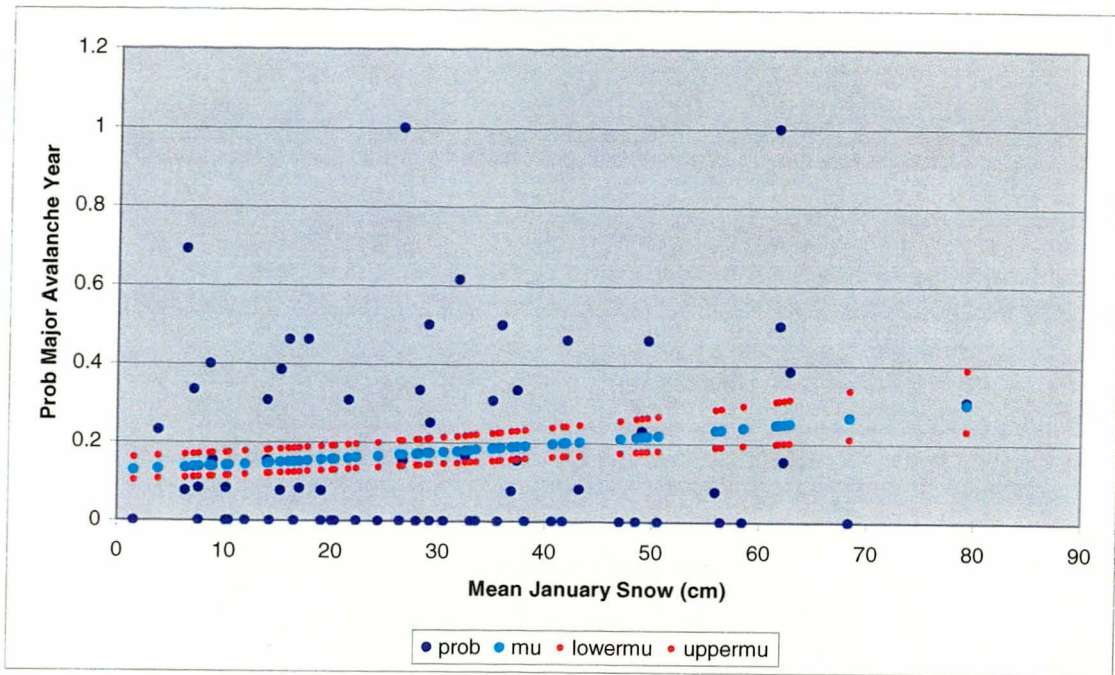


Figure 2.5. GLIMMIX plots of mean January snowfall values and predicted probabilities of major avalanche years for the Ephraim Canyon avalanche path

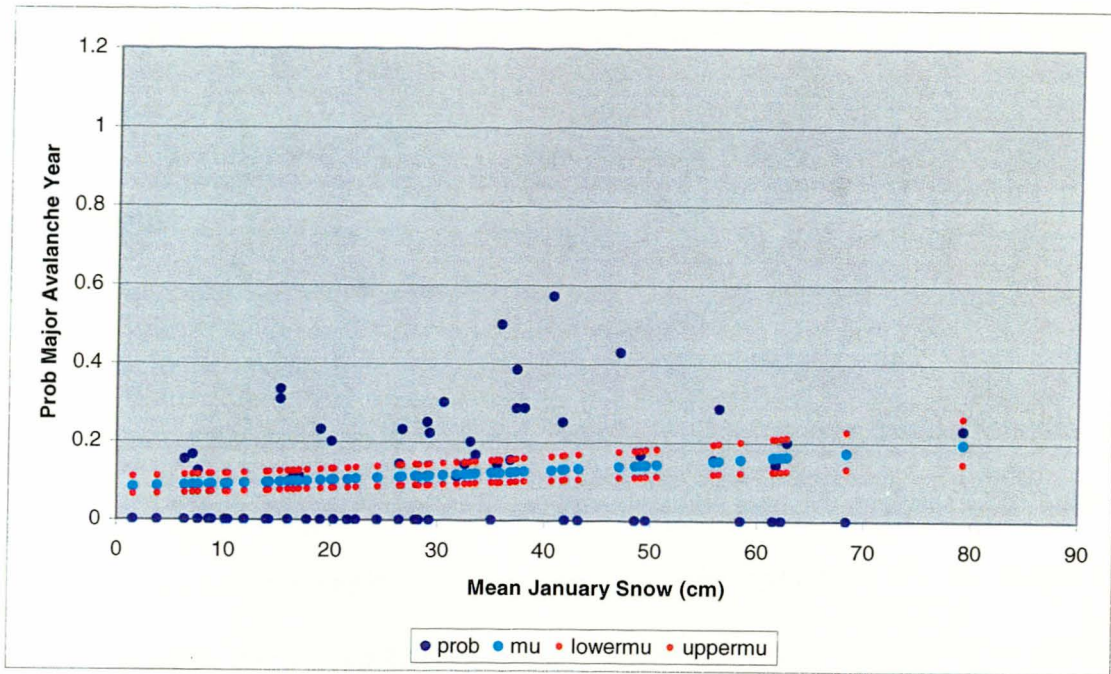


Figure 2.6. GLIMMIX plots of mean January snowfall values and predicted probabilities of major avalanche years for the Mount Baldy 2 avalanche path

suitable form of the regression line is unknown and when there are outliers in the data (Littell et al., 2001). LOESS formed a smooth line of the predicted probabilities for major avalanche from values of mean monthly January snowfall and also provided estimates of the 95% upper and lower confidence limits (shown in red) for the smoothed line (Figure 2.7).

2.3. Results

2.3.1. Dates of Major Avalanche Years

Increment cores, scars and other samples were collected from 297 trees in the 16 sampled avalanche paths on the Wasatch Plateau. Following examination, samples from 36 trees were undecipherable leaving samples from 261 trees for analyses. The number of trees used to date avalanche occurrence in each path ranged from 8 to 26. Reaction wood formation, narrow rings, scars and other event responses were evident in over 90% of the trees sampled. The oldest tree sample dated to 1847. This sample also had the earliest event response dating to 1861 and provided an avalanche chronology of 135 years for the Plateau. Early dates lacked sufficient cross replication precluding them from further analyses in this study. Many dates, however, coincided with early avalanches dated from chronologies constructed for paths in northern Utah, newspaper articles (Jenkins and Hebertson, 1994; Jenkins and Hebertson, *unpublished reports*) and other historic accounts (Gallagher, 1967; Williams and Armstrong, 1984; Utah Department Of Transportation [UDOT], 1987; Martinelli and Leaf, 1999). Northern Utah avalanche chronologies included No Name in Snowbasin; Nordic Knob in Park City; Little Pine East, Ben Hame, Culp's West Hellgate, East Hellgate all in Little

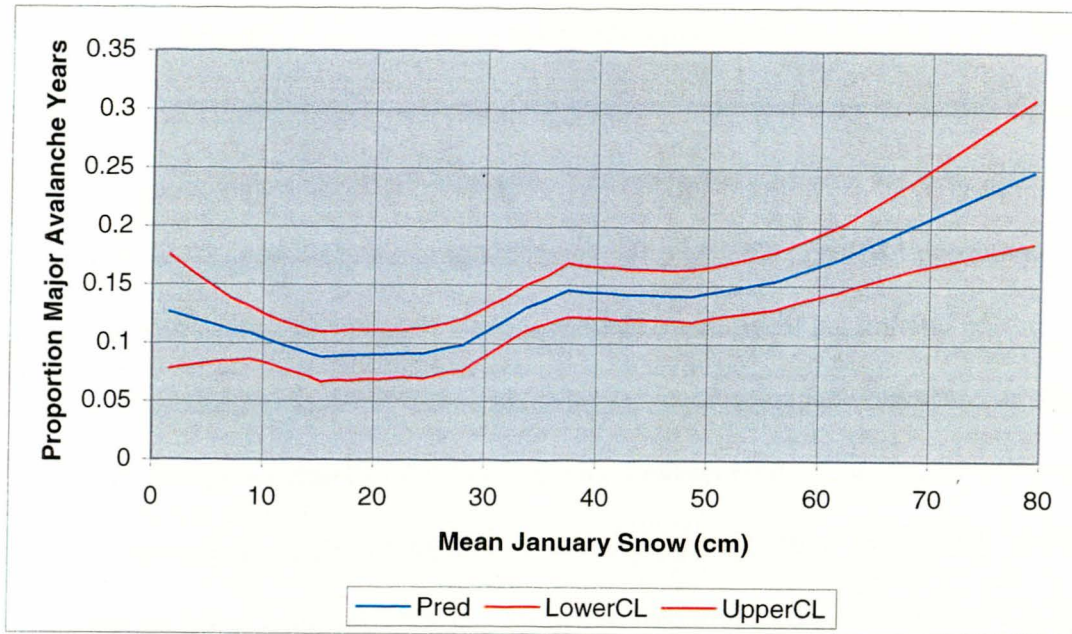


Figure 2.7. Smoothed lines of the predicted probabilities for major avalanche years and 95% upper and lower confidence intervals for values of mean January snowfall

Cottonwood Canyon; Grey Cliffs in American Fork Canyon; and Bridal Veil Falls in Provo Canyon.

The earliest avalanches dated in the tree ring chronologies on the Wasatch Plateau potentially occurred during the winters of 1870, 1871, 1875, 1883, 1885, 1893, 1898, 1901, 1906, and 1907.² Large avalanches resulting from heavy snowfall and rain were reported to kill 2 miners in American Fork Canyon, Utah and bury structures at Alta, Utah in late January and early February of 1883 (The Park Mining Record, Vol. 12). Martinelli and Leaf (1999) reported that the winters of 1883 and 1884 accounted for about 28% of avalanche fatalities in mountainous locations of central and northern Colorado up until about 1950. These records helped substantiate avalanches on the Wasatch Plateau that dated to the same period. Several Utah chronologies indicated that avalanches were particularly widespread across northern Utah in 1898, 1906, and 1907. The 1898 date may coincide with reports of extreme avalanching in southern Colorado (Gilliland, 1980) and a large avalanche that struck a wagon, killing two horses near Park City, Utah (The Park Mining Record, Vol. 28) during the snowy winter of 1898-1899. Avalanches dated in 1906 and 1907 also plagued mountain communities and railroads in central Colorado in both these years resulting in the destruction of buildings, trains and causing several fatalities (Martinelli and Leaf, 1999). Historic records from Alta, Utah also verified the 1906 avalanche event alluding to the broad extent of major avalanches during that year (Kalatowski, 1988). Schroder (1978) observed reaction wood responses in trees examined from a boulder deposit on Barney Top, Table Cliffs Plateau, Utah in

²For clarity of discussion, all dates comprise months from fall of the prior year through spring of the given year.

1883 and also in 1906 and 1907. Although Schroder attributed these event responses to mass movement events, snow avalanches may have caused the atypical growth responses.

From 1910 to 1920, potential avalanche activity was relatively high on the Wasatch Plateau. Two large and widespread avalanche events also occurred during this period in northern Utah. The first occurred in the winter of 1911 when destructive avalanches struck the town of Alta, Utah (Kalatowski, 1988) and six men were killed while camping near Silver Lake in Brighton, Utah on February 4th of that same year (The Park Mining Record, Vol. 40). The avalanche cycle of 1911 was also dated in the Culp's, Snowbasin and Bridal Veil Falls chronologies. While only a few samples from the Wasatch Plateau recorded event responses in 1911, the 1912 date may coincide with major avalanches during this year. Both the 1911 and 1912 dates, however, correspond with historic accounts of avalanches in the northern Front Range and central and southern mountains of Colorado (Martinelli and Leaf, 1999). The next apparently large avalanche event on the Wasatch Plateau occurred in 1916. The 1916 event was verified by several historic accounts. The Park Record (Vol. 31) relates one account of a deadly avalanche that devastated a portion of Park City, Utah on March 11th of that year. On that same day, avalanches also buried railroad tracks in Glenwood Canyon, Colorado (Martinelli and Leaf, 1999). The 1916 date is also evident in three northern Utah chronologies from Little Cottonwood Canyon and one from No Name at Snowbasin.

The years with relatively large numbers of event responses through the first half of the 1920's were 1924 followed by 1921, 1922, and 1926. Several northern Utah chronologies dated avalanches in 1921 and 1922. Extensive avalanching also occurred along the northern Front Range of Colorado in 1921 as a result of over 100 cm of wet

snow that fell during one 24-hour period in April. Although only one other northern Utah chronology substantiated the 1924 and 1926 dates, Gallagher (1967) relates an account of a major storm cycle experienced in Telluride, Colorado between March 22 and April 2 of 1926. This storm spawned a major avalanche that destroyed several homes in the town and was probably responsible for subsequent avalanches affecting other locations in central Colorado during April of that year (Martinelli and Leaf, 1999).

Numerous avalanches were dated on the Wasatch Plateau between 1928 and 1996. Major avalanche years beginning with the most recent included 1992, 1984, 1982, 1979, 1978, 1969, 1968, 1957, 1954, and 1952 as determined by avalanche rank (Table 1). The year of 1968 had the greatest number of verified event responses relative to sample size followed by 1982, 1952, and 1957. Widespread avalanching was most evident in 1978, 1968, 1982, and 1992.

Of the above years, avalanches in 1952, 1978 and 1992 were substantiated by the northern Utah chronologies. Large avalanches in the Tanner's slide path, Little Cottonwood Canyon reached maximum runout in 1952 and again in 1982 (UDOT, 1987). The 1957 event was recorded in the No Name and Culps avalanche chronologies from northern Utah. Gallagher (1967) also provides accounts of avalanches that damaged homes, trains and resulted in numerous casualties in Idaho, Montana and Colorado during February of that year. Schroder (1978) observed a 1958 release pattern in samples from his Barney Top, Utah chronology that could be attributed to a major avalanche that occurred in 1957. In February of 1979, a large wet slide damaged a bridge in Glacier National Park, Montana (Butler, 1986) while another killed a mineworker in Helper, Utah (Williams and Armstrong, 1984). During that same time, two avalanches buried highway

U-210 in Little Cottonwood Canyon, Utah (UDOT, 1987). The Utah Department of Transportation Avalanche Atlas (1987) reported that several paths in Little Cottonwood Canyon that seldom slide avalanched in December of 1983. This record provides some verification of the 1984 date on the Wasatch Plateau. Using dendro-ecological analyses, Malanson and Butler (1984) dated 1954, 1957, and 1982 avalanches in a path on the southern boundary of Glacier National Park, Montana.

Other years on the Wasatch Plateau with a relatively high avalanche rank were 1989, 1986, 1985, 1983, 1980, 1974, 1975, 1962, 1961, and 1938. The 1986 avalanche was dated in three northern Utah chronologies and also widely documented in locations throughout the Intermountain west (Bear River Avalanche Information Center, *unpublished report*; Birkeland and Mock, 2001). Large avalanches ran in the No Name and East Hellgate avalanche paths in 1974 coinciding with the event recorded on the Wasatch Plateau during the same year. Numerous locations reported of large avalanches throughout the western United States in 1962. Most notably, two natural avalanches near Loveland Pass, Colorado struck the highway on January 7, capturing and partially burying some motorists. Later in that same month, a family of five and the four children of another family were killed when an extreme avalanche destroyed their homes in the town of Twin Lakes, Colorado. Only the No Name chronology dated the 1962 avalanche in northern Utah. The 1961 date was supported by evidence of a large avalanche that ran in Grey Cliffs slide path during that same year and four northern Utah chronologies dated the 1938 avalanche event. Few northern Utah chronologies or historic accounts had avalanches that coincided with the other dates.

2.3.2. *Associations Between Major Avalanche Years and Climate*

Results of the logistic regression analysis indicate that the probability of major avalanche occurrence was significantly associated with mean January snowfall ($p < 0.0001$). The probability of a major avalanche year was estimated to increase by 0.0279 with a respective 1 cm increase in mean January snowfall. The extremely low Pseudo- R^2 value (0.056), however, indicates that the model did not account for considerable sources of variation in the data. This finding was supported by the 95% upper and lower confidence limits best shown in Figure 2.7. While the model was relatively precise at predicting the probability of major avalanche years with low values of mean January snowfall, the confidence limits got significantly wider with increased mean monthly snowfalls.

2.4. Discussion and Conclusions

2.4.1. *Predicting Major Avalanche Years*

Climate is one of the most important factors contributing to the formation and initiation of major avalanches in mountainous terrain. Analyses of historic temperature, precipitation, snowfall and hydrologic data indicated that mean January snowfall was significantly related to the probability of major avalanche years on the Wasatch Plateau for years from 1928-1996. The highest probabilities of major avalanche years generally corresponded with high mean January snowfall, while low snowfall resulted in relatively low probabilities. The confidence limits for estimates of major avalanche year probabilities were also greater with low mean January snowfall values. Examination of snowfall data revealed that 68% of years with below average annual snowfall also had

below average snowfall in January. Seventy-six percent of these same years also had below average early seasonal snowfall. With low seasonal snow covers, surface roughness features would serve as anchors in avalanche starting zones and tracks and create friction for moving snow. This would influence avalanche initiation and runout distances (McClung and Schaerer, 1993). Insufficient loading due to the lack of substantial mid-winter snows might also prohibit the initiation of sizable avalanches. With the release of an avalanche, shallow snow covers would minimize the additional entrainment snow thus limiting the size of avalanches (McClung and Schaerer, 1993). As a consequence, we considered this a reasonable result because major avalanches would not likely occur during years with generally low seasonal snowfall.

The inability of the model to reliably estimate avalanche probabilities associated with high mean snowfall values, however, suggests considerable sources of variation not integrated in the model. Perhaps the primary factor limiting these analyses was the lack of complete, long-term climate records for the Wasatch Plateau. Although the Manti weather station and Sevier River stream gauge provided the longest, most complete datasets for the study area, the short length of these records (68 years) could have inhibited reliably determining the frequency of extreme, or atypical short-term (annual) climate patterns simply because few had occurred during the past century. Also, climate patterns throughout the Upper Colorado River Basin and Southwestern United States from the late 19th century have demonstrated a high degree of multi-decadal variability (Shepard et al., 2000). Ninety-five percent confidence intervals originally calculated for mean monthly values of weather and discharge data from the Wasatch Plateau between 1928 and 1996 reflected this variability, particularly in transitional months. A longer

climate record might have reduced the variability in these data sufficiently enough to obtain more precise estimates of major avalanche probability.

Inclusion of other climate factors such as measures for wind, solar radiation, and the type, intensity, and duration of weather events in addition to snowpack information might have also improved the precision of the model. Natural avalanches generally result from sudden changes that apply excessive stress on the mountain snowpack (Fredston and Fesler, 1999). Among those changes are heavy amounts of precipitation and/or wind-deposited snow over a short period of time that overloads weak layers within the snowpack, and intense warming that decreases the strength between snow layers and increases down slope deformation of the snowpack (McClung and Schaerer, 1993, Fredston and Fesler, 1999). The potential for major avalanches also rises with increased loading during prolonged storm events and extended periods of warming that often lead to the development of deep slab instabilities (McClung and Schaerer, 1993; Fredston and Fesler, 1999).

A third source of variability may have been the relatively small number of trees used for dating avalanche events in some paths. Samples collected from several trees were disregarded because they were either undecipherable or lacked sufficient cross-replication to provide reliable dates. Other samples had complacent rings with no apparent evidence of event responses. Many samples provided relatively short tree-ring records. These cases resulted in fewer trees for constructing avalanche chronologies and a consequent reduction in sample depth for early years in some paths. For example, although the majority of avalanche chronologies dated back to the middle of the 19th century, 50% of all event responses were recorded after 1948. With small sample depth,

the confidence of dating early avalanches decreased, and in turn, likely affected the ability to derive accurate avalanche probabilities for early years.

Finally, comparing GLIMMIX plots of major avalanche year probabilities of individual avalanche paths revealed considerable variability among paths. Dates compared with sample tree locations revealed that avalanches variously affected different portions of each path. The data also indicated that all paths seldom avalanched during otherwise major avalanche years. These observations support those of others (Mears, 1992; Rayback, 1998) and attest to the importance of terrain features in influencing avalanche behavior. Again, collecting samples from a larger number of trees across a given path and sampling more paths across the Wasatch Plateau would have improved the ability to reliably date avalanche events.

In spite of the limitations in this study, these results serve to substantiate existing explanations of major avalanche occurrence in the Intermountain region. Additionally, they are heuristic and allow for the generation of alternative hypotheses for predicting major avalanche years. For example, on the Wasatch Plateau, 68% of major avalanche years were best characterized as having continental-like climate conditions during the period of study. The remaining 32% of major avalanche years occurred during winters characterized by generally heavy seasonal snowfall. These results support the conclusions of previous studies that avalanche formation and initiation in Intermountain locations can resemble either continental or maritime avalanche classifications (Roch, 1949; LaChapelle, 1966; Armstrong and Armstrong, 1987; Changnon, 1993; Mock and Birkeland, 2000). The evidence that mean January snowfall is important for predicting increased likelihood of major avalanches years in the Intermountain region, may also

help elucidate the occurrence of major avalanches in either scenario.

Major avalanche years best characterized by continental-climate conditions included 1933, 1936, 1938, 1939, 1944, 1950, 1954, 1957, 1961, 1968, 1975, 1978, 1980, 1984, 1985, 1986, and 1992. Under these conditions, major avalanches are attributed to the development of unstable snow structures that evolve under the dominance of a ridge pattern (Armstrong and Armstrong, 1987). When a ridge pattern dominates the Intermountain west, storms produce little to no precipitation (Jensen et al., 1990). Early season snow accumulation often results in shallow snow packs that may experience steep temperature gradients causing the formation of depth hoar. Depth hoar and other faceted layers tend to persist well into winter months, especially during years with atypically low snow accumulations associated and cold temperatures (McClung and Schaerer, 1993).

Of the above years, 56% had early season snowfall followed by below average December snowfall and average January snowfall. Heavy January storms might have triggered avalanches with the capacity to step down into buried weak layers thus entraining a greater volume of snow and increasing avalanche size. Exceptional years included 1938, 1939, 1984, and 1986. During these years, generally below average early seasonal snowfall was followed by copious amounts of February snowfall or rain. This pattern was well-documented in 1986 when throughout the western United States, large, widespread avalanches resulted from unseasonably warm temperatures and rain that fell up to elevations above 2600 m in February (Birkeland and Mock, 2001). In the winter of 1968, all months had below average snowfall except for December, which received the second highest monthly snow total during the period of study. Another exception was the years of 1936, 1961, and 1985. These years were characterized by generally below

average snowfall, but heavy spring snowfall or precipitation.

Major avalanche years with generally heavy snowfall included 1952, 1962, 1969, 1974, 1979, 1982, and 1989. During heavy snowfall years, faceted layers typically develop within early season snow covers. Continued snow accumulation, however, soon mitigates the effects of temperature gradient metamorphism and the overall development of weak snow structures. The occurrence of major avalanches is more often related to intense storm events. Loading from new snow may cause slabs to fail on buried surface hoar, or near-surface faceted layers (Armstrong and Armstrong, 1987). January snowfall in all of the above years was higher than average and any storms were probably sufficient to trigger major avalanches. But, because intense storms likely occurred throughout these winters, further speculation about the role of January snowfall in contributing to major avalanches would require more detailed study. Such studies might include associations between January storms and existing snowpack structures, or with prevailing synoptic and meso-scale circulation patterns. Also, not all heavy snowfall years on the Wasatch plateau produced major avalanches or widespread avalanche activity. The years 1941, 1947, and 1973, for example, all had high seasonal snowfall values suggesting that during some years, the right combination of factors including deep snow packs and warm snow pack temperatures might have allowed for the development of stable structure.

2.4.2. *The Implications of Major Avalanche Events*

Major avalanches have great human, as well as ecological significance in the intermountain region. As the number of people living and recreating in avalanche-prone terrain rises, the probability of damage to property, structures and transportation corridors

continues to increase. More importantly, the annual number of avalanche fatalities has nearly doubled during the past decade (Atkins, 2002). Infrequent, large avalanches also play an important role in the disturbance regimes of alpine and subalpine forests.

Avalanche damage can predispose injured trees to insect damage and disease (Miller et al., 1979; Jenkins et al., 1998). Avalanche paths create natural firebreaks (Veblen et al., 1994). Woody avalanche debris increases fuel loads, resulting in local fire hazards, and provides habitat for sensitive and endangered wildlife species (Dueser and Shugart, 1978; Miller et al., 1979; Bartels et al., 1985; Taylor and Fonda, 1990; Hecnar, 1994; Veblen et al., 1994; Butts, 1997; Krajick, 1998; Ruggiero, et al. 1998). Debris deposited in streams can also improve or adversely impact fisheries (Bilby and Likens, 1980; Dudley and Anderson, 1982; Sedell et al., 1988).

Perhaps the greatest ecological consequence of major avalanches is the production of suitable host material for the Engelmann spruce beetle (*Dendroctonus rufipennis* Kirby (Coleoptera: Scolytidae) (Jenkins et al., 1998). Once beetle populations reach outbreak levels, the spruce beetle will infest and kill live trees (Schmid and Frye, 1977). Recent spruce beetle outbreaks have resulted in deaths of over 1 million spruce trees in the intermountain region (USDA FS, 2002). The mortality of large trees modifies stand structure and species composition in affected forests (Baker and Veblen, 1990; Veblen et al., 1991; Veblen et al., 1994; Jenkins et al., 1998). Bark beetle mortality also increases fuel loads and stand-replacing fires are possible under the appropriate fire weather conditions (Jenkins et al., 1998). Historic bark beetle outbreaks of 1875, 1916, 1951, 1950, 1958, 1961, 1968, 1978, 1984, 1988, and 1992 in several western states appear coincident with the occurrence of major avalanche years.

It has also been speculated that potential relationships exist between major avalanches and El Niño-Southern Oscillation (ENSO) events (Fox, 1973). Mock and Birkeland (2000), however, were unable to find evidence substantiating these relationships. They suggested that predicting potential avalanche responses necessitates better understanding of the magnitude of seasonal climate anomalies, the intra-seasonal variability of synoptic-scale circulation and surface climatic responses and potential snow pack processes. Interestingly, over half of ENSO events between 1900 and 1996 (National Climate Data Center, 1998) were coincident, or occurred one year prior to several major avalanche years on the Wasatch Plateau. These years included 1901, 1906, 1912, 1915, 1926, 1933, 1952, 1954, 1958, 1973, 1978, 1983, 1986, 1987, and 1992. Although beyond the scope of this research, this observation might warrant further investigation.

2.4.3. *Conclusions*

With the addition of the Wasatch Plateau chronology, the range of dated avalanche events now encompasses several sites from the Wasatch Front to central Utah. The inclusion of events from the Wasatch Plateau also served to substantiate several early major avalanches prior to the 1900's and verify more recent events in the intermountain region. Since the 1900's, avalanche chronologies and historic documents indicate that large, generally widespread avalanche events occurred during the winters of 1906, 1907, 1911, 1916, 1926, 1933, 1936, 1938, 1944, 1952, 1957, 1965, 1974, 1977, 1978, 1983, 1986, 1989, and 1992. Other possible years include 1883, 1899, 1948, 1946, 1954, 1961, 1962, 1988, and 1996. Binary logistic regression analyses in addition to

classification tree analyses indicated that the probability of major avalanche years was significantly related to mean January snowfall, although model relationships were extremely low. Variability in the data resulting from potential dating errors, lack of high quality climate data and the absence of snow pack information may have prohibited obtaining higher model correlations. The results, however, also served to substantiate and enhance current explanations of intermountain avalanche classification systems. Increasing the reliability of future studies could be accomplished by 1) developing historic avalanche chronologies for a larger number of paths 2) improving dendro-ecological methods used to date avalanches, including the design for sampling avalanche paths and the procedures for analyzing tree samples, 3) better documentation of major avalanches that naturally occur in remote sites, 4) developing models to rectify historic climate data or reconstruct historic climate patterns, thus providing more complete long term climate data, and 5) creating a more extensive network of weather station instrumentation at remote sites to obtain more timely, accurate and relevant data.

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CHAPTER 3

THE SEASONAL AVAILABILITY OF HOST MATERIAL PRODUCED BY SNOW
AVALANCHES AND IMPLICATIONS FOR SPRUCE BEETLE OUTBREAKS IN
THE INTERMOUNTAIN ROCKY MOUNTAINS¹

Abstract In the Intermountain Rocky Mountains, major snow avalanches may severely damage spruce-forests resulting in large quantities of host material for spruce beetle colonization. The deposition of host material may occur at a time and in an environment optimal for successful brood development. This study examined the seasonal availability of downed spruce and the potential influence on spruce beetle production in spruce-fir forests on the Wasatch Plateau, Utah. Thirty-three matched pairs of Engelmann spruce trees were selected in the spring of 1996 for study. One tree of each pair was cut during August of 1996 (summer-felled), and the other tree in early April of 1997 (spring-felled) so trees would be colonized by spruce beetles of the same flight period. Brood adults were collected from bark samples removed from top, bottom and lateral aspects of sample pairs in October of 1998 and counted. The number of emergent adults produced in 1999 was determined from exit holes counted in bark samples removed from these same aspects. Analysis of variance was used to compare differences in the mean number of adults produced in summer versus spring-cut trees for each year. The results indicated that significantly fewer mean numbers of spruce beetles were produced in downed spruce cut during the summer of 1996 than from trees cut in the spring of 1997. More brood adults were also present in or emerged from the bottom surfaces of sample trees than

¹ Coauthored by Elizabeth G. Hebertson and Michael J. Jenkins

either unexposed (North, East) or exposed (South, West) aspects. With greater potential for spruce beetle populations to build in host material first available in the spring, snow avalanche disturbances may contribute to the risk of outbreaks.

Introduction

The spruce beetle (*Dendroctonus rufipennis* Kirby (Coleoptera: Scolytidae) is a native insect of Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) forests in the Intermountain Rocky Mountains. Endemic populations of spruce beetles typically inhabit recently fallen spruce, although declining and stressed trees will also get attacked (Dyer and Taylor 1971; Schmid and Frye 1977; Schmid 1981; Hard 1985). The spruce beetle's preference for downed trees may be due to snow that insulates the developing brood from lethally cold winter temperatures and protects beetles from predation by woodpeckers and squirrels (Knight 1958; Schmid 1981; Werner and Holsten 1985). During the warm summer months, shade and soil also serve to buffer high temperature extremes and decrease rates of evapotranspiration from the unexposed and bottom surfaces of downed logs (Graham 1924; Maser and Trappe 1984). Resources beneath these surfaces remain cool and moist providing a favorable environment for spruce beetle habitation and brood production (Massey and Wygant 1954; Dyer and Taylor 1971; Schmid 1981; Werner and Holsten 1985).

As spruce beetle populations deplete available resources, and/or the host material begins to deteriorate, they will infest living trees (Massey and Wygant 1954). The actual mechanisms responsible for triggering spruce beetle outbreaks are not well understood. Most historic outbreaks have been reported to follow extensive blow down events and

logging operations that created large amounts of downed spruce (Miller 1970; Schmid and Hinds 1974; Schmid and Frye 1977; Werner et al. 1977; Schmid 1981). Not all disturbances, however, result in the eruption of spruce beetle populations. Stand conditions, host vigor, climate, and existing population levels are all known to influence the initiation of outbreaks and rate of spread through living stands (Schmid and Frye 1976; Hard 1985; Holsten et al. 1999; Paine et al 1997; Hansen et al. 2001). The suitability of down host material may also limit the capacity of spruce beetle populations to reach outbreak levels.

Within a fallen tree, spruce beetles utilize the inner bark tissues for brood production. These tissues contain higher levels of nitrogen, soluble carbohydrates and minerals, and fewer toxins than either the outer bark or heartwood furnishing the most nutritious food resource for colonizing organisms (Graham and Cromack 1982; Maser and Trappe 1984). The relatively high moisture content of these tissues also makes them more easily digested (Anderson 1960). Inner bark tissues, however, are perishable and insects must exploit this resource before their habitat and food supply desiccate, or become altered by other organisms (Maser and Trappe 1984). The spruce beetle particularly avoids colonizing dry material. Following blow down, for example, Schmid (1981) observed that spruce beetles might attack host material during a second flight period provided the material remained fresh. Spruce beetles were also more attracted to partially uprooted trees than broken portions, or uprooted trees that had lost contact with the soil (Schmid 1981). Schmid (1977) also indicated that logging slash remained attractive only during one flight period, and that infestation was unlikely following that time.

Disturbances such as wind and logging may result in downed host material at any time during the year. If the host material is produced after peak flight, spruce beetles do not have the opportunity for colonization until the next flight period. During the interim (up to 18 months), the exposed surfaces of logs can desiccate becoming unsuitable for brood production. Competing insects, particularly spruce engraver beetles (*Ips pilifrons* Swaine (Coleoptera: Scolytidae)) can also infest the inner bark tissues usurping available resources (Schmid and Frye 1977). Insect activity accelerates the rate of desiccation and allows for the entry of other arthropods and fungi (Schmid and Frye 1977; Maser and Trappe 1984).

In mountainous terrain, snow avalanches are another important disturbance agent of spruce-fir forests (Veblen et al. 1994; Jenkins and Hebertson 1998). Rarely, unique mountain weather and snowpack conditions contribute to major avalanche events that severely damage trees within the runout zones of avalanche paths (Smith 1974; Burrows and Burrows 1976; Butler 1979; Malanson and Butler 1984). Major avalanches uproot trees or break main stems and branches creating woody debris (Burrow and Burrows 1976). This woody debris provides a local source of host material for spruce beetle colonization. Widespread avalanche cycles, such as those that occurred across the Intermountain west during the early to mid 1980's, resulted in a significant amount of host material across the landscape (Fig. 3.1).

A spruce beetle generation can take either 1 or 2 years, depending on temperature during the summer and fall following adult flight, which typically occurs in May and



Figure 3.1. Down woody material within the runout zone of the Clayton Peak avalanche path, Utah (circa 1983)

June (Hansen et al. 2001). In contrast to other disturbances, snow avalanches produce host material at a time (just prior to flight), and in an environment optimal for spruce beetle brood production. As avalanches lose momentum, they deposit snow and debris containing host material in the lower portion of the runout zone (McClung and Schaerer 1993). Snowmelt exposes the host material just prior to, or coincident with the onset of the spruce beetle flight in the spring. Shade and moisture provided by snow and piled debris would keep the condition of host material favorable for colonization and brood production. These conditions might also deter competing organisms from initially colonizing the resource.

The objective of this study was to determine if the seasonal availability of host material would influence spruce beetle production. With the potential for snow

avalanches to create suitable host material just prior to spruce beetle flight, their role might equal that of wind and other disturbances that contribute to the growth of spruce beetle populations and the initiation of outbreaks.

Methods

Study Area

The selected study area was located on the Wasatch Plateau in south-central Utah (Fig. 3.2). The Wasatch Plateau is a north-south high plateau bounded by Castle Valley to the east and Sanpete Valley to the west. The topography varies from rolling plateaus to steeper, east-west drainages and associated canyons with the highest elevations exceeding 3,300 m. Limestone rock formations with surface materials including glacial till, colluvium and alluvium characterize the geology of the area. The average annual precipitation is 70 to 90 cm that falls mostly in the form of snow. Temperatures in the area typically range from - 46 to 32° C. A neutral to unstable atmosphere predominates with winds usually from the southwest during the day and local light down canyon winds at night. Storm systems generally come from northwest or west, preceded by winds from the southwest to southeast. Engelmann spruce and subalpine fir forests occur at elevations from 2,200 to 3,000 m growing in discontinuous stands interspersed with subalpine meadows. Wildfires, landslides, and human activities have historically influenced the character of the area. These forests have been subject to an on-going spruce beetle outbreak first detected by aerial surveys in 1987 (Dymerski et al. 2001).

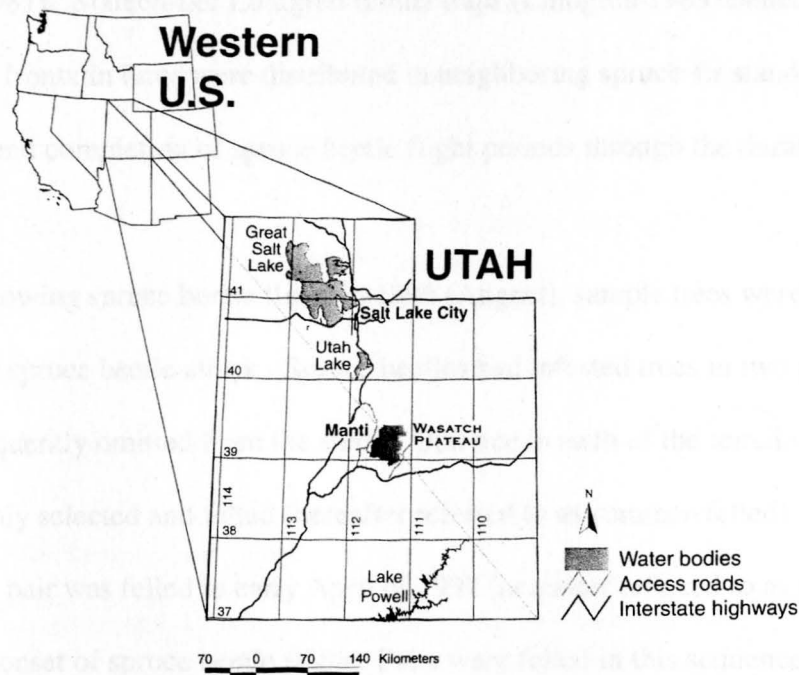


Figure 3.2. Location of the study area on the Wasatch Plateau in south-central Utah

Since that time, over 80% of spruce greater than 20 cm diameter at breast height (dbh) in infested stands have been attacked and killed by the beetles (Dymerski et al. 2001; USDA Sampling Procedures October 1994; Forest Service 2002).

Study Design

In March 1996, 33 pairs of healthy Engelmann spruce greater than 36 cm diameter at breast height (dbh) were selected as sample trees in an area where spruce beetle populations were relatively low. Trees of each pair were similar with respect to age, height and dbh. A minimum distance of 10 m was kept between all sample pairs to avoid secondary attraction that could potentially confound spruce beetle selection

(Schmid 1981). Sixteen-tier Lindgren funnel traps (Lindgren 1983) baited with alpha-pinene and frontalin lures were distributed in neighboring spruce-fir stands to monitor the beginning and completion of spruce beetle flight periods through the duration of the study.

Following spruce beetle flight in 1996 (August), sample trees were examined for evidence of spruce beetle attack. Spruce beetles had infested trees in two pairs and these were subsequently omitted from the study. One tree in each of the remaining 31 pairs was randomly selected and felled (hereafter referred to as summer-felled). The second tree of each pair was felled in early April of 1997 (hereafter referred to as spring-felled) prior to the onset of spruce beetle flight. Pairs were felled in this sequence to subject both trees to similar levels of population pressure of same flight period. Falling constraints made it impossible to keep trees within each pair oriented in the same direction. As a consequence, pairs typically did not have the same exposure to sun. All trees were tagged for identification and the location of pairs mapped for future reference.

Sampling Procedures October 1998

Spruce beetle broods in all trees were first examined in late July of 1997. The majority of larvae were in their third instar. On the Wasatch Plateau, spruce beetle populations generally had two-year life cycle and adult emergence was expected in the spring of 1999. All pairs were first sampled in October 1998 by removing a 480 cm² bark sample from the top, bottom and sides of all trees at 1.5 and 3 m locations from the base of the log (8 samples per tree). The majority of the beetles observed within the bark samples had developed into brood adults. Exposed, live spruce beetles and other insects

were captured and placed in vials. The bark samples were then dissected to remove beetles and other insects residing deeper within the bark tissues. Any pupae or larval life stages found were placed in vials containing 70% ethyl alcohol. The vials were then labeled for identification and refrigerated. In this sampling, spruce beetle density per unit of bark surface area was used to determine brood production for sample trees. The density of beetles was quantified by counting the number of living brood adults, pupae and larvae collected from bark samples.

Sampling Procedures June 1999

During the winter of 1998-1999, spruce stands within the study area were logged resulting in the loss of five more sample pairs. Following peak spruce beetle flight in June of 1999, the remaining pairs were sampled a second time by removing bark samples using the same procedures as in October 1998 (8 samples per tree). To determine the number of adults that emerged from each bark sample, the number of exit holes was counted. However, because emergent adults might utilize a previously constructed exit hole (Cunningham 1997), it was necessary to first determine a number of beetles per exit hole ratio. This was accomplished by cutting 60 cm long bolts from trees of five sample pairs in early spring of 1999 prior to spruce beetle flight. The ends of each bolt were waxed to prevent desiccation, then, the bolts were placed in an upright position and caged using mesh screening stapled to the former bottom surface. Each cage covered a bark surface area of approximately 960 cm². A vial was attached underneath each cage to capture emerging adults during the flight period. Beetles were collected from these vials two to three times per week and counted. At the termination of flight, the bark

underneath the caged areas was removed and the number of emergence holes in each sample was counted. Once the number of exit holes in each bark sample had been determined, it was compared to the number of beetles collected from corresponding cages. Using these data, the mean number of beetles to emerge per hole was calculated. On average, 2 and 3 brood adults emerged per exit hole from bark samples of summer-felled and spring-felled trees, respectively (Table 3.1). Mean differences in the number of beetles, exit holes and emerged beetles per exit hole between summer-felled and spring-felled trees were significantly different (Table 3.1). As a result, it was determined that multiplying the number of exit holes in bark samples from summer-felled cut trees by 2, and spring-felled cut trees by 3 would provide reliable estimates of the total number of adults that emerged from those samples. In some cases, it was difficult to differentiate between exit holes and the variety of other holes that spruce beetles created during attack and gallery construction. Exit holes were therefore only counted if they were associated with sites of pupation.

Data Analyses

Proc Mixed (SAS© Institute, Release 7.01) was used to test for differences in the mean number of brood adults prior to winter (October 1998 samples) and mean adult emergence (June 1999 samples) taken from the summer-felled and spring-felled trees. Fixed effects included in the model were 1) season [with two levels: summer-felled and spring-felled], 2) downed tree orientation [with two levels: North-South and East-West], and 3) aspect [with three levels: unexposed (i.e. North and East), exposed (i.e. South and West), and bottom]. Because spruce engraver beetles only colonized the top surfaces of

Table 3.1. Mean number of spruce beetles to emerge per exit hole from caged bolts of summer and spring-felled trees in June 1999

	<i>n</i>	<i>df</i>	summer-felled	spring-felled	<i>t</i>	<i>s</i>	<i>p</i>
Spruce Beetles	5	4	15	45	-4.69	-29.6	0.009
Exit Holes	5	4	8	15	-3.31	-7.2	0.030
Beetles per Hole	5	4	2	3	-3.04	-1.1	0.038

sample trees, these were not included in the analysis. Random-effects factors included sample pairs, trees within pairs and bark samples from trees within pairs. The data normalized prior to the analysis using a square root transformation. Where appropriate, Tukey-Kramer pairwise comparisons were used to test differences among main-effect means. Models for each year were fit using PROC MIXED in SAS (SAS[®] Institute, Release 7.01).

Results

The total number of brood sampled in October 1998, and emergent adults sampled following flight in June 1999 from paired trees pooled across downed tree orientation and aspect are given in Table 3.2. In ninety percent of the trees sampled in October 1998, a greater number of beetles were collected from bark samples of spring-felled cut trees compared to trees cut in the summer. Greater adult emergence in 1999 was also estimated for samples collected from spring-felled trees. Scatter plots of total brood in spring-felled verses summer-felled trees show considerable variability in the data, particularly in samples collected in June of 1999 (Figures 3.3 and 3.4). Sources of unexplained variation may have included local differences in spruce beetle population densities, microclimate, topography, and stand conditions. Spruce beetle emergence was

Table 3.2. Total number of brood adults produced in October 1998, and emergent adults estimated in June 1999 from paired trees pooled over tree orientation and bark aspect

Pair ID	October 1998		June 1999	
	summer-felled	spring-felled	summer-felled	spring-felled
13	34	98	20	159
14	1	135	0	183
15	47	102	-	-
17	92	230	24	282
18	71	180	-	-
19	46	122	30	228
20	160	373	50	328
23	50	111	6	291
24	64	154	38	220
34	3	12	24	50
35	24	50	2	51
37	1	33	24	48
38	44	122	24	86
39	2	26	12	19
41	56	17	-	-
42	53	58	18	60
43	14	97	28	72
44	6	36	-	-
48	23	126	54	348
49	139	208	46	277
60	5	24	53	27
61	36	147	0	27
62	54	142	28	144
63	19	113	18	87
64	17	54	30	144
65	37	83	40	141
66	57	27	56	75
67	29	101	34	81
68	109	96	32	69
69	73	114	60	102
76	14	79	-	-

*Total numbers determined from actual beetle counts

† Total numbers estimated by multiplying emergence hole counts of summer-felled trees by 2, and spring-felled trees by 3

- No data

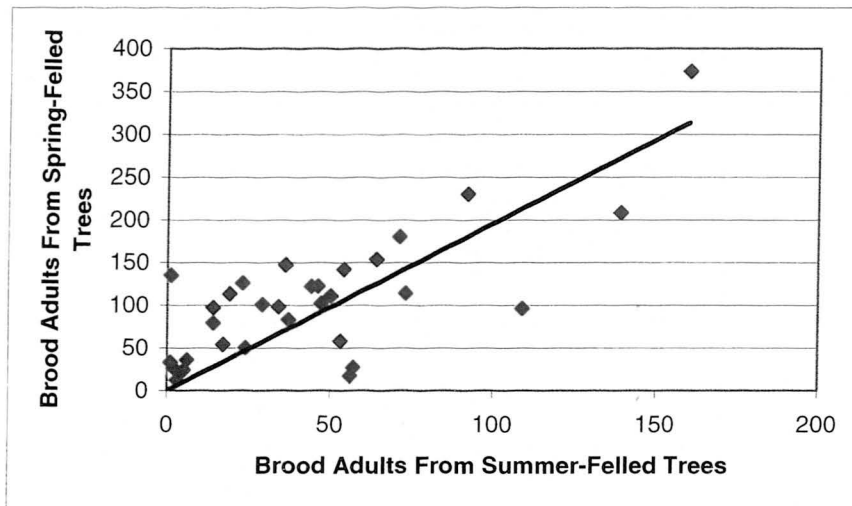


Figure 3.3. Total number of brood adults collected from summer-felled verses spring-felled trees of each sample pair pooled over tree orientation and bark aspect in October 1998

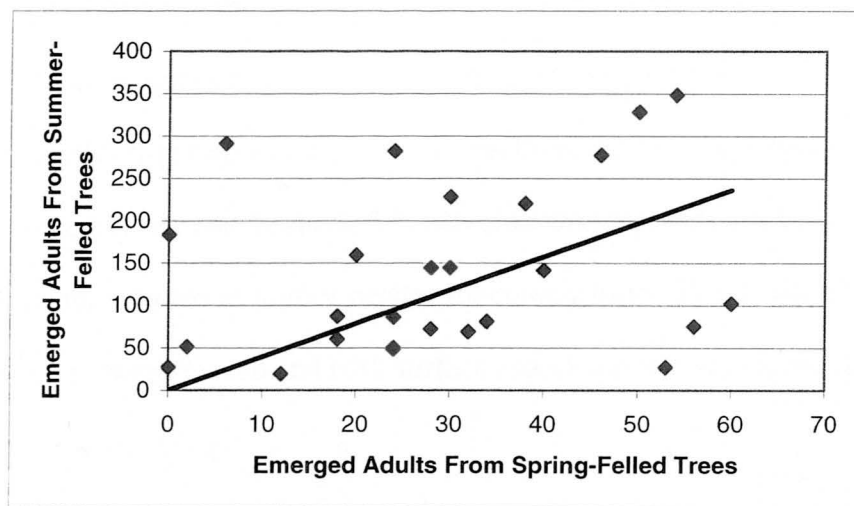


Figure 3.4. Total number of emergent adults estimated from exit hole counts of summer-felled verses spring-felled trees of each sample pair pooled over tree orientation and bark aspect in June 1999

also estimated from exit hole counts in 1999 perhaps affecting the reliability of these data. Even with this variation, however, regression lines plotted for data in both years indicated that season influenced spruce beetle brood production with the majority of cases lying above the regression line. The results of mixed model procedures for both years supported these observations. Season explained a significant source of variation ($p < 0.001$) in spruce beetle production in both years (Tables 3.3 and 3.4). The least squares means of spruce beetle numbers in both 1998 and 1999 were significantly higher in spring-felled versus summer-felled trees (Table 3.5).

Aspect provided another significant source of variation in the models derived for both years ($p < 0.001$) (Tables 3.3 and 3.4). Greater mean numbers of brood adults were present in or emerged from the bottom surfaces of sample trees than either unexposed (N, E) or exposed (S, W) aspects (Tables 3.6 and 3.7). Although tree orientation had no significant effect on spruce beetle numbers, unexposed surface aspects produced greater numbers of beetles than exposed aspects (Tables 3.6 and 3.7). These results support the findings of others (Dyer and Taylor 1971, Schmid 1981) that bark surface aspect strongly influences niches selected by spruce beetles for colonization. The model also found that the interaction between season and bark surface aspect was weakly significant ($p = 0.118$).

Discussion

The Suitability of Host Material

The suitability of downed host material has long been recognized as an important

Table 3.3. Results of mixed model procedures for spruce beetle brood production in October 1998

Tests of Fixed Effects				
Source	df	Error term	F	P
Season	1	Tree(Pair)	76.47	<0.001
Orientation	1	Tree(Pair)	0.74	0.396
Season*Orientation	1	Tree(Pair)	1.00	0.325
Aspect	2	Residual	120.51	<0.001
Season*Aspect	2	Residual	2.18	0.118
Orientation*Aspect	2	Residual	0.89	0.415
Season*Orientation*Aspect	2	Residual	1.22	0.300
Covariance Parameter Estimates				
Parameter	df	Estimate		
Pair	30	2.38		
Tree (Pair)	28	0.44		
Residual	116	1.81		

Table 3.4. Results of mixed model procedures for spruce beetle brood production in June 1999

Tests of Fixed Effects				
Source	df	Error term	F	P
Season	1	Tree(Pair)	54.39	<0.001
Orientation	1	Tree(Pair)	0.03	0.860
Season*Orientation	1	Tree(Pair)	3.50	0.070
Aspect	2	Residual	29.43	<0.001
Season*Aspect	2	Residual	4.61	0.010
Set*Aspect	2	Residual	1.74	0.180
Season*Orientation*Aspect	2	Residual	0.16	0.850
Covariance Parameter Estimates				
Parameter	df	Estimate		
Pair	26	0		
Tree (Pair)	24	1.79		
Residual	93	3.86		

Table 3.5. Least squares means for spruce beetle counts of summer and spring-felled trees in October 1998 and June 1999*

Season	Mean [†]	68% CI
<i>October 1998</i>		
Summer	45	(38, 42)
Spring	105	(88, 118)
<i>June 1999</i>		
Summer	29	(26, 32)
Spring	138	(118, 158)

* Data estimated by multiplying emergence hole counts of summer cut trees by 2, and spring cut trees by 3
[†] Adj. $p < 0.001$

Table 3.6. Least squares means and differences of least squares means by aspect for spruce beetle counts in October 1998

Least Squares				
Aspect	df	Mean	68% CI	
B	116	38.0	(33.7, 42.3)	
U	116	14.0	(11.3, 16.7)	
E	116	5.7	(4.0, 7.4)	
Differences of least squares				
Aspect	df	Mean	Pr > t	Adj P
B vs U	116	24.0	<0.001	<0.001
B vs E	116	32.3	<0.001	<0.001
U vs E	116	8.3	<0.001	<0.001

B = bottom; U = unexposed; E = exposed

Table 3.7. Least squares means and differences of least squares means by aspect for spruce beetle estimates in June 1999*

Least Squares				
Aspect	df	Mean	68% CI	
B	93	36.2	(31.9, 40.5)	
U	93	15.1	(12.4, 17.8)	
E	93	8.8	(6.7, 10.9)	
Differences of least squares				
Aspect	df	Mean	Pr > t	Adj P
B vs U	93	21.1	< 0.001	< 0.001
B vs E	93	27.4	< 0.001	< 0.001
U vs E	93	6.2	0.023	0.060

*Data estimated by multiplying emergence hole counts of summer cut trees by 2, and spring cut trees by 3; B = bottom; U = unexposed; E = exposed

factor for spruce beetle colonization and brood production (Massey and Wygant 1954; Schmid and Frye 1977). The results of this study are unique in demonstrating that the time of year when host material becomes available is associated with the number of brood adults ultimately produced. Although no attempt was made to quantify the physical attributes of downed spruce in this study, visual inspection of pairs over time indicated that spring cut trees possessed attributes consistent with those of downed host material typically preferred by spruce beetle for colonization. Factors observed to limit the suitability of downed trees for spruce beetle colonization and brood production in this study included desiccation, bark surface aspect, and competition with other organisms.

Factors Contributing to Tree Desiccation. At the initiation of spruce beetle flight, in late May of 1997, spring-felled trees showed no evidence of desiccation. The outer bark of trees examined remained intact and adhered to the bole. Bark samples removed from various aspects of several trees revealed that the inner bark and cambium

was moist and suitable for spruce beetle habitation. Inspection of spruce felled the previous summer (August 1996), however, indicated that trees had begun to dry out. A combination of factors likely contributed to the initial desiccation of these trees. During summer, downed trees are subjected to longer days, warmer air temperatures and decreased precipitation and relative humidity (Maser and Trappe 1984). These factors combine to alter the moisture content of substrates within downed host material. Desiccation appeared most advanced in top and exposed lateral aspects. Maser and Trappe (1984) indicated that with direct sun exposure, the water-holding capacity of substrates changes in response to dramatic evapotranspiration accelerating the drying process. The desiccation of these surfaces was likely accelerated by the colonization of engraver beetles.

By late October 1996, engraver beetles had colonized the top and lateral surfaces of some summer-felled trees. Maser and Trappe (1984) suggested that once insects created entrance holes, the outer bark no longer protected the inner bark and cambium from the drying effects of sun and wind. By the summer of 1997 (one year later), the bark of top and exposed lateral aspects (South and West) exhibited signs of desiccation including the presence of small fissures. In extreme cases, the outer bark had begun to peel. The removal of bark samples from these aspects revealed the presence of adult engraver beetles and larvae, with the inner bark tissues thoroughly mined by their feeding and other activities. By penetrating the outer bark, the engraver beetles potentially opened the inner bark and sapwood to invasion by other insects and decomposers. The combined activity of all organisms may have fragmented the bark tissues creating greater surface area for moisture loss and exposing the cambium and sapwood (Maser and

Trappe 1984). With exposure, the rate of desiccation in these tissues would accelerate due to their greater porosity (Maser and Trappe 1984).

Woodpecker feeding may have also contributed to the initial desiccation of summer-felled trees (Knight 1958). Following snowmelt in spring 1997, bark flakes removed by searching woodpeckers were often found beneath trees. The loss of outer bark resulting from woodpecker feeding likely exposed the inner bark and sapwood to the drying effects of the sun and wind. McCambridge and Knight (1972) also observed that woodpeckers contributed indirectly to additional mortality by hastening bark desiccation of spruce beetle infested trap trees.

Although the level of spruce beetle mortality attributed directly to desiccation was not determined, mummified beetles of various life stages were often found in bark samples removed from exposed aspects. Vigorous spruce beetle larvae in August 1997 trees were most evident under moist, unexposed portions of trees with intact outer bark. The top and exposed lateral aspects of these trees were usually void of bark by the summer of 1998. The exposed upper portions of spring-felled trees eventually dried out as well. The outer bark of most trees, however, generally remained intact until late summer of 1999. This probably protected the developing brood from the effects of desiccation until maturity was reached. Mature brood adults had greater mobility and the capability to seek out suitable habitat beneath the bark until emergence.

The Influence of Bark Surface Aspect. Sun exposure altered the moisture content of substrates on exposed bole aspects and likely served to accelerate their rates of desiccation. Associated warm temperatures may have also had a direct influence on spruce beetle colonization and brood production (Graham 1924; Dyer and Taylor 1971).

Significantly more brood adults were associated with unexposed bark aspects as opposed to exposed bark aspects. This result suggests that 1) colonizing spruce beetles preferentially selected unexposed aspects resulting in higher attack rates and subsequently, greater brood densities, and/or 2) the condition of resources beneath unexposed aspects was more favorable for brood survival. Spruce beetles preference for the unexposed aspects of downed material may have evolved in response to the extreme temperatures characteristic of high elevation environments. Temperatures of spruce-fir sites can range from 32°C in August, to - 15°C in January (Alexander 1987). Temperatures below - 15°C will kill adult beetles, while larvae begin to die at temperatures below - 40°C (Massey and Wygant 1954; Frye et al. 1974). With soil temperatures remaining close to freezing during winter, the undersides of downed material may protect spruce beetles from lethally cold temperatures. Snow cover may also insulate downed material reducing brood mortality (Frye et al. 1974). Mitchell and Schmid (1973) found that varying percentages of brood mortality occurred at temperatures above 78° C. Schmid (1977) observed that spruce beetles avoided logging residuals exposed to direct sunlight. The unexposed aspects of down spruce tended to remain cool during summer months allowing spruce beetles to escape heat. Spruce beetles also avoided inhabiting the inner bark and cambium of exposed surfaces of standing dead spruce, even though these tissues remained moist.

Season in combination with bark aspect also influenced spruce beetle brood production in both years. This result indicates that the importance of season with respect to the creation of host material and spruce beetle population dynamics is related to

timing. For example, regardless of when a disturbance produces host material, spruce beetles will infest those portions of downed trees that have remained suitable for habitation. These are generally the bottom and unexposed bole aspects. When disturbances produce host material in the late summer, however, bottom and unexposed aspects have time to deteriorate prior to the colonization phase of the insect. This results in a reduction of available habitat for brood production. With the exposure of fresh host material coincident with spruce beetle flight in the spring, suitable habitat for colonization is maximized. Resources within fresh host material would also remain favorable for spruce beetle broods through the duration of their development.

Effects of Other Organisms. Competition with engraver beetles and other organisms for resources within downed spruce also explains the greater production of spruce beetle adults in spring cut trees. Engraver beetles were first to exploit suitable substrates in summer-felled spruce making these trees amenable to many other insects, saprophytic fungi and bacteria. By late summer 1996, engraver beetles had colonized the top and lateral surfaces of all summer-felled trees. Attacks by late flying spruce beetles were not evident on any trees examined at this time. Initial engraver and spruce beetle colonization, however, was coincident in trees felled during April of 1997. This timing potentially allowed spruce beetles to become successfully established in desirable substrates before extensive colonization by engravers and other organisms. Other scolytid beetles often found inhabiting the inner bark included species from the genera *Polygraphus*, *Scierus*, *Dryocoetes*, *Pityophthorus*, *Pityokteines* and *Pityogenes* (Coleoptera: Scolytidae). The presence of these beetles could have subsequently attracted spruce beetle predators. Ambrosia beetles (*Trypodendron* spp. Coleoptera:

Scolytidae) were also common in the wood tissues of downed trees and stumps.

Fungal mycelia and wood stain became apparent in inner bark and wood tissues of Summer-felled cut trees by the spring of 1997. Fungi and microorganisms compete for food and cause chemical alterations that diminish the quality of substrates for habitation (Maser and Trappe 1984). Unidentified fungi also infected some spruce beetle larvae and living adults contributing to mortality.

Although their abundance and potential impact on spruce beetle populations were not determined, predaceous beetles including species in the genus *Thanasimus* (Coleoptera: Cleridae) and the genus *Rhizophagus* (Coleoptera: Rhizophagidae) were observed feeding on spruce beetle larvae and adults. Insect parasites causing larval mortality included *Coeloides* species (Hymenoptera: Braconidae) and unidentified flies (Diptera).

Snow Avalanches and Spruce Beetle Implications

Few studies have examined the influence of snow avalanche disturbance on spruce beetle population dynamics. Veblen and others (1994) investigated spatial relationships between historic spruce beetle outbreaks, fire and snow avalanches in Colorado and concluded that outbreaks were not related to snow avalanche disturbance because spruce growing within avalanche paths were generally too small to support beetle populations. Their study, however, failed to consider the importance of available host material to the population dynamics of the insect. This study indicates that major avalanches may contribute to the risk of spruce beetle outbreaks because host material becomes available at a time optimal for colonization and remains more suitable for

successful brood production. Spruce beetle populations could potentially build to outbreak levels following major snow avalanche events and/or widespread avalanche cycles that result in an abundance of host material. With depletion of the resource, adults could initiate attacks on living trees.

Snow avalanches could also contribute to the spread of spruce beetle populations in several ways. In the Rocky Mountains, stands with a high hazard of outbreak are typically comprised of more than 65% spruce, with diameters greater than 40 cm dbh and basal areas exceeding 32 m² per hectare (Schmid and Frye 1976; Reynolds and Holsten 1994). Undisturbed stands adjacent to avalanche paths and runout zones often have structures and compositions well within this range of susceptibility. Optimal conditions for Engelmann spruce occur at mid to high elevations (2,600 to 3,200 m) on cool, moist northerly sites (Alexander 1987; Long and Barrett 1994). These same physiographic locations are also prone to snow avalanches during winter. Weak snowpack structures tend to persist on cold, shaded, northerly aspects (Armstrong and Armstrong 1987). With prevailing winds, large cornices develop along north-facing ridgelines and northerly slopes often become loaded with wind deposited snow. Avalanches occur when loading from heavy snowfall, wind transported snow, or a trigger, such as cornice fall, imparts excessive stress on the snowpack (Fredston and Fesler 1999). Dense stands comprised of high percentages of large diameter spruce also occur at lower elevations in cool, moist creek bottoms and drainages (Alexander 1987). These stands have the highest risk for spruce beetle attack (Knight 1958) and generally coincide with the maximum extent of avalanche deposition.

Both chronic avalanching and infrequent, large slides disrupt root systems and

cause cambial damage that weakens trees adjacent to paths (Burrows and Burrows 1976). Spruce subjected to continual environmental stress, often show increased susceptibility to beetle attack. In Alaska for example, spruce beetles were more likely to attack large diameter trees with significantly less mean radial growth in recent years than comparable trees with average or higher mean radial growth (Hard 1985). Stress induced by avalanche damage can also predispose injured trees to root disease and decay pathogens, especially when trees are subject to numerous events (Gregory et al. 1991; Wargo and Harrington 1991). Root diseases in particular can further increase the susceptibility of infected trees to bark beetle attack (Cobb 1989). The distribution of root diseases is generally restricted to more mesic sites (McDonald 1999) that often include lower avalanche runout and deposition zones. Root disease fungi also survive saprophytically in woody substrates in the soil, and spread through the soil to infect the roots of living trees (Redfern and Filip 1991). As a result, woody avalanche debris may provide a food base for root disease inoculum on the site. Some evidence suggests that wounded or physiologically weakened roots may also provide entry courts for root diseases and other pathogens (Redfern and Filip 1991). As a result, injuries inflicted by avalanches may facilitate the infection process.

Conclusions

The results of this study indicate that the seasonal availability of host material influences spruce beetle brood production. Significantly greater numbers of brood and emergent adults were produced in spring-felled spruce than in spruce felled the previous August. With greater potential for spruce beetle populations to build in downed host

material first available in spring, snow avalanche disturbance may contribute to the risk of outbreaks. Dense stands comprised of large spruce within avalanche runout zones can facilitate the spread of spruce beetle populations. Stress and damage associated with injury and subsequent infection by diseases further increases the susceptibility of living trees to spruce beetle attack. With susceptible spruce-fir stands in the vicinity of avalanche prone terrain, land managers could devise strategies for minimizing the risk of spruce beetle outbreak following major avalanche events.

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CHAPTER 4

AN INVESTIGATION OF HISTORIC SPRUCE BEETLE OUTBREAKS AND
MAJOR SNOW AVALANCHE YEARS IN UTAH AND COLORADO¹

Abstract This study investigated potential relationships between major snow avalanche years, climate and spruce beetle outbreaks between 1905 and 1996 in portions of northern and southeastern Utah and western Colorado. Chronologies of avalanche and outbreak years were constructed from historic records, research papers, newspapers and other sources of information. Preliminary examination of the historic chronologies suggested that several major avalanche years were coincident with spruce beetle outbreaks at the turn of the last century and during periods from 1911-1916, 1938-1944, 1957-1962, 1965-1968, and 1982-1989. Historic climate data for the region were obtained from the National Climate Data Center and included mean monthly temperature and precipitation variables, in addition to Palmer Drought Severity Index values. Classification tree analysis (CART) was used to predict historic spruce beetle outbreaks from major avalanche years, and climate variables. Of the variables considered in the CART analysis, major avalanche years were not identified as significant in predicting the probability of spruce beetle outbreaks during the period of study. The variables identified as most significant included mean December temperature, mean September temperature one year prior to outbreak, the mean estimated PDSI value of the 5-year period prior to outbreak, and mean October precipitation. The resulting model correctly classified non-outbreak and outbreak years 67% and 70% of the time, respectively, although,

¹ Coauthored by Elizabeth G. Hebertson and Michael J. Jenkins.

unexplained variability in the data resulted in low model correlations. These results, however, are consistent with climate factors known to influence spruce beetle epidemiology.

Introduction

Snow avalanches hold great importance for people who live and work in mountainous locations. Every winter, snow avalanches result in extensive property damage, interrupt transportation corridors and harm people (McClung and Shaerer 1993). As a consequence, much research has been devoted to understanding mountain weather and climate, properties of the mountain snowpack, terrain characteristics and avalanche mechanics and dynamics. This information has allowed snow scientists and avalanche professionals to develop and employ a variety of tools and strategies for avalanche forecasting, protection, land use planning, and education.

Because snow avalanches commonly disturb alpine and subalpine ecosystems, they also have broad ecological implications. Snow avalanche disturbance in conjunction with local topography often determines the distribution and assemblages and successional stage of plant species in avalanche paths (Smith 1974; Butler 1979; Malanson and Butler 1984; Butler 1985). Grasses, herbaceous plants and shrubs typically occupy the inner portion of avalanche paths frequently disturbed by small avalanches and where snow deposition retards plant growth (Smith 1974; Cushman 1976; Butler 1979; Malanson and Butler 1984). Deer, elk and other ungulates benefit from the diverse and nutritious forage these plant communities provide (Krajick 1998). Stands of small trees and shrubs become established toward the flanks of paths where avalanche return intervals average

approximately 5 years (Malanson and Butler 1984). Increasingly older deciduous trees and conifers comprise the margins and trim lines of avalanche paths that experience less frequent avalanching (Malanson and Butler 1984).

Rarely, unique combinations of weather, terrain and the mountain snow pack result in major avalanches and/or widespread avalanche cycles. These events may be attributed to the development of unusually unstable snow structures when continental-like climate patterns prevail, or occur during winters characterized by heavy seasonal snowfall, or rain (Roch 1949; LaChapelle 1966; Armstrong and Armstrong 1987; Mock and Kay 1992; Changnon 1993; Mock and Birkland 2000; Birkland and Mock 2001; Hebertson and Jenkins, Chapter 2). Major avalanches often cause extensive damage to forests adjacent to avalanche paths (Figure 4.1). Stress caused by stem breakage, wounds and severe root system disruption predispose injured trees to attack by insects and decay fungi (Cobb 1989; Wargo and Harrington 1991). Dead, broken and uprooted trees may contribute to local fuel loads and increased fire hazard (Taylor and Fonda 1990). The production of downed woody materials, however, also benefits many terrestrial animal species by providing food, shelter, hiding cover and breeding habitat (Dueser and Shugart 1978; Bartels et al. 1985; Hecnar 1994; Butts 1997; Krajick 1998; Ruggiero et al. 1998). Wounds on trees damaged by avalanches can serve as entry courts for decay fungi that over time create cavities important for nesting birds (Miller et al. 1979). The deposition of woody avalanche debris in streams stabilizes channels and creates pools that enhance habitat for fish and other water-dwelling species (Bilby and Likens 1980; Dudley and Anderson 1982; Sedell et al. 1988). Conversely, the rupture of debris jams can also scour stream channels destroying critical spawning habitat (Sedell et al. 1988). Downed woody

material prevents erosion from wind, rain and melting snow and facilitates the regeneration of trees by trapping soil and litter and providing shade (Maser et al. 1988; Harmon and Franklin 1989). The decomposition of woody material contributes organic matter to the soil and is important for nutrient cycling (Maser et al. 1988; Arthur and Fahey 1990; Edmonds and Marra 1999). Avalanche paths also create discontinuities in otherwise contiguous forests that can influence the spread of fire (Veblen et al. 1994).

Major snow avalanches and/or widespread avalanche cycles affecting spruce-fir forests can also produce large quantities of downed host material for the Engelmann spruce beetle (*Dendroctonus rufipennis* Kirby (Coleoptera: Scolytidae). Endemic populations of spruce beetles typically infest the inner bark of downed spruce to mate and lay eggs. After hatching, spruce beetle larvae feed and develop within the inner bark until they have reached maturity. The life cycle of the spruce beetle commonly requires 2 years, although 1 and 3-year populations often occur (Massey and Wygant 1954). With insufficient quantities of downed host material, newly emerged adults may attack and kill live trees (Schmid and Frye 1977). Since the late 1980's, a spruce beetle epidemic has resulted in death of over 1 million mature and old growth spruce on the Manti-LaSal and Dixie National Forest in south-central and southern Utah (Dymerski et al. 2001; Matthews et al. 2002). Similar levels of spruce mortality were documented for historic epidemics in Utah, Colorado, Arizona and New Mexico during the mid 1800's, 1916-1928, 1940's, and the 1950's. Extensive spruce beetle tree mortality modifies stand structure and species composition in affected forests with reductions in average spruce diameter, height, basal area and age (Baker and Veblen 1990; Veblen et al. 1991; Veblen et al. 1994). Heavy spruce mortality can adversely affect watershed, timber, wildlife,

aesthetics, and recreational resources (Bethlahmy 1974; Schmid and Frye 1977; Holsten et al. 1999). Spruce beetle mortality can also alter fuel loads and profile development potentially resulting in high fire hazard over time (Schmid and Frye 1977; Arno 1980, Jenkins et al. 1998). The lack of bare, mineral soil following beetle disturbance may deter the establishment of spruce seedlings (White 1979). Stands affected by past beetle outbreaks generally have a scarcity of spruce older than 140 years and non-host species typically become stand dominants (Veblen et al. 1994; Jenkins et al. 1998).

Historic spruce beetle epidemics in the western United States have been mainly attributed to blowdown and timber harvesting activities. The potential role of other disturbances such as major snow avalanche events and/or widespread avalanche cycles in initiating outbreaks, however, has remained relatively unexplored (Schmid, *pers. comm.*²). Local spruce beetle-caused tree mortality often is observed in forests adjacent to avalanche runout zones (Figure 4.1). Snow avalanches produce downed host material at a time and in an environment optimal for successful spruce beetle colonization and brood production (Hebertson and Jenkins, Chapter 3). Spruce beetles begin flight in the spring just when melting debris exposes fresh host material. Avalanche debris covering host material helps prevent desiccation and deters competing insects and fungi from initial colonization. The deposition of host material typically coincides with lower slope positions in drainages and creek bottoms and on aspects sheltered from direct sun. These conditions provide an optimal environment for successful spruce beetle colonization and

² John M. Schmid, Forest Entomologist (retired), Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO



Figure 4.1. An aerial photo of spruce beetle mortality adjacent an avalanche path in Utah brood production. Spruce beetles may also attack large spruce within runout zones that have been seriously injured by avalanche debris.

Unprecedented large, widespread avalanche cycles during the winters of 1982 to 1986, for example, may have contributed to the most recent spruce beetle epidemic on the Wasatch Plateau in south-central Utah. Small pockets (1-10 trees) of spruce beetle mortality were first aerielly detected on the Wasatch Plateau in 1986 in the vicinity of several large avalanche paths. The occurrence of avalanches dated in these paths fit within the time frame expected for spruce beetle populations to build in host material and initiate attacks on live trees.

This study investigated the potential relationship between major avalanche years and historic spruce beetle outbreaks in the Intermountain and southern Rocky Mountains. Several historic climate factors including regional temperature, precipitation and drought severity were also examined to help elucidate the nature of this relationship.

Methods

The Study Area

The study area encompassed the Wasatch Range in northern Utah, the Uinta Basin, High Plateaus and Canyonlands portions of the Colorado Plateau in south-central and southern Utah and western Colorado, and the southern Rocky Mountains in southern Colorado (Figure 4.2). Mountains and high plateaus characterize most of this region with principal ranges such as the Wasatch Mountains and Southern Rocky Mountains in Colorado running north and south. The Uintas in northeastern Utah are the only major mountain range that runs east and west in the United States. Elevations of the highest crest lines in Utah are mostly above 3000 m but do not exceed 4250 m. The majority of peaks in the southern Rocky Mountains of western Colorado, however, range between 3330 m to over 4200 m. A large portion of storms originating over the Pacific Ocean lose moisture over the Sierra or Cascade ranges resulting in an arid or semi-arid climate over this area. Low-pressure systems that approach from the south or southwest deliver the majority of precipitation to the area (Jensen et al. 1990). Annual precipitation amounts to less than 20 cm at lower elevations. The highest elevations, however, may receive over 65 cm of annual precipitation falling mainly as snow in winter months. Winter temperatures during extremely cold periods may reach -45.6°C with maximum summer temperatures reaching 32°C to 35°C in the mountains. Engelmann spruce (*Picea engelmannii* Parry ex Engel.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.)

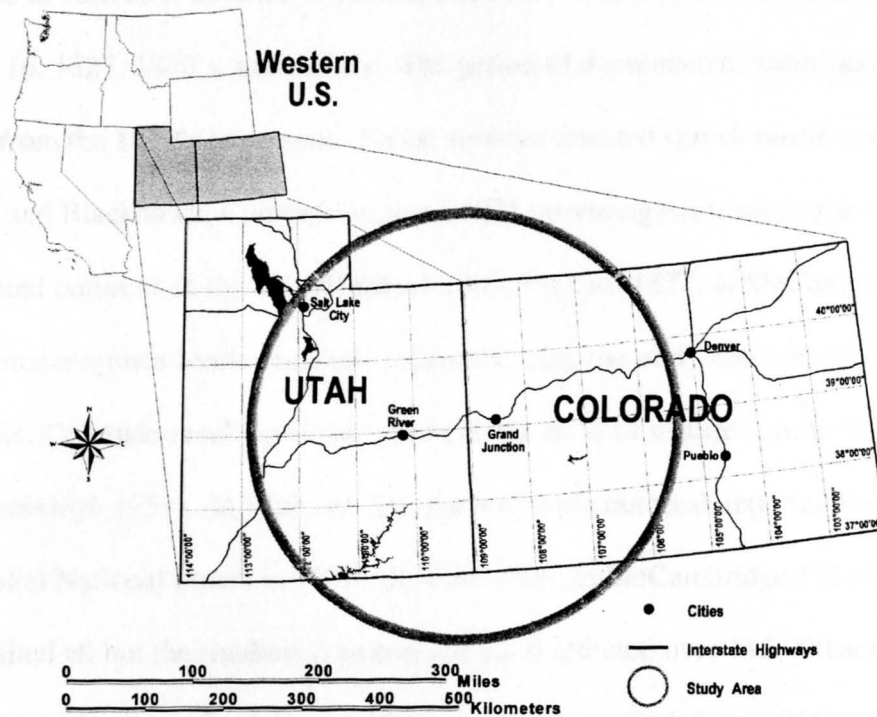


Figure 4.2. The general study area

forests occur at elevations from 2,400 to 3,300 m often interspersed with meadows.

Historic Spruce Beetle Outbreaks

A chronology of historic spruce beetle outbreaks within the area was constructed from various sources including United State Department of Agriculture (USDA) forest insect reports and biological evaluations, research papers and personal communications. Few records of outbreaks exist prior to the 20th century, most likely due to limited access and the detection methods available during that time. Veblen and others (1994) and Eisenhart (1999), however, used dendrochronological techniques to date several early

outbreaks in various sites in northwestern Colorado. These years included *circa* 1490, 1585, 1716, 1827, 1840's, and 1870's. The period of documented outbreaks for this area extends from the 1870's to present. Forest surveys detected spruce beetle activity near Manitou and Blackhawk, Colorado in about 1875 providing evidence of the oldest documented outbreak in the area (Hopkins 1909; Packard 1877, *in* McCambridge 1951). Another major spruce beetle outbreak occurred during the mid 1880's in the vicinity of Deep Lake, Colorado resulting in the loss of about 20 % of mature spruce (Hopkins 1906, *in* McCambridge 1951). In Utah, the first spruce beetle outbreak reported was on the Manti-LaSal National Forest in 1905 (Hopkins 1906, *in* McCambridge 1951). Spruce beetles killed all but the smallest diameter trees and affected over 115,000 acres in a more devastating outbreak on the Aquarius Plateau in southern Utah from 1916 and 1928 (Mielke 1950). The largest, most widely documented outbreaks occurred during 1941 to 1952 on the Routt National, Grand Mesa, Umcompahgre and San Juan National Forests in Colorado (McCambridge 1951; Massey and Wygant 1954; Schmid and Frye 1977). Localized outbreaks affected spruce-fir forests in both Colorado and Utah during the 1950's. More recently spruce beetles have killed over 1 million trees since 1987 on several National Forests in south-central and southern Utah (Matthews et al. 2002).

Historic Snow Avalanches

A chronology of major snow avalanche years for the area was compiled from late 19th, and early 20th century reports in the Park Mining Record, Volumes 28, 31, and 40 (Park City, Utah), and several other sources providing historic accounts (Gallagher 1967; Gilliland 1980; Kilpatrick 1982; Williams and Armstrong 1984; UDOT 1987; Kalatowski

1988; Tremper 1992; Martinelli and Leaf 1999). Dates of major avalanches for paths in the Wasatch Mountains and the Wasatch Plateau in south-central Utah also were obtained from chronologies constructed using dendro-ecological methods (Jenkins and Hebertson 1994; Hebertson and Jenkins, Chapter 2). Dendro-ecology utilizes tree ring analyses along with the examination of scars, reaction-wood formation, suppressed growth, tree age, vegetative conditions and other indicators of avalanche damage to date disturbance events. These methods have proven useful for dating snow avalanches in previously undocumented paths and are described in detail elsewhere (Smith 1974; Burrows and Burrows 1976; Schroder 1978; Bryant et al. 1989; Jenkins and Hebertson 1994; Rayback 1998; Hebertson and Jenkins, Chapter 2). The Utah avalanche chronologies included No Name in Snowbasin, Nordic Knob in Park City, American Fork Canyon and Bridal Veil Falls in Provo Canyon and Little Pine East, Ben Hame, Culp's West Hellgate, and East Hellgate all in Little Cottonwood Canyon. Although these sources might indicate the occurrence of major avalanches and avalanche cycles for a particular location in a given year, only those major avalanche years documented in more than three different locations throughout the entire area were used in this study. Major avalanche years were also lagged at 3 and 5 years after their occurrence. These lag variables were included to account for the time required for spruce beetle populations to build in downed host material and the time when mortality may have been first detected.

Historic Climate Data

Climate data obtained from the National Climate Data Center (1994) for Divisions 4, 5, and 7 in Utah, and Division 2 in western Colorado, was used to examine

historic climate conditions throughout the study area. These climate divisions corresponded best with areas in which historic spruce beetle outbreaks and avalanche chronologies were derived. The specific climate division data set was TD-9640 that consisted of sequential "Time Biased Corrected" mean monthly temperatures and precipitation for each division. Monthly averages within each climate division in this data set were calculated giving cooperating stations that report both temperature and precipitation equal weight using the Time Bias Model developed by Karl and others (1986). This model adjusts the climate division monthly averages to rectify differences of the 24-hour period over which observations from individual stations are gathered. The mean monthly temperature and precipitation data were also used to derive mean seasonal values for each climate division during the period of study. This was done to investigate any seasonal influences on spruce beetle outbreaks. Fall included the months of September to November, winter, December to February, spring, March to May, and summer, June to August. The months within each season were selected to best correspond with the developmental life stages of the spruce beetle. Moving averages were calculated for all monthly and seasonal temperature and precipitation data for 3 and 5 -year periods preceding the observed year. All climate variables were also lagged 1, 2, 3, 4 and 5 years prior to the observed year.

The relative severity of dry or wet periods within the study area was also examined using Palmer Drought Severity Indices (PDSI). The PDSI data selected for this study were reconstructed by Cook and others (1998) for 154 grid points spaced at 2° latitude x 3° longitude locations in the continental United States from a dense network of annual tree-ring chronologies. The grid points covering the study area were 39, 40, 49,

and 50, located near Price, UT, Kanab, UT, Gunnison, CO, and Denver, CO, respectively. Palmer Drought Severity Indices derived from instrumental measurements for each of the corresponding grid points were originally developed to test the validity of tree-ring estimates (Cook et al. 1998) and also used for analyses in this study. The range of PDSI values in each data set ranged from -6 to 6. Mean annual estimates from the reconstructed PDSI data set were considered most meaningful for this analysis because historic spruce beetle outbreak and snow avalanches were based on yearly observations. Also, the reconstructed PDSI estimates were of particular interest because they would reflect physiological responses of trees to stress induced by periods of drought. Drought stress has often been cited as one factor that may predispose trees to spruce beetle attack (Schmid and Frye 1977). As with the climate division data, 3 and 5 year moving averages of PDSI values for years prior to the observed year were included in the analyses, as well as lagged PDSI values.

Data Analyses

The range of years providing the most complete data set from all sources of historic data was from 1905 to 1996. As a consequence, spruce beetle outbreaks and snow avalanches occurring outside of that time period were omitted from further analyses. A classification tree analyses (CART) (Brieman et al. 1984; Steinberg and Colla 1997) was used to predict historic spruce beetle outbreaks from the set of historic snow avalanche, climate and PDSI data within each climate division. Several CART models were constructed with spruce beetle outbreak years grouped into two response classes (0 = non-outbreak years, 1 = outbreak years). The default setting of equal priors

gave the most satisfactory analysis "...because it tends to treat each class as equally important for classification accuracy" (Steinberg and Colla 1997). Setting priors to other configurations such as proportional to the observed data or an average of the data proportions generally failed to produce trees. This is likely due to the noisy nature of the underlying signal or relationship between the predictor variables and the outbreaks.

The CART procedure considered all variables from the initial data using recursive binary splitting to produce trees of increasingly homogenous subsets. At each split, CART imposed a "goodness of split criterion," not unlike the method of least squares, to optimize splitting for each variable and ultimately minimize the overall probability of misclassifying the response variable. CART continued splitting until the classification tree achieved a maximum size. This maximal model was then "pruned" by removing or collapsing splits that contributed minimally to reducing the measure of error. The model growing procedure was then cross-validated by partitioning the original data set into ten subsets. Observations in each subset were estimated from the tree grown from the other nine subsets. The final tree was the one that minimized the overall misclassification probability. To further explore model results, student's *t* tests were also used to compare mean differences between non-outbreak and outbreak years for variables comprising the final tree.

Results

The chronology of historic spruce beetle outbreaks documented within the study area is given in Table 4.1. Seventeen outbreak years occurred from 1905 to 1996. Several distinct periods (comprised of > 4 years) of outbreak are apparent within the

chronology. The first period includes the years from 1937 to approximately 1944 when the large Colorado outbreaks of the 1940's were initiated, in addition to several sizable infestations detected on various portions of the Cedar City Ranger District, Dixie National Forest and at Cedar Breaks National Monument. During this same time, spruce beetle outbreaks were also reported on the Santa Fe National Forest in New Mexico (Appendix A.2). Widespread outbreaks were also apparent during the early to mid 1950's. Outbreaks on the Uncompaghre National Forest and Dixie National Forests were the only ones to occur within the study area; however, high levels of spruce beetle activity was reported in several other western states including Idaho, New Mexico and Arizona (Appendix A.2). Spruce beetle outbreaks affected several National Forests in Utah during the late 1950's and early 1960's. In 1957, spruce beetles were reported in several locations along the Provo River corridor on the Wasatch National Forest. Other outbreaks erupted in neighboring stands on the Ashley and Uinta National Forests in the Uinta Wilderness. As these outbreaks continued, others were detected in the Abajo Mountains of southeastern Utah and on the Aquarius Plateau, Utah.

New infestations were also reported on the Santa Fe National Forest, New Mexico (Appendix A.2). Localized spruce beetle infestations occurred within the study area from the mid 1960's through the early 1980's; however, a fourth period of extensive activity began in 1984 when spruce beetle populations erupted on the Manti-LaSal, Dixie, Fishlake, and Wasatch-Cache National Forests in Utah. Although numerous spruce beetle outbreaks were reported across New Mexico and Arizona in 1967 and 1968 (Appendix A.2), a large outbreak also occurred near Mt. Hilgard on the Fishlake

Table 4.1. Chronology of historic spruce beetle outbreaks within the study area*

Year	Outbreak	State	Source
1870's	Grand Mesa	Colorado	1. Knight and McCambridge 1952 2. Schmid and Frye 1977,
1875	White River Plateau	Colorado	1. Packard 1877, <i>in</i> Hopkins 1909 2. McCambridge 1952 3. Hopkins 1909
~1884	White River NF	Colorado	1. Hopkins 1909
1905	Manti National Forest	Utah	1. Hopkins 1909
1916	Aquarius Plateau	Utah	1. Schmid and Frye 1977
1937	Dixie NF, Cedar City RD	Utah	1. Jones 1937
1940	Dixie NF, Cedar City RD	Utah	1. Furniss 1940
1941	White River NF	Colorado	1. Knight 1953 1. Massey and Wygant 1954
1944	Grand Mesa NF	Colorado	1. Knight 1953 2. Schmid and Frye 1977
1944	Cedar Breaks National Monument, Dixie NF, Cedar RD	Utah	1. Rice 1944
1950	Uncompahgre and San Juan NF	Colorado	1. Wygant 1956
1955	Dixie National Forest, Boulder Top	Utah	1. Anon. 1960.
1957	Ashley, Unita, Wasatch NF, Uinta Mountains	Utah	1. Washburn and Knopf 1958 2. Anon. 1960
1961	Dixie NF, Abajo Peak	Utah	1. Knopf 1962
1962	Dixie NF, Aquarius Plateau, Griffin Springs	Utah	1. Knopf 1962
1967	Fishlake NF, Loa RD	Utah	1. Klein 1967
Early 1970's	Wolf Creek Pass	Colorado	1. Schmid and Frye 1972 2. Schmid and Frye 1977
1970	Manti-LaSal NF, Huntington Cyn.	Utah	1. Parker 1973
1970	Fishlake NF, Beaver RD	Utah	1. Klein 1971
1981	Uinta NF, Heber RD, Mill Hollow	Utah	1. Holland 1983
1981	Manti LaSal NF, Moab RD	Utah	1. Knopf 1981
1984	Manti-LaSal NF, Moab RD	Utah	1. Knapp 1985
1984	Manti-LaSal NF, Monticello RD	Utah	1. Knapp 1985
1987	Wasatch-Cache NF, Salt Lake RD	Utah	1. Anhold 1987
1987	Manti LaSal NF, San Pete RD	Utah	1. Dymerski et al. 2001
1989	Dixie NF	Utah	1. Munson and DeBlander 1992
1989	Fishlake NF, Loa RD	Utah	1. Anhold et al. 1992

* Only outbreak years from 1905 to 1996 were used in the data analysis

National Forest, Utah and another on the Flathead National Forest in Montana alluding to the extent of activity during those years.

Resources documenting historic avalanches throughout the study area resulted in the chronology given in Table 4.2. Twenty-four major avalanche years occurred during the period of study with the most widely reported slides occurring in 1906, 1907, 1911, 1916, 1926, and 1957. The major avalanches in 1906 and 1907 plagued mountain communities and railroads in central Colorado resulted in the destruction of buildings, trains and several fatalities. The 1906 avalanche event was also documented in historic records from Alta, Utah (Kalatowski 1988). Several chronologies indicated that avalanches affected paths on the Wasatch Plateau and in northern Utah in both years (Hebertson and Jenkins, Chapter 2). Schroder (1978) observed reaction wood responses in trees examined from a boulder deposit on Barney Top, Table Cliffs Plateau, Utah also in 1906 and 1907. Although Schroder attributed these event responses to mass movement events, snow avalanches may have caused the atypical growth responses. Destructive avalanches struck the town of Alta, Utah again in 1911 (Kalatowski 1988) and were dated in the Culp's, Snowbasin and Bridal Veil Falls chronologies. The 1911 event was also dated on the Wasatch Plateau and found in historic accounts of avalanches in the northern Front Range and central and southern mountains of Colorado (Martinelli and Leaf 1999). The 1916 avalanche event was dated in the Wasatch Plateau and was also evident in three northern Utah chronologies from Little Cottonwood Canyon and one from No Name at Snowbasin. The Park Mining Record (Vol. 40) relates one account of a deadly avalanche that devastated a portion of Park City, Utah on March 11th of that year. On that same day, avalanches also buried railroad tracks in Glenwood Canyon, Colorado

Table 4.2. Chronology of major avalanche years between 1899 and 2000 occurring within the study area*

Year	Source	Year	Source
1899	1. The Park Mining Record Vol. 28 2. Gilliland 1980, 3. Hebertson and Jenkins, Ch. 2	1957	1. Gallagher 1967 2. Schroder 1978 3. Malanson and Butler 1984 4. Hebertson and Jenkins, Ch. 2 5. Jenkins and Hebertson, <i>unpublished report</i>
1906	1. Schroder 1978 2. Kalatowski 1988 3. Martinelli and Leaf 1999 4. Hebertson and Jenkins, Ch. 2	1962	1. Williams and Armstrong 1984 2. Martinelli and Leaf 1999 3. Hebertson and Jenkins, Ch. 2
1907	1. Schroder 1978 2. Kalatowski 1988 3. Hebertson and Jenkins, Ch. 2	1965	1. UDOT 1987 2. Jenkins and Hebertson 1994 3. Jenkins and Hebertson, <i>unpublished report</i>
1911	1. The Park Mining Record, Vol. 40 2. Kalatowski 1988 3. Martinelli and Leaf 1999 4. Jenkins and Hebertson, <i>unpublished report</i>	1968	1. Hebertson and Jenkins, Ch. 2
1916	1. The Park Mining Record, Vol. 31 2. Martinelli and Leaf 1999 3. Hebertson and Jenkins, Ch. 2 4. Jenkins and Hebertson, <i>unpublished report</i>	1974	1. Hebertson and Jenkins, Ch. 2 2. Jenkins and Hebertson, <i>unpublished report</i>
1921	1. Martinelli and Leaf 1999, 2. Hebertson and Jenkins, Ch. 2 3. Jenkins and Hebertson, <i>unpublished report</i>	1978	1. Hebertson and Jenkins, Ch. 2 2. Jenkins and Hebertson, <i>unpublished report</i>
1924	1. Hebertson and Jenkins, Ch. 2 2. Jenkins and Hebertson, <i>unpublished report</i>	1982	1. Kilpatrick 1982 2. Malanson and Butler 1984 3. Hebertson and Jenkins, Ch. 2
1926	1. Gallagher 1967 2. Jenkins and Hebertson 1994 3. Martinelli and Leaf 1999 4. Hebertson and Jenkins, Ch. 2 5. Jenkins and Hebertson, <i>unpublished report</i>	1983	1. UDOT 1987 2. Hebertson and Jenkins, Ch. 2 3. Jenkins and Hebertson, <i>unpublished report</i>
1938	1. Hebertson and Jenkins, Ch. 2 2. Jenkins and Hebertson, <i>unpublished report</i>	1986	1. Birkeland and Mock 2001 2. Hebertson and Jenkins, Ch. 2 3. Jenkins and Hebertson, <i>unpublished report</i>
1944	1. Martinelli and Leaf 1999	1988	1. Hebertson and Jenkins, Ch. 2
1952	1. UDOT 1987 2. Hebertson and Jenkins, Ch. 2 3. Jenkins and Hebertson, <i>unpublished report</i>	1989	1. Hebertson and Jenkins, Ch. 2
1954	1. Malanson and Butler 1984 2. Hebertson and Jenkins, Ch. 2	1992	1. Tremper 1992 2. Hebertson and Jenkins, Ch. 2 3. Jenkins and Hebertson, <i>unpublished report</i>

*Only major avalanche years from 1905 to 1996 were used in the analysis

(Martinelli and Leaf 1999). Throughout central and southern Colorado, numerous large avalanches also slid during the months of January and February in 1916. Gallagher (1967) relates an account of major storm cycle experienced in Telluride, Colorado between March 22 and April 2 of 1926. This storm resulted in a major avalanche that destroyed several homes in the town and probably was responsible for subsequent avalanches affecting other locations in central Colorado during April of that year (Martinelli and Leaf 1999). Avalanches in 1926 were also dated in the Wasatch Plateau and northern Utah chronologies. The 1957 event was recorded in the No Name and Culps avalanche chronologies from northern Utah. Gallagher (1967) also provides accounts of avalanches that damaged homes, trains and resulted in numerous casualties Idaho, Montana and Colorado during February of that year. Schroder (1978) observed a 1958 release pattern in samples from his Barney Top, Utah chronology that could be attributed to a major snow avalanche that occurred in 1957.

Classification Tree Analyses

The best CART model selected mean December temperature, mean September temperature of the year prior to the observed year (September^{t-1})³, the mean estimated PDSI of the 5 year period prior to the observed year (PDSIT^{MA t-5})⁴ and mean October precipitation as the most important factors for correctly classifying non-outbreak and outbreak years (Figure 4.3).

³ t = the observed year

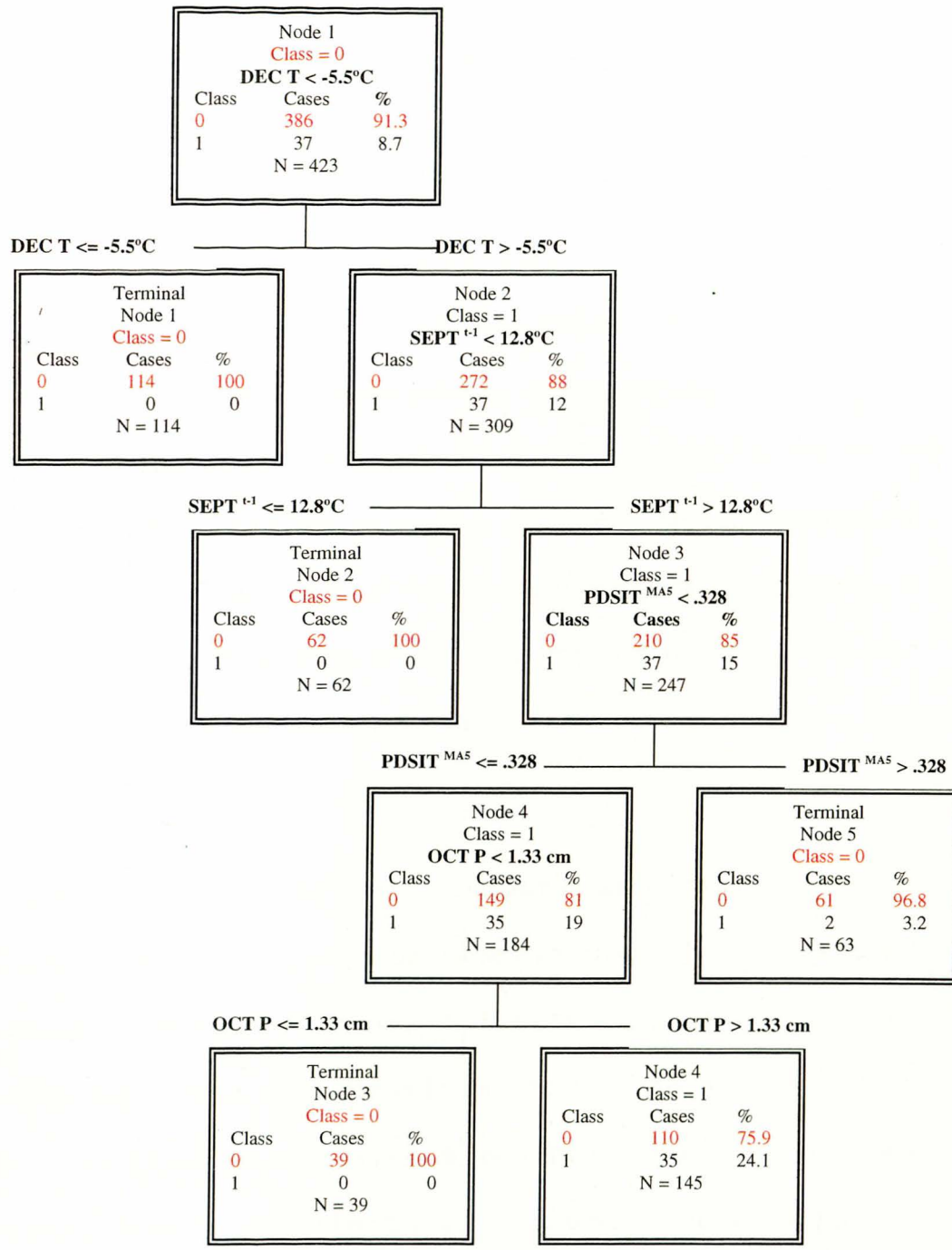
⁴ MA = moving average

(Mantel and Haenszel 1959). Throughout central and southern Colorado numerous papers
 have also been published during the months of January and February in 1916. Colorado
 1967, which is an account of major storm cycle experiments in Telluride, Colorado.
 between March 22 and April 2 of 1920. This storm resulted in a major epidemic that
 destroyed several homes in the town and probably was responsible for subsequent
 epidemics affecting other locations in central Colorado during April of that year.
 (Mantel and Haenszel 1959). Epidemics in 1920 were associated with the March pattern

Figure 4.3. The CART model of factors and associated splitting values selected for
 classifying non-outbreak and outbreak years within the study area. Class 0 = non-
 outbreak years; class 1 = outbreak years; t = the observed year; N = number of cases;
 DEC T = mean December temperature; September t^{-1} = mean temperature of the
 September one year prior to the observed year; $PDSIT^{MA t-5}$ = mean estimated Palmer
 Drought Severity Index of the 5-year period prior to the observed year

(Classification Tree Analysis)
 The best CART model selected mean December temperature, mean September
 temperature of the year prior to the observed year (September t^{-1}), the mean estimated
 PDSI of the 5-year period prior to the observed year ($PDSIT^{MA t-5}$) and mean October
 precipitation as the most important factors for correctly classifying non-outbreak and
 outbreak years (Figure 4.3).

t = the observed year
 MA = moving average



The cross validation classification procedures indicated that the model correctly classified non-outbreak and outbreak years 67% and 70% of the time, respectively (Table 4.3).

The model had a relative re-substitution error of 0.339 making the R^2 value 0.64. The cross-validated relative cost, however, was 0.626 making the adjusted Pseudo- R^2 value 0.374. This relatively low model correlation can be attributed to unexplained sources of variation and the complex nature of variable interactions.

For each of the model variables, CART also provided a set of closely associated variables to use as surrogates if necessary in further analyses, or explanations of potential relationships. The surrogates most closely associated with each model variable and their respective splitting values are given in Table 4.4. Associations between surrogate and model variables were fair with cases split somewhat differently than the primary splits. The surrogates did not perform nearly as well in the correct classification of cases as indicated by the relatively low improvement values.

Mean Comparison Tests

The results of Student's t tests used to compare mean differences between non-outbreak and outbreak years for each model variable are given in Table 4.5. In general, mean December and September t^{-1} temperatures of outbreak years were approximately 2° C warmer than non-outbreak years. This difference was significant at an $\alpha = 0.05$ level. The 5-year periods preceding outbreak years also had significantly lower mean estimated PDSI values than non-outbreak years. No difference in mean October precipitation was detected between outbreak and non-outbreak years.

Table 4.3. Cross validation classification probability table

Actual Class	Predicted Class		Actual Total
	0	1	
0	0.671	0.329	1.000
1	0.297	0.703	1.000

Table 4.4. The most closely associated surrogate variables selected for each model variable and their respective splitting values

Model Variable*	Surrogate Variable	Splitting Value	Association	Improvement
Mean December Temperature	Mean Winter Temperature	-5.3°C	0.400	0.061
	Mean December Temperature ^{MA t-3}	-6.2°C	0.377	0.044
Mean September ^{t-1}	Mean September Temperature ^{MA t-5}	12.3°C	0.371	0.024
	Mean August Temperature ^{MA t-3}	16.8°C	0.306	0.026
Estimated PDSI ^{MA t-5}	Estimated PDSI ^{t-2}	2.9	0.247	0.036
	Estimated PDSI ^{MA t-3}	1.3	0.205	0.024
Mean October Precipitation	Mean October Precipitation ^{MA t-5}	1.3 cm	0.128	0.010
	Mean October Precipitation ^{MA t-3}	1.0 cm	0.128	0.007

*t-1 = lagged one year prior to the observed year; MA = moving average of the number of years indicated prior to the observed year.

Table 4.5. Results of Student's *t* tests comparing mean differences between non-outbreak versus outbreak years for each model variable

Model Variable*	Non-Outbreak years	Outbreak Years	<i>df</i>	<i>t</i>	<i>P</i> <i>t</i>
Mean December Temperature	-3.9° C	-2.2° C	50	4.93	<0.0001
Mean September Temperature ^{t-1}	14.4° C	16.1° C	45	7.37	<0.0001
Estimated PDSI ^{MA t-5}	0.141	-0.679	36	3.58	<0.0001
Mean October Precipitation	3.4 cm	3.3 cm	52	0.34	<1.0

*t-1 = lagged one year prior to the observed year; MA = moving average of the number of years indicated prior to the observed year.

Discussion

In Intermountain spruce-fir forests, spruce beetle outbreaks primarily influence vegetative patterns (Baker and Veblen 1990; Veblen et al. 1994; Jenkins et al. 1998). By producing suitable host material for the spruce beetle, major snow avalanche years were hypothesized to contribute to the initiation of historic spruce beetle outbreaks. The historic spruce beetle and avalanche chronologies suggested that major avalanche years at the turn of the last century, and during the periods of 1911 to 1916, 1938 to 1944, 1957 to 1962, 1965 to 1968, and 1982 to 1989 coincided with the periods of spruce beetle outbreaks within the study area. Of the variables considered in this study, however, major avalanche years were not significant for spruce beetle outbreaks occurring from 1905 and 1996.

The lack of an association between historic spruce beetle outbreaks and major snow avalanche years indicates that other factors have a more important role in the development and spread of spruce beetle populations. The results of the CART analysis indicated that climate factors including seasonal temperatures and drought were significantly related to historic spruce beetle outbreaks during the period of study. The variables identified by CART as important for predicting spruce beetle outbreaks are consistent with current explanations of the population dynamics and ecology of the insect. While climate factors, particularly drought, have often been implicated in the initiation of spruce beetle outbreaks, these findings are unique in relating specific temperature, drought and other climate variables to historic spruce beetle outbreaks in the Intermountain region.

Temperature has long been recognized as an important factor in regulating the birth and death rates of bark beetles, and the rate of their developmental processes (Safranyik 1990). Spruce beetles, for example, can generally tolerate low temperatures (-34°C), however, significant spruce beetle mortality has often been associated with cold winter temperatures (Massey and Wygant 1954). Wygant (1956) indicated that the White River outbreak in Colorado finally collapsed as a result of extremely low temperatures during the winter of 1951 that killed approximately 75% of the overwintering larvae. Forty-two percent of spruce beetles were killed by record cold in Idaho and Montana during the winter of 1953-1954, and in 1971, on the Fort Apache Indian Reservation, Arizona, one week of low temperatures near -40°C resulted 88% brood reduction (Frye et al. 1974).

Mean December temperature was identified in the CART analyses used in this study as the most important variable for classifying outbreak and non-outbreak years in this study. All outbreak years had mean December temperatures approximately 3°C higher than the model splitting value of -5.5°C suggesting that relatively warm seasonal temperatures characterized these years. Approximately 70% of non-outbreak years also had mean December temperatures that exceeded the splitting value for this variable. Mean comparison tests, however, generally indicated that mean December temperatures during outbreak years were significantly warmer than non-outbreak years. Mild winter conditions would favor spruce beetle survival, particularly, during years with relatively low snow covers to insulate more vulnerable life stages, such as hibernating adults (Schmid and Frye 1977).

Conversely, 30% of non-outbreak years were relatively cold, with mean December temperatures $\leq -5.5^{\circ}\text{C}$. Visual examination of the climate data showed that in some non-outbreak years, mean December temperatures were extremely low. For example, mean winter temperatures in 1910, 1917, 1929, 1933, 1937, 1949, and 1973 throughout the study area ranged from -11°C to -8.3°C . Conceivably, mortality resulting from extremely cold periods during these years would decrease the potential for outbreak.

CART used mean September t^{-1} temperatures with a splitting value of 12.8°C in the second node to further partition non-outbreak and outbreak years. All outbreak years had mean September t^{-1} temperatures higher than the splitting value of 12.8°C . Additionally, mean August MAI-3 and mean September MAI-5 were selected as surrogate variables, with splitting values of 12.2°C and 16.8°C , respectively. These splitting values were approximately 2°C to 3°C cooler than the mean August and September temperatures of the years preceding major outbreak years. These results indicate that periods characterized by warm, late summer and fall temperatures were important to the initiation of outbreaks.

This observation is consistent with the influence of temperature on the duration of spruce beetle life cycles and subsequently, the population dynamics of the insect. A spruce beetle life cycle of 2 years is typical in the Intermountain region (Schmid and Frye 1977), although, 1 and 3 - year life cycles are not uncommon (Massey and Wygant 1954; Knight 1961; Schmid and Frye 1977; Werner and Holsten 1985). Dyer (1969) demonstrated that cold temperatures (10°C to 13.3°C) generally retarded larval

development. The majority of spruce beetle broods subject to a constant temperature regime of 21.1° C, however, reached pupal and teneral adult stages without interruption after an accumulation of 1050-degree days above the developmental temperature threshold (6.1° C) (Dyer and Hall 1977). Warm fall temperatures were found to delay diapause allowing for continued larval development and shortening the typical life cycle from 2 to 1 year (Dyer 1969). The sun-exposed aspects of downed trees and trees in south-facing stands were also observed to contain a preponderance of one-year life cycle beetles (Werner and Holsten 1985). Werner and Holsten (1985) found that direct solar heating raising phloem temperatures to a threshold of 16.5° C was necessary during the development of early instars for beetles to complete a 1-year life cycle. Temperature-based voltinism models developed by Hansen and others (2001) suggested that July through September temperatures were the primary regulators of spruce beetle voltinism. With local average air temperatures in August above 17° C, the majority of spruce beetle broods would develop in 1 year (Hansen et al. 2001). The intensification and expansion of spruce beetle populations in Alaska and western states during recent years has been attributed to the occurrence of 1-year life cycle beetles resulting from unusually warm temperatures (Werner and Holsten 1985; Reynolds and Holsten 1994; Hansen et al. 2001). Interestingly, the splitting value of 16.8° C for mean August MA_t-3 temperature in these analyses closely corresponds to the critical temperature threshold of 17° C Hansen and others (2001) found necessary for the development of univoltine broods suggesting that 1 year life cycle beetles had the potential to contribute to outbreak initiation.

The large proportion (77%) of non-break years in the second split with mean

August and September temperatures exceeding the given splitting values is likely due to the generally warm, dry climate that characterizes these months in the Intermountain region. This result also suggests that warm summer and fall temperatures are necessary, but not sufficient for outbreak occurrence. Twenty-three percent of the non-outbreak years had relatively cool mean September ^{t-1} temperatures and generally low fall temperatures. The potentially slower rates of spruce beetle development under these conditions would potentially limit the opportunity for rapid population growth and the initiation of outbreaks.

The CART analyses also indicated that drought served as a predisposing factor to spruce beetle outbreaks. Hopkins (1909) generally dismissed the importance of drought for western bark beetle species, concluding that dry conditions were unfavorable for infestation by the insects. Subsequent investigations, however, indicated that environmental stresses on trees, such as drought, have an important role in the dynamics of bark beetle outbreaks (Blackman 1924; Craighead 1925; Beal 1927; Hopping and Mathers 1950; Hall 1958; Lorio et al. 1995; Paine et al. 1997). Water stress adversely affects tree tissues by compromising or inhibiting important physiological processes including photosynthesis, the movement of gases, the flow of latex and oleoresins and the absorption of water and ions (Kozlowski 1982). Bark beetles are attracted to weakened trees and can overcome compromised host defense mechanisms with mass attacks (Paine et al. 1997).

Ninety-five percent of outbreak years in this study had mean estimated PDSI^{MA t-5} values ≤ 0.328 indicating that trees had been subject to prolonged drought stress. Estimated PDSI^{MA t-5} values ≤ 0.328 also accounted for the partitioning of 39% of the

remaining non-outbreak years. In general, however, values of mean estimated PDSI^{MA t-5} for outbreak years were significantly lower than those of non-break years.

Visual examination of mean precipitation data revealed the prevalence of relatively dry fall and winter conditions in conjunction with the warm fall and winter temperatures that characterized outbreak years. Conversely, mean winter precipitation during 70% of non-outbreak years was above average. These observations are consistent with winter climate patterns observed in the Intermountain region where precipitation is typically associated with below average temperatures (Jensen et al. 1990).

Stress associated with winter droughts can also predispose trees to bark beetle attack. Warm winter temperatures associated with dry conditions can cause excessive transpiration from tree foliage. Because water remains frozen in the soil, the tree receives no compensation for water loss from the ground resulting in the desiccation of tree tissues and water stress (Grier 1988; Miller 1970). The rate of desiccation increases with drying winds and insufficient snow cover to insulate the ground (Grier 1988; Miller 1970). In Montana, Gibson (1992) observed large numbers of Douglas-fir (*Pseudotsuga menziesii*)(Mirb.) Franco) and white pines (*Pinus monticola* Doug. Ex D. Don) attacked by Mountain pine beetles (*Dendroctonus ponderosae* Hopkins Coleoptera: Scolytidae) following severe drought during the winter of 1991-1992.

In the final split, three quarters of the remaining non-outbreak years, and all remaining outbreak years had mean October precipitation > 1.33 cm. Differences in mean October precipitation between outbreak and non-outbreak years were not significant. The lack of moisture during this month, however, was associated with 26% of the remaining non-outbreak years. Precipitation during these years was on average 2

cm less than the mean October precipitation (3.3 cm). The majority of remaining years (75%) with October precipitation ≤ 1.33 were also characterized by above average October temperatures, with some years having temperatures $> 3^{\circ}$ C above normal. While bark beetles may preferentially attack drought-stressed trees, excessively dry conditions may accelerate the deterioration of host material limiting brood success. Cole (1975) found that excessive drying of infested lodgepole pine was an important factor causing mountain pine beetle populations to return to endemic levels. Dry phloem deprived larvae of necessary moisture causing them to cease feeding, shrivel and die (Cole 1975). Amman (1977) observed that these effects were usually more pronounced in small diameter trees. These observations indicate that while drought may generally contribute to outbreaks, unusually warm and dry fall conditions may serve to inhibit them.

In addition to the climate variables identified above, factors not considered in this study also have a strong influence on spruce beetle epidemiology. Outbreak initiation and spread has been related to stand attributes, such as, structure, composition, and age. Stands most susceptible to outbreak are generally dense ($BA > 35 \text{ m}^2/\text{ha}$) and comprised of a high proportion of mature, large diameter spruce (Schmid and Frye 1977). Local weather patterns can either enhance or inhibit population growth affecting spruce beetle risk (Samman and Logan 2000). At high elevations, colder, wet conditions contribute to greater bark beetle mortality during dispersal and lower rates of bark beetle colonization than at low elevation sites (Johnson 1967). Predation and parasitism of all life stages can also limit population growth decreasing spruce beetle risk (Schmid and Frye 1977). With these influences, disturbances, such as snow avalanches, would not precipitate outbreaks if 1) populations were insufficient to usurp available host material before it became

unsuitable for colonization, 2) stands adjacent to avalanche paths were comprised of mostly non-host species or small diameter trees (Veblen et al. 1994), or 3) flight concurred with cold, wet weather (Schmitz and Rudinsky 1968; Holsten et al. 1999).

Several historic reports and other observations provide some anecdotal evidence that snow avalanche disturbances have contributed to the initiation of local spruce beetle outbreaks in western forests. Lessard (1976) reported that spruce beetles infested host material on the west side of Agassiz Peak (San Francisco Peaks) in Arizona that was produced by heavy snows and wind during an intense storm in December 1966. This same storm resulted in numerous avalanches that closed Little Cottonwood Canyon, Utah (UDOT 1987). Subsequent blow down provided additional brood material and beetles spread into living trees. A spruce beetle outbreak was detected on 15 acres of avalanche-damaged spruce on the east side of the San Francisco Peaks in 1973 (Lessard 1976). The population continued to build in damaged spruce during 1974 until sanitation strategies were employed to treat the infested material in 1975 (Lessard 1976). The initiation of a severe spruce beetle outbreak on the Wasatch Plateau, Utah in the late 1980's appears coincident with widespread, damaging avalanche cycles affecting that same area earlier in the decade (Hebertson and Jenkins, Chapter 3). Evidence of spruce beetle-infested debris was also observed in Big Cottonwood Canyon, Utah in paths that slid during an extremely widespread avalanche cycle in February of 1986. In 2000, we observed spruce beetle attacked trees in forests adjacent to avalanche paths in the Madison Range, Montana and the Wasatch Range of northern Utah. Other scolytid beetle species including the roundheaded beetle (*Dendroctonus adjunctus* Blanford Coleoptera: Scolytidae) and *Ips spp.* (Coleoptera: Scolytidae) were reported to infest host material in

avalanche debris throughout Kyle Canyon, Charleston Range, Nevada in the spring of 1969 (Klein 1971).

The ability to reliably predict spruce beetle outbreaks from the snow avalanche and climate variables used in this study was potentially limited by several factors. Foremost, the majority of historic reports did not provide reliable dates when major spruce beetle outbreaks were first initiated. The 19th century spruce beetle outbreaks, for example, were not detected until extensive bark beetle surveys were conducted in the early 1900's decades later (Hopkins 1909). Prior to that time, tree mortality was also often attributed to fire until evidence of spruce beetle galleries was observed on snags and logs (Hopkins 1909). The occurrence of outbreaks in Colorado circa 1850's and 1870's was verified using dendrochronological methods, however, release was not evident in rings of sample trees until several years following the mortality of canopy trees (Eisenhart 1999). As a consequence, errors were possible when deducing the dates of outbreak initiation.

The few historic records of spruce beetle outbreaks also prevented the development of a long-term outbreak chronology. Examination of the data revealed relatively long periods without outbreaks, particularly during the first half of the study period. While outbreaks may not have occurred during these periods, a more plausible explanation is that access prohibited the early exploration of remote locations, and only the most apparent outbreaks were reported (Schmid *pers. comm.*). The number of documented outbreaks appeared to increase during the 1940's with the employment of aerial detection surveys. Interestingly, this observation was supported by an alternate CART model, which selected the year of 1949 as a highly significant explanatory

variable. An incomplete chronology might have resulted in an unrealistically disproportionate number of non-outbreak versus outbreak years making meaningful associations with major avalanche years difficult.

The construction of chronologies for major avalanche years was limited by similar constraints. Little historic documentation exists of avalanche occurrence in remote locations. The vast majority of reported avalanches were human-triggered and not considered valid for use in these analyses. While dendro-ecological methods have proven useful for dating avalanche events where reliable records are lacking (Burrows and Burrows 1976), difficulties with collecting and preparing tree samples, lack of sample depth, deciphering tree-rings within samples and obtaining sufficient cross-replication can introduce potential dating errors (Schroder 1978; Hebertson and Jenkins, Chapter 2).

Other sources of variation not integrated in the CART analyses might have also prohibited obtaining higher classification probabilities and greater model correlations. Historic reports, for example, did not provide information on spruce beetle risk and stand hazard. Consequently, risk and stand attribute data associated with individual outbreak events were not analyzed. Spruce beetle outbreaks occurring prior to the turn of the last century also were not included in these analyses due to the lack of corresponding climate data for those years. A greater number of cases could have improved estimates of spruce beetle outbreak probabilities.

Conclusions

While anecdotal information provides some evidence that snow avalanches may

contribute to the initiation of local spruce beetle outbreaks in the Intermountain region, the results of this study do not indicate a significant relationship between major snow avalanche years and spruce beetle outbreaks. Classification tree analysis, however, indicated that historic outbreak years in the Intermountain region were significantly related to generally warm fall and winter temperatures and drought. This finding is consistent with climate factors known to influence spruce beetle brood success, development, life cycle duration, population dynamics and host relationships. Unexplained variability in the data likely prohibited obtaining higher model correlations. The inclusion of finer scale historic climate data (i.e. mean daily and minimum/maximum values for temperature and precipitation, monthly PDSI values, etc.), the development of longer, more reliable historic spruce beetle outbreak chronologies, and information to characterize site and historic stand attributes would help improve the reliability of model estimates.

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CHAPTER 5

SUMMARY

Snow avalanches commonly occur in mountainous terrain of the Intermountain region. The occurrence of major snow avalanches can cause significant damage to forest vegetation within avalanche runout zones potentially impacting important resource values. Because Intermountain winters often embody characteristics of both maritime and continental climates, however, factors contributing to major avalanche occurrence remain poorly understood. One ecological consequence of major avalanche occurrence is the production of host material for the Engelmann spruce beetle. Although most documented outbreaks have followed extensive blow down and logging disturbances snow avalanches were hypothesized to produce host material at a time and in an environment optimal for brood production. Stress induced by avalanche damages would also serve to predispose injured trees to spruce beetle attack. As a result of these factors, major avalanches might have a role equal to wind and other disturbances known to influence the build up and spread of spruce beetle populations.

This research investigated climate factors contributing to major avalanche years on the Wasatch Plateau in south-central Utah and potential associations of major avalanches with important stages in the development of spruce beetle outbreaks. In the first study, historic climate factors used to predict major avalanche occurrence. Only mean January snowfall was significantly related to the probability of major avalanche year. The probability of a major avalanche year was estimated to increase by 0.0279 with a respective 1 cm increase in mean January snowfall. Model correlations, however, were

low. Variability in the data resulting from potential dating errors, the lack of high quality climate data and the absence of snow pack information may have prohibited obtaining higher model correlations. This result, however, served to substantiate and enhance current explanations of Intermountain avalanche classification systems. Dendro-ecological methods also resulted in a long-term chronology of major avalanche years on the Wasatch Plateau for use in subsequent research.

The results of the second study indicated that the seasonal availability of host material significantly influenced spruce beetle brood production in downed host material. Spruce beetle populations have greater potential to build in downed host material first available in spring suggesting that snow avalanche disturbance may contribute to the risk of outbreaks. Classification tree analysis used in the third study to relate major snow avalanche years and climate variables with historic spruce beetle outbreaks in Utah and Colorado, however, indicated that major snow avalanche years were not important for outbreak initiation. Historic outbreak years were significantly related to generally warm, dry fall and winter conditions and drought. Mean December temperature, mean September temperature one year prior to outbreaks, the 5-year average estimated Palmer Drought Severity Index in years preceding outbreaks, and mean October precipitation correctly classified non-outbreak and outbreak years 67% and 70% of the time, respectively, although, unexplained variability in the data resulted in low model correlations. These results, however, support explanations of factors important for spruce beetle outbreaks including brood survival and life cycle duration.

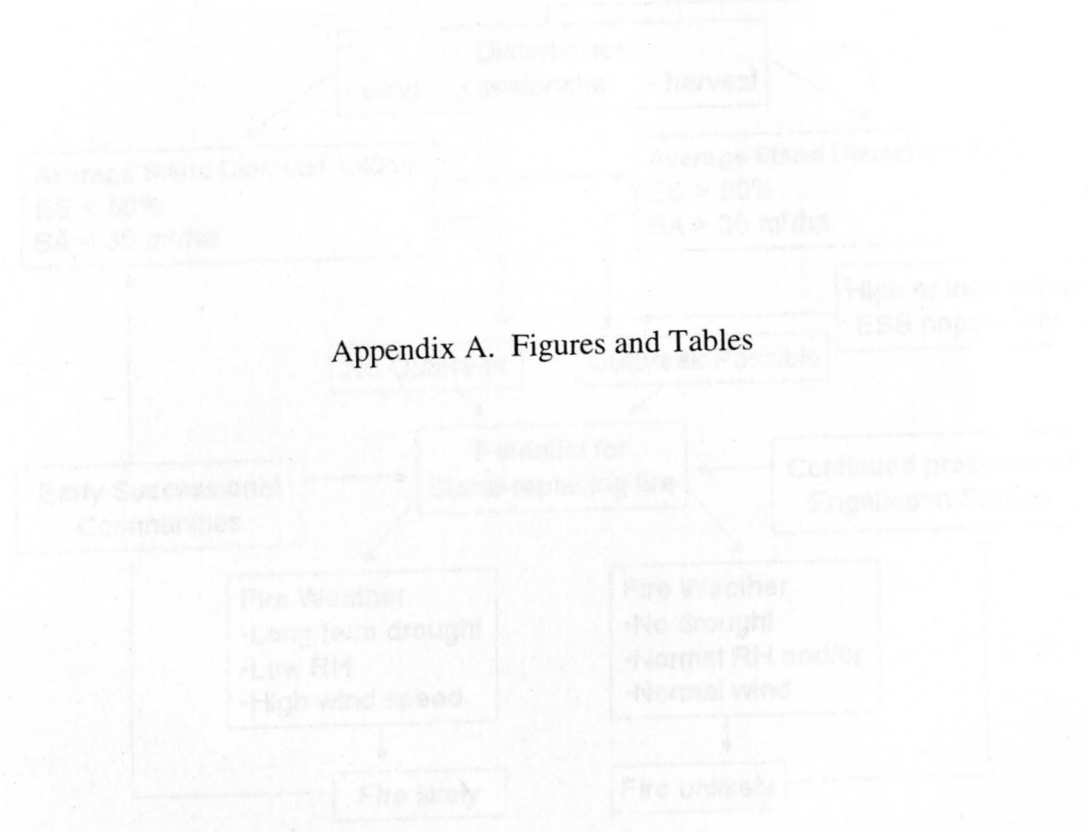
Understanding the role of each agent within disturbance regimes has become vital to maintaining forest ecosystems within a desired range of proper functioning condition

for overall forest health and to satisfy resource management objectives. Land managers may use this information to identify factors that contribute to major snow avalanche years and spruce beetle outbreaks, and devise strategies to mitigate potentially adverse impacts to natural resource and social values.

APPENDICES

APPENDICES

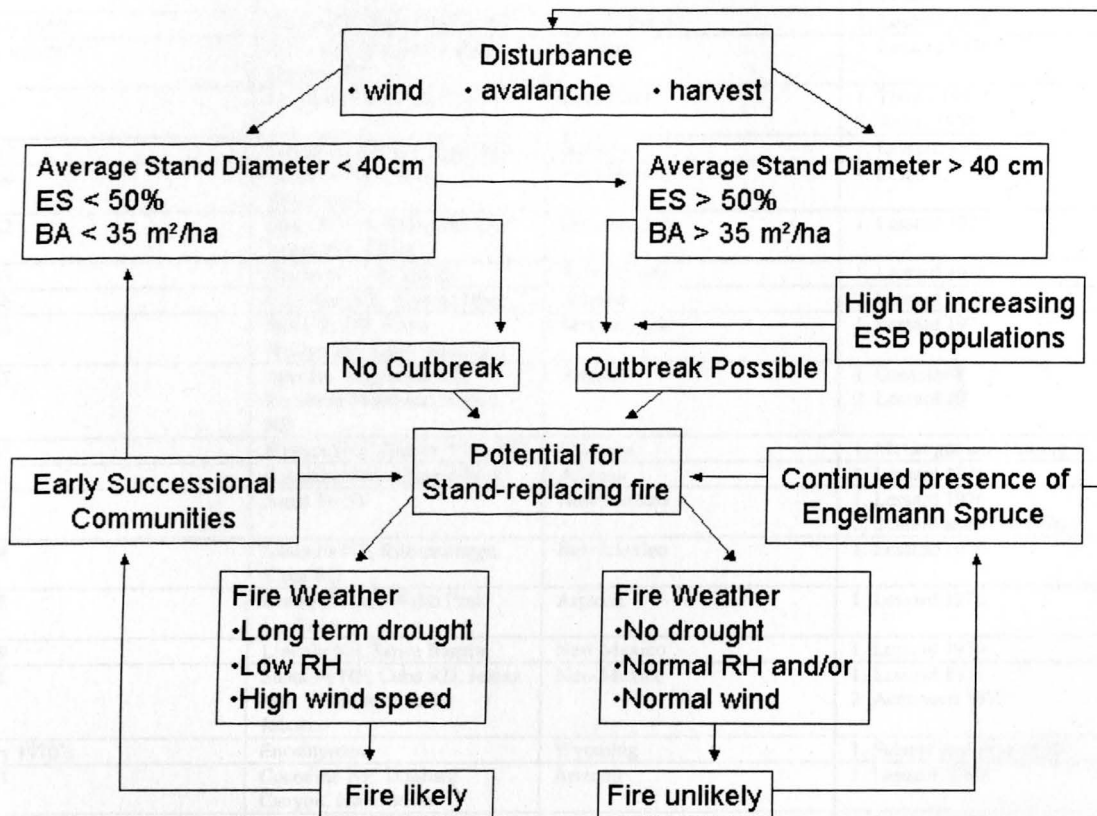
Figure A.1. Conceptual model of the relationship between fire, spruce beetle outbreaks, and stand disturbance in the spruce-fir zone, and their influence on the development of forest fire communities (LS = long-term spruce, BA = basal area, RH = relative humidity, RH = relative humidity).



Appendix A. Figures and Tables

After Jenkins ML, Dixon CA, Hebertson EG. 1978. Positive succession and disturbance interactions on an intermountain subalpine spruce-fir forest. In Proden RL, Brennan LA (eds.) Fire in ecosystem management: reducing the paradigm from suppression to prescription. Tall Timbers Fire Ecology Conference Proceedings, No. 20. Tall Timbers Research Station, Tallahassee, FL. Pp. 225.

Appendix A.1. Conceptual model of the relationship between fire, spruce beetle outbreak and other disturbances in the spruce-fir zone, and their influence on the development of spruce-fir communities (ES = Engelmann spruce, BA = basal area, ESB = spruce beetle, RH = relative humidity).



After Jenkins MJ, Dicus CA, Hebertson EG. 1998. Postfire succession and disturbance interactions on an intermountain subalpine spruce-fir forest. *In* Pruden RL, Brennan LA (eds.). *Fire in ecosystem management: shifting the paradigm from suppression to prescription*. Tall Timbers Fire Ecology Conference Proceedings, No. 20, Tall Timbers Research Station, Tallahassee, FL, Fig.6, pp. 226

Appendix A.2. Chronology of historic spruce beetle outbreaks in other western States			
Year	Outbreak	State	Source
~1860's	White Mountains, Lincoln NF	New Mexico	1. Schmid and Frye 1977
~1890's	Lincoln NF, Sierra Blanca	New Mexico	1. Lessard 1976
1904	White Mountains	New Mexico	1. Lessard 1976
1925-1930	Lincoln NF, Sacramento RD	New Mexico	1. Lessard GD. 1976
Mid 1930's	Santa Fe NF, Pecos and Las Vegas RD	New Mexico	1. Lessard 1976
1946	Carson NF	New Mexico	1. Lessard 1976
1946	Santa Fe NF, Pecos RD	New Mexico	1. Lessard 1976
1948	White Mountains	New Mexico	1. Bennett 1954 2. Lessard 1976
Early 1950's	Carson NF, Tres Piedras RD	New Mexico	1. Lessard 1976
Early 1950's	Coronado NF, Mt. Graham, Safford RD	Arizona	1. Lessard 1976
1952	Northern Idaho, Western MT	Idaho, MT	1. Terrell 1952 2. Anon. 1956.
1953	Coconino NF, San Fran Peaks	Arizona	1. Lessard 1976
1960	Santa Fe NF, Pecos Wilderness	New Mexico	1. Lessard 1976
1962	Santa Fe NF, Pecos and Las Vegas RD, Elk Mt	New Mexico	1. Lessard 1976
1963	Cibola NF, Mt. Taylor	New Mexico	1. Lessard 1976
1966	Coconino NF, Agassiz Peak	Arizona	1. Lessard 1976
1966	Santa Fe NF, Pecos Wilderness, Lake Johnson	New Mexico	1. Lessard 1976
1967	Apache- Sitgreaves NF, Escudilla Mountain, Alpine RD	Arizona	1. Germain 1972 2. Lessard 1976
1967	Flathead NF, Glacier View RD	Montana	1. McGregor and Honing 1970
1968	Coconino NF, Agassiz Peak	Arizona	1. Lessard 1976
1968	Santa Fe NF	New Mexico	1. Lessard 1976 2. Schmid and Frye 1976
1968	Santa Fe NF, Rito drainage, Cuba RD	New Mexico	1. Lessard 1976
1968	Coronado NF, Webb Peak Lookout	Arizona	1. Lessard 1976
1969	Lincoln NF, Sierra Blanca	New Mexico	1. Lessard 1976
1971	Santa Fe NF, Cuba RD, Jemez Mts. Wilderness, Lake Johnson	New Mexico	1. Lessard 1976 2. Acciavatti 1977
Early 1970's	Encampment	Wyoming	1. Schmid and Frye 1977
1973	Coconino NF, Dunham Canyon, Inner Basin	Arizona	1. Lessard 1976
1974	Coconino NF, Snow Bowl	Arizona	1. Lessard 1976
1975	Santa Fe NF, Cuba RD, Jemez Mts.	New Mexico	1. Acciavatti 1975
1981	Panhandle NF, Bonners Ferry RD	Montana	1. Gibson and Oakes 1981
1981	Fort Apache IR	Arizona	1. Linnane 1985
1981	Glacier NP	Montana	1. Eglitis et al. 1982

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B.3. Permission to Use Personal Communication

November 18, 2003

Dear Dr. Schmid:

I am preparing my dissertation in the Department of Forest, Range and Wildlife Sciences at Utah State University. I hope to complete my degree in the Fall of 2003.

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As co-author of the papers "The Seasonal Availability of Host Material Produced by Snow Avalanches and Implications for Spruce Beetle Outbreaks in the Intermountain Rocky Mountains" and "An Investigation of Historic Spruce Beetle Outbreaks and Major Avalanche Years in Utah and Colorado", I am requesting your permission to include these papers as Chapter in my dissertation. I will include acknowledgements and/or appropriate citations for your contributions. Please advise me of any changes you require.

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CURRICULUM VITAE

Elizabeth G. Hebertson

2243 Fruitland Dr.
North Ogden, UT 84414

(December 2003)

Telephone: (H) 801-737-0295
(W) 801-476-4420

Fax: 801-479-1477
Email: lghebertson@fs.fed.us

CAREER OBJECTIVE:

To continue working as a Forest Health Specialist for a natural resource agency providing expertise in insect and disease and disease management and forest disturbance ecology. Special areas of interest include disturbance agents (insects, disease, fire, snow avalanches) that influence the vegetative dynamics and patterns in Intermountain subalpine forests, developing techniques for reconstructing disturbance histories, and using this information to evaluate human influences on disturbance regimes.

EDUCATION:

1982 Bachelor of Science, Biology/Botany and Physical Education
University of Utah
Salt Lake City, UT

Graduated Magna Cum Laude
Member, Phi Kappa Phi National Honor Society

1995 Master of Science, Forest Pathology
Utah State University
Logan, UT

Member, Xi Sigma Pi National Honor Society

Exp 2003 Doctor of Philosophy, Forest Ecology
Utah State University
Logan, UT

EXPERIENCE:

Secondary Educator: 1982-1989, Biological and Physical Science, Jordan School District and Granite School District, Salt Lake City, Utah

Biological Technician: 1989-1991, Forest Health Protection, Missoula Field Office, Missoula, Montana

Teaching Assistant: 1993-1998, College of Natural Resources, Utah State University, Summer Camp Program; Department of Forest Resources, Forest Pathology, Snow and Avalanche Dynamics

Instructor: 1993-1998, Department of Forest Resources, Principles of Natural Resources, Principles of Forestry, Forest Entomology

Program Assistant: 1995-1997, Bear River Avalanche Information Center

Avalanche Forecaster: 1997-1999, Bear River Avalanche Information Center

CERTIFICATES:

Basic Professional Teaching Certificate, 1982

National Avalanche School, 1997

AWARDS:

First Team All Conference (NCAA Western Athletic Conference), Volleyball, 1981

First Team All American, USSSA, Softball, 1987

SPECIAL INTERESTS:

Sports, skiing, backpacking, hiking, biking, sea-kayaking, glass beads, art

PUBLICATIONS:

Jenkins MJ, Hebertson EG. 1994. Using vegetative analysis to determine the extent and frequency of avalanches in Little Cottonwood Canyon, Utah. *In*: Decker R (editor), Proceedings of the International Snow Science Workshop, Oct. 30 – Nov. 3, Snowbird, Utah, University of Utah. pp. 91-104.

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- Hebertson EG, Jenkins MJ. *In Prep*. The seasonal availability of host material produced by snow avalanches and implications for spruce beetle outbreaks in the Intermountain Rocky Mountains. *Canadian Entomologist*
- Hebertson EG, Jenkins MJ. *In Prep*. An investigation of historic spruce beetle outbreaks and major avalanche years in Utah and Colorado. *Canadian Entomologist*