THESIS

TIME-SINCE-DEATH AND ITS EFFECT ON WOOD FROM BEETLE-KILLED ENGELMANN SPRUCE IN SOUTHWEST COLORADO

Submitted by

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ABSTRACT

TIME-SINCE-DEATH AND ITS EFFECT ON WOOD FROM BEETLE-KILLED ENGELMANN SPRUCE IN SOUTHWEST COLORADO

Spruce beetles (*Dendroctonus rufipennis)* have caused extensive mortality on 1.5 million acres in Colorado during the current epidemic. There is considerable interest in harvesting treatments aimed at removing dead trees for reasons of fire risk, watershed health, and human dimensions. The byproducts from these treatments can either be viewed as a difficult and costly disposal problem or an opportunity for the recovery of forest products. However, a major barrier to the latter option is the lack of knowledge about how the material changes with time standing dead.

Ten plots were selected on the Rio Grande National Forest (RGNF), from which 86 Engelmann spruce (*Picea engelmannii*) trees were felled and sampled. Tree rings were analyzed to determine Time-Since-Death (TSD) on all study trees. TSD and other variables such as diameter, elevation, and bark retention were used to develop models predicting the deterioration rate from beetle mortality (seasoning check, heart rot, and sap rot). In a separate mill study, eleven trees from the RGNF were milled to dimensional lumber to determine the lumber tally, prevalence of blue stain, and lumber grade breakdown.

Checking was found to be most strongly correlated with tree diameter, and the effect of TSD was most pronounced at larger diameters. Higher elevations and increased bark retention served to reduce or slow checking. Sap rot was found to increase with TSD, but heart rot was not. Many study trees had moisture contents suitable for the development of rot. In the mill study, older dead trees produced a lower percentage of select structural lumber than control trees. Net Scribner was a poor predictor of lumber tally; gross Scribner and product potential cubic were more accurate.

Results from this study may help land managers maximize sawtimber recovery by prioritizing treatment areas. Information such as tree diameter, TSD, and elevation will allow foresters to better differentiate stands that have already been subject to severe deterioration from those that will in short order.

ACKNOWLEDGMENTS

This project was far from a solo effort- many parties helped with study design, data collection, and analysis. For help in designing the study, and for single-handedly felling and measuring 86 trees, I'd like to thank Jim Webb (Forest Stewardship Concepts Ltd.). Rocky Mountain Timber Products of Del Norte, Colorado, were responsible for processing boards used in the mill study. A debt of gratitude is owed to Evan Mackes for preparing samples and painstakingly measuring tree rings.

I feel very fortunate in my assembly of committee members. Yu Wei, for helpful comments regarding the analysis, excellent instruction in undergrad/grad classes, and for providing TA opportunities to keep me going through grad school. Patrick Rastall- how many students happen to randomly run into their committee members while climbing a mountain just weeks before the defense? And of course my advisor Kurt Mackes. For his dedication to his students, for always being available to offer advice, and for some reason thinking that I would be good at this kind of stuff. Many thanks.

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TSD: Time-Since-Death

WRNF: White River National Forest

FSP: Fiber Saturation Point

MC: Moisture Content

EMC: Equilibrium Moisture Content

RGNF: Rio Grande National Forest

CCF: Hundred Cubic Feet

MPB: Mountain Pine Beetle

DBH: Diameter at Breast Height

WWPA: Western Wood Products Association

SS: Select Structural

1. INTRODUCTION

Since the turn of the century, the spruce beetle (*Dendroctonus rufipennis*) has caused extensive mortality on 1.5 million high elevation forested acres in Colorado (CSFS 2016), and is now considered the most devastating insect to the state’s forests. Much of the damage is concentrated in the southwest portion of the state. The vast acreage of dead trees is problematic to land managers for a variety of reasons that include fire risk, watershed health, and human dimension concerns. Thus, there is considerable interest in restoration treatments aimed at removing dead trees (USFS 2011). The byproducts from these treatments can either be viewed as a difficult and costly disposal problem or an opportunity for the recovery of wood products. The current study was conducted to help promote the latter view by investigating the effect that beetle mortality has on the yield and quality of spruce wood in southwest Colorado.

There is a common perception that wood from infested trees quickly deteriorates and loses all value within five years or less (Nelson 1950; Nelson 1954; Schmid and Frye 1977). Others have reported that deterioration is not so severe in all cases and wood may have value for a much longer period (Mielke 1950; Lowell and Willits 1998; Lewis and Hartley 2006). If the trees have suitable properties, there are sawmills in southwest Colorado that could process wood recovered from treatments. However, if the wood is unsuitable for solid-sawn products, there are few other viable options; no biomass or pellet plants are nearby. If no markets exist for the wood, it will likely be disposed of in another way such as piling and burning or chipping.

The USDA Forest Service is in the final planning phases of a large project designed in response to the outbreak on the Grand Mesa, Uncompaghre, and Gunnison National Forests (GMUG). The Spruce Beetle Epidemic and Aspen Decline Management Response (SBEADMR) has been designed to meet the objectives identified in the U.S. Forest Service's "Western Bark Beetle Strategy" (USFS 2011) of addressing the beetle epidemic and improving forest safety, resilience, and recovery. The ten-year project is currently (Summer 2016) in the final pre-implementation stage, with treatments anticipated to begin in 2017. According to the project's Record of Decision, a maximum of 120,000 acres of the GMUG will be treated, 60,000 of which will yield commercial products (Armentrout 2016). SBEADMR is one example of a project that seeks valuable uses for restoration treatment byproducts and has the potential to produce a steady supply of raw materials for conversion into forest products.

The results of this study will aid land managers and mills by providing information on how deterioration with time affects the volume and value of Engelmann spruce wood as it stands on the stump. Knowing the value of a resource is integral in making management decisions. Land managers with extensive beetle mortality to address, such as the U.S. Forest Service, will benefit from having more accurate resource appraisals. This can aid them in deciding which forest stands to pursue for treatments, and in assigning stumpage rates to a unit. Mills in the area have recently been plagued by underrun, or a lower-than-predicted recovery rate from logs. This presents a financial problem for the mills, and they may find this study's results useful in providing more accurate scaling methods that better account for the various defects that can result from beetle caused mortality.

Study Goals and Objectives

The primary goal of this study is to investigate the effect that mortality by spruce beetle has on lumber quality and yield in southwest Colorado. Four specific objectives were designed to achieve this goal:

1. Hypothesis test for Time-Since-Death**:** Test the hypothesis that wood quality and yield are influenced by the amount of time since a beetle attack. Stated as a null hypothesis:

   $$H_0: \beta_{TSD} = 0$$

   Where β_{TSD} is the regression coefficient associated with Time-Since-Death (TSD) in models predicting deterioration.
2. Identify other significant predictors of deterioration: Investigate other factors that may play a role in wood deterioration. Examples are diameter, slope and aspect, elevation, and percent bark cover.
3. Develop yield model: Propose new methods or modifications to current methods that can be employed by scalers to take Time-Since-Death into account and more accurately appraise standing dead timber.
4. Verification: Ground-truth results with a mill study. Use models developed in objective 3 to make predictions on trees that can then be verified by processing the trees into dimensional lumber.

2. LITERATURE REVIEW

The spruce beetle has been a recurrent theme in Colorado; therefore there is an extensive literature base to draw from, much of it specifically focused on the Rockies and on Colorado. The findings from these studies have been exhaustively synthesized not only historically in the publication “Spruce beetle in the Rockies” (Schmid and Frye 1977) but recently by Jenkins et al. (2014) in their “Spruce beetle biology, ecology, and management in the Rocky Mountains”. This literature review draws heavily from these sources and is intended to provide the reader with sufficient information to understand the context for and the mechanics of the current study. Four broad topics are reviewed here: Spruce beetle biology and landscape-scale effects, background on wood properties and utilization, marketing of beetle-killed spruce wood, and a review of prior bark beetle deterioration studies.

Introduction to the Host, the Beetle, and their Interactions

The Forests

Dendroctonus rufipennis, like other bark beetles, depends on a host tree for survival and brood production. The typical host in the Rocky Mountain region is *Picea engelmannii* (Engelmann spruce). Blue spruce (*P. pungens*) is an infrequent host, and in Canada and Alaska, the beetle feeds on white spruce (*P. glauca*) and Sitka spruce (*P. sitchensis*; Schmid and Frye 1977). There are also reports of spruce beetles attacking other species, such as lodgepole pine (*Pinus contortus*), during outbreak conditions (Massey and Wygant 1954; McCambridge and Knight 1972). The most suitable host material is windthrown trees or logging slash, but beetles also attack overmature host trees during the endemic state and all host trees during epidemic states.

Engelmann spruce grow in high elevation, cold climates in Colorado, typically from 9,000 to 12,000 feet (CSFS 2010). They are commonly accompanied by other conifer species, most notably the subalpine fir (*Abies lasiocarpa*). The spruce-fir forest type is one of Colorado's largest, covering 4.6 million acres, or 19% of the state's forested lands (CSFS 2010). Figure 2.1 shows the distribution of spruce-fir forest type in Colorado, which occurs in all of the high mountain ranges of the state.

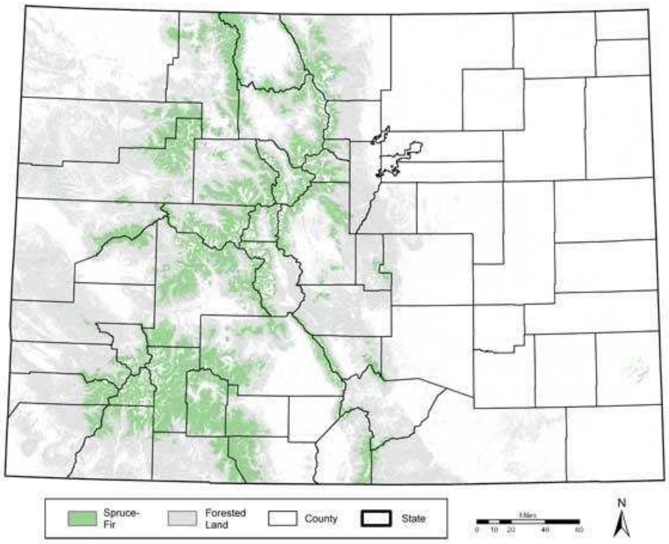


Figure 2.1 - Distribution of the spruce-fir forest type in Colorado. Source: https://csfs.colostate.edu/colorado-forests/forest-types/spruce-fir/

Veblen et al. (1994) studied the disturbance interactions in a high elevation Colorado forest dominated by *Picea engelmannii*. They found that spruce beetle outbreaks have a shorter return interval than wildfires, and are more important than any other disturbance type in influencing the forest's ecology. Spruce-fir forests are not adapted to fire like the lower elevation ponderosa pine (*Pinus ponderosa*); rather, fires tend to be stand replacing events. The fire return interval for the spruce-fir forest can be 300-400 years (Veblen et al. 1994; Jenkins et al. 1998; CSFS 2010), allowing large fuel accumulation in the intervening years. Because fires are stand replacing, bark beetle outbreaks do not follow fires and around 70 years of regeneration is required before the stands again become susceptible (Veblen et al. 1994).

Spruce forests provide a multitude of benefits to humans and wildlife. The forests hold considerable snowpack, providing delayed release of a much-needed water supply for many areas of the Colorado. This is particularly important on north facing slopes of lower elevations, where the dense canopy of spruce allows snowpack to persist long after surrounding patches have melted. The forests also provide habitat for many important wildlife species, such as the red squirrel, pine marten, snowshoe hare, boreal owl, Clark’s nutcracker, and three-toed woodpecker (CSFS 2010).

Engelmann spruce is an important species for the timber industry in Colorado (Hayes et al. 2012; Sorensen et al. 2016). In 2012, 15.5 million board feet of spruce timber were harvested throughout the state, making up 18.9% of the overall harvest (Sorensen et al. 2016). Of that harvest, 9.1% became house logs and 89.4% were processed as sawlogs. Spruce is the dominant species used for house logs; in 2012, 46.1% of the house log material came from Engelmann spruce. Outside of the traditional markets, there is plenty of room for creativity. One example of this is the “shadow array” art installation at Denver International Airport. Large spruce logs were installed on the grounds to produce shadow patterns that can be seen by passengers from the air. One goal of the shadow array project was to highlight Colorado’s potential for re-using beetle-killed trees in the form of forest products.

The Beetle: Biology, Life Cycle, and Populations

Spruce beetles advance through four life stages during their development: egg, larva, pupa, and adult (Fig 2.2; Schmid and Frye 1977). The eggs are oblong and pearly white in color, about 0.75-1 mm long. The larvae are 6-7 mm long, white, and cylindrical, with feeding mouthparts that are used to feed on the tree's phloem. Larvae have four instar stages before pupation. The pupae are a similar size to the adult, but creamy white in color. Adults are 4.4-7 mm in length, which is about the size of a grain of rice (CSFS 2014). Their color gradually darkens from the pupal stage, going from white, to reddish brown, to dark brown and eventually black. The phrase "callow adult" is often used to describe adult beetles that are light in color (Schmid and Frye 1977).

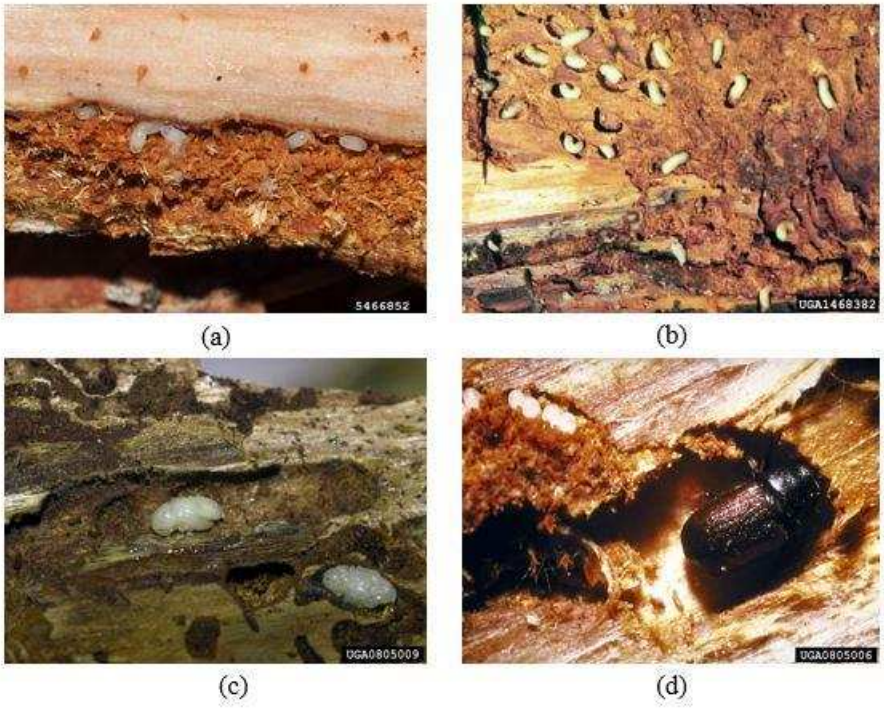


Figure 2.2 - Life stages in spruce beetle development. Source: bugwood.org (a) Eggs and egg gallery (William M. Ciesla) (b) Larvae (USFS Ogden, UT) (c) Pupae (Edward H. Holsten) (d) Adult spruce beetle (Edward H. Holsten)

The life cycle for *D. rufipennis* typically takes two years to complete. However, in rare cases the beetle's life cycle can be shortened or lengthened, mostly due to climatic conditions (Hansen et al. 2001; Jenkins et al. 2014). Massey and Wygant (1954) reported on spruce beetles in southern latitudes of Colorado completing their life cycle within one year, which is known as a univoltine brood. In this case, the beetles overwinter as adults during the same year as the initial attack. The proportion of beetles that exhibit the univoltine life cycle is likely very low (Schmid and Frye 1977). However, research by Hansen et al. (2001) suggests that the absence of cold temperatures will promote this cycle, and furthermore that univoltine broods are equally "fit" and capable of flight and infesting new trees.

Schmid and Frye (1977) advise that as a general rule the two-year cycle should be assumed by managers, so it will be described here. In late May to July of year one, female beetles fly from their host tree and seek out new hosts. Beetle flight date is typically determined by the date at which maximum shade temperatures reach 16°C (61°F; Schmid and Frye 1977). When adult beetles find a suitable host, they send aggregation pheromones to attract mates (Hard 1989; Jenkins 2014). After mating, the females burrow just underneath the bark, creating egg galleries and depositing eggs along the way. Many beetles are capable of additional flights in the same season; after constructing egg galleries they re-emerge to attack another tree. However, in the majority of cases, the beetles' flight muscles are too degenerated for additional flights beyond the first (Lawko and Dyer 1974).

The eggs hatch later in the summer and the larvae tunnel perpendicularly away from the egg gallery, feeding on the tree's phloem. The larvae diapause (halt development) around October, by which time they have reached the second to fourth instar stage (Schmid and Frye 1977; Hansen et al. 2011). Diapause allows the beetles to survive potentially hazardous winter conditions before developing into more sensitive stages. In the spring of year two, approximately one year after the initial attack, the larvae pupate and eventually resume in the adult stage. The second winter is typically spent as an adult. Beetles often leave their galleries and re-infest the same tree closer to ground level, most likely to seek protection from the cold and woodpeckers (Knight 1960). The adult beetles do not fly until late May-July the following year, approximately two years after the initial attack, when they emerge to infest new trees and perpetuate the cycle. During larval development, the tree is girdled and killed (CSFS 2014).

The number of attacks necessary to cause mortality in a tree is mostly determined by the square feet of phloem available (Knight 1960), and thus varies with the diameter and the height of the tree. Beetles do not attack at heights greater than 40-50 feet on a standing tree, so additional height increases beyond this don’t add appreciably to the number of beetles. Knight (1960) found the mean number of attacks of a 10-, 15-, 20-, and 25-inch tree to be, respectively, 282, 541, 745, and 965. Because each attack involves two beetles, these numbers can be doubled to estimate the total number of beetles infesting each tree.

Spruce beetles are capable of very long flight distances, allowing them to cross long host-free stretches during epidemics. Chansler (1960) found that under controlled settings beetles could fly seven miles or more nonstop. However, even this might underestimate the beetle’s capabilities. Schmid and Frye (1977) proposed that flights of thirty miles must have been necessary during the White River National Forest (WRNF) outbreak of the 1940’s for the beetles to cross the non-host inhabited area between the Flat Top Mountains and stands south of the Colorado River.

Epidemics: Landscape-Scale Effects and Management

Past epidemics have spurred considerable research into the causes for, implications of, and best management practices for spruce beetle outbreaks. Studies in Utah and Colorado have shown that the return interval for spruce beetle outbreaks at a given site is around 75 years, and that there have been four periods of broad-scale outbreaks in recorded history: 1843-1860, 1882-1889, 1931-1957, and 2004-2010 (Hart et al. 2014; Jenkins et al. 2014). Although not the first recorded outbreak in Colorado, the White River National Forest (WRNF) outbreak of the 1940’s is commonly cited as being the most devastating, and was the genesis of much research. In affected stands, 99% of the overstory spruce trees were killed, for a total of between 3.8 and 4 billion board feet of spruce mortality (Nelson 1950; Schmid and Frye 1977). Hart et al. (2014), in a study that related periods of spruce beetle outbreaks with large scale climatic drivers, concluded that drought was the most important inciting factor in these outbreaks. However, temperature and windthrow are also considered important drivers in spruce beetle outbreaks (Jenkins et al. 2014). No other quantitative studies were found that made similar investigations into potential contributing factors that affect spatial distribution of stands, such as fire suppression or management activities.

Epidemic level outbreaks can have drastic effects on future stand composition, watershed health, fire risk, and aesthetics. As the mature spruce are killed and light enters the forest floor, the sub-dominant subalpine fir (*Abies lasiocarpa*) will initially dominate. In the absence of logging or other disturbance, fir will persist in the overstory for 125-175 years before again being overtaken by the more shade tolerant and longer living spruce (Schmid and Frye 1977; Dymerski et al. 2001). Until the dead spruce trees blow down, the landscape is dominated by grey, dead trees. These trees can pose a hazard to human safety and infrastructure, as well as negatively affecting the recreational opportunities in the area. Additionally, widespread spruce mortality can lead local communities to a reduced quality of life, increased conflict, increased perception of risk, and difficult economic challenges (Flint et al. 2008).

There is much debate about the implications of bark beetle infestations on wildfire risk and severity. The spruce-fir zone is cool and moist, and typically is subject to infrequent, high intensity wildfires. Wildfire models have been developed that predict general crown fire behavior; however, because of a lack of understanding about fuel continuity, these models may not be suitable for beetle-killed stands (Jenkins et al. 2012). The initial crown-fire risk associated with beetle-killed lodgepole pine may be less severe in Engelmann spruce, because the spruce typically only hold their dead needles for one year. This shortens the period of increased fire risk associated with “red stage” beetle-killed pine, which retain needles for several years (Page et al. 2014). However, the high fuel loads present in attacked stands, under the right conditions, can result in devastating fires. In a review of the 2013 West Fork Complex fire in southwest Colorado, fire managers noted that many of the burned stands contained 80% or more of spruce beetle mortality (Fig 2.3; National Incident Management Organization 2014). In any case, the hazards to firefighters are elevated when working in beetle-killed stands (USFS 2011).

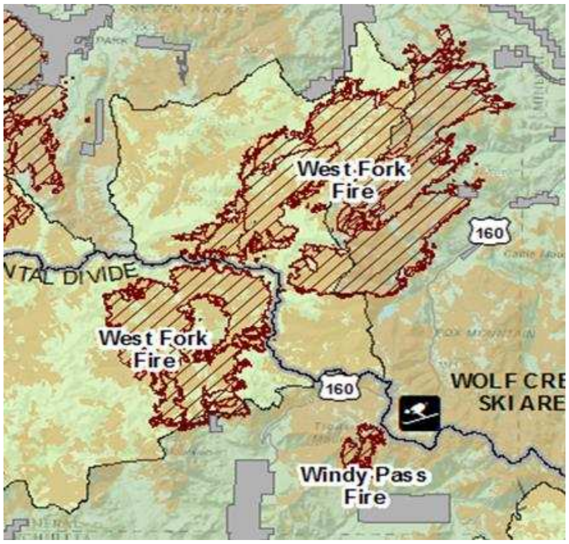


Figure 2.3 - Map of the West Fork Fire of southwest Colorado, with fire perimeter (hatched) and spruce beetle-kill shaded in the background (tan). Source: National Incident Management Organization 2014.

Salvage logging is one opportunity to mitigate fire risk and speed up regeneration of beetle-killed stands. Outbreaks can have disastrous effects on the landscape and stands can take 300-400 years to regenerate (Jenkins et al. 2014), a period which could be accelerated by human intervention. However, as noted by Schmid and Frye (1977), logging can negatively affect the understory regeneration and slash can be a breeding ground for beetles. These factors must be taken into account when planning operations. The U.S. Forest Service identifies tree removal as an essential tool in promoting human safety as well as forest recovery and resilience after a bark beetle attack. In their “Western Bark Beetle Strategy” (USFS 2011), they detail several action items to meet these three goals, including cutting hazard trees, fuel breaks, planting new trees, and silvicultural treatments that include thinning. However, restricted budgets will necessitate the movement of funds from other program areas, such as road/trail maintenance and non-bark beetle vegetation treatments, in order to meet a bare minimum of priority areas (USFS 2011). With this in mind, providing an economic return from salvage operations could be a tremendous benefit to rehabilitation efforts.

Wood Properties and Deterioration

Wood-Moisture Relations

The principle mechanisms that affect the forest product yield and grade of standing trees are sap rot, heart rot, and seasoning checks (Aho and Cahill 1984; Lowell and Willits 1998; Lewis and Hartley 2006). These defects are all largely influenced by one of the most important properties of wood: its relations with moisture. Glass and Zelinka (2010) provide an excellent resource for moisture relations in Chapter Four of “The Wood Handbook”. Wood is a hygroscopic material, meaning that it constantly exchanges moisture with its surrounding environment. In saturated wood, “free water” occupies the cell lumens and “bound water” is bonded to the cell walls (Reeb 1995). When the wood dries, water first leaves the cell lumens, resulting in no dimensional changes. The wood’s Fiber Saturation Point (FSP) describes the moisture content at which the lumens are empty and only bound water remains; this is typically 25-30% (Reeb 1995). Below the FSP, shrinking and swelling of wood occurs as the cell walls lose or gain moisture. Both the total amount of water in a wood specimen (moisture content) and the exchange of bound water (shrink/swell) have important implications for defect formation.

Live Engelmann spruce has an average moisture content of 51% in the heartwood and up to 173% in the sapwood (Glass and Zelinka 2010). These values, as well as all other MC values reported in this thesis, use the oven-dry basis for calculating moisture content:

$$(M_{wet}-M_{dry})/M_{dry}*(100\%)$$

Where:
M_{wet} = Mass of wood before drying
M_{dry} = Mass of wood after drying

Because the mass of water in the wood can exceed the mass of the wood itself, this value is often greater than 100%. Another important concept in moisture relations is the Equilibrium Moisture Content (EMC). Wood above EMC loses moisture to the atmosphere and wood below EMC gains moisture from the atmosphere. This value is determined by temperature and relative humidity. In Alamosa Colorado, near the study sites for this project, the EMC ranges from a low of 9.4% in June to a high of 13.0% in January (Simpson 1998). Higher elevation values, such as those at the actual study sites, may be lower than this because of cooler temperatures.

Wood shrinks and swells irregularly with respect to its three major axes: tangential, radial, and longitudinal (Fig 2.4). Engelmann spruce has a reported shrinkage value of 3.8% in the radial direction and 7.1% in the tangential direction as it moves from green to oven-dry (Glass and Zelinka 2010). This means that dimensional changes in the tangential direction are approximately double that of the radial, a fact that has important implications for the development of surface checks.

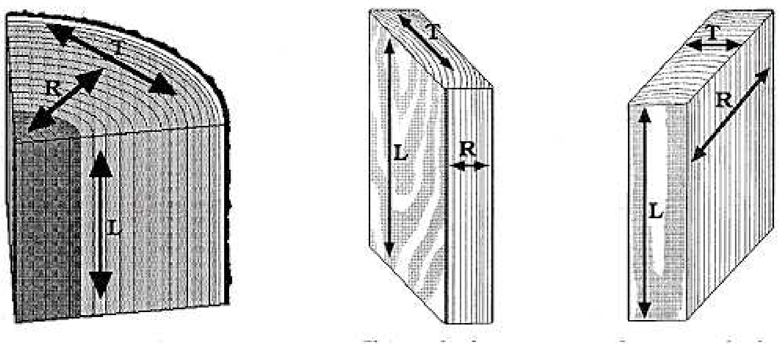


Figure 2.4 - Major axes in wood. T= Tangential, R= Radial, L= Longitudinal. Source: http://www.woodweb.com/knowledge_base/Warp_in_Drying.html

Deterioration

Deterioration, in this thesis, refers to any changes in a tree's bole that affect its lumber yield and/or value as it stand on the stump after being attacked by spruce bark beetles. Deterioration can be caused by mortality (seasoning checks and sap rot) or unrelated to mortality (heart rot). Bark beetle galleries themselves do not affect lumber recovery, since they are restricted to the outer portion of the bole.

Season Checking

Beetle-kill trees typically develop "seasoning checks" (Fig 2.5) as they dry, which can have a substantial effect on yield and value of lumber (Cahill 1980; Lowell and Willits 1998; Lewis and Hartley 2006). Once a tree dries below its fiber saturation point, shrinkage occurs- greater in the tangential direction than in the radial. This means that rather than contracting and reducing diameter, the tangential forces cause portions of the tree bole to open like a book to relieve stress. If the tree bole dries from the outside inward, surface checks begin to form before the entire bole has dried below the FSP. Thus, the rate of drying could have important implications on the type of checking that occurs; whether it is a single deep check, many smaller checks, or some combination.

Figure 2.5- Seasoning checks (left) and heart rot (right). Photo Credit: Jim Webb

Decay Fungi (Rot)

Decay fungi can attack various parts of the tree and cause volume loss due to rot. Heart rot attacks the heartwood first and progresses outward, while sap rot progresses from the outside inward (Hinds et al. 1965). Decay fungi require a vector or path to infect the wood, and can only survive with the right temperature and moisture conditions. Aho and Cahill (1984) reported that the optimum temperature for most decay fungi to grow ranges from 27°C to 33°C (80.6°F to 91.4°F), temperatures only reached in high elevation forests for a brief portion of the year. Additionally, a moisture content above 20% is required (Hinds et al. 1965; Eslyn and Highley 1976; Aho and Cahill 1984). However, if moisture is too high, oxygen is limiting; therefore live sapwood is not typically attacked. Heart rot is more likely to infect trees while the tree is alive and moisture content is suitable than after it has been killed and begun to dry (Hinds et al. 1965). At this point, especially with fluctuating moisture conditions at ground level, sapwood becomes prime for infection. This implies that sap rot defect can be attributed to beetle-kill, while heart rot initiates before the tree is attacked and may continue to progress after death.

Colorado Engelmann spruce trees are subject to significant losses from decay. Worrall and Nakasone (2009) reported that decay causes cull of 15% of the gross merchantable board foot volume of *Picea engelmannii* in the state. Hinds et al. (1965), in a study on beetle-killed spruce trees from the White River outbreak, identified *Fomes pini* (a common red ring rot) as the principal decay fungus, accounting for twenty four percent of the total volume loss from rot in the sampled trees. Mielke (1950), studying beetle-killed spruce in southern Utah, also found *F. pini* to be the most common decay fungi. *F. Pini* has gone through several nomenclature changes in the intervening decades, being known as *Phellinus pini* and now *Porodaedalea pini* (Glaeser and Nakasone 2010). When it comes to sap rots, Hinds et al. (1965) identified *Fomes pinicola* (now *Fomitopsis pinicola*) as being the most damaging. The authors reported that the rot sometimes extended 10-15 feet high, although generally sap rots do not extend more than 3-4 above the ground.

Tests have been done on the susceptibility of Engelmann spruce to various types of fungi. The heartwood is considered “slightly or not resistant” to decay (USFS 1961). Eslyn and Highley (1976) conducted studies on susceptibility of Engelmann spruce sapwood to various decay fungi. They found a generally higher resistance to sap rot than other commonly beetle-attacked softwoods such as ponderosa pine and lodgepole pine. However, field studies that isolated sap rot fungi from beetle-killed Engelmann spruce in Colorado (Hinds et al. 1965) found none of the specific fungi tested for by Eslyn and Highley (1976), other than *Poria sp*.

Some beetle-kill utilization studies have assumed that heart rot ceases after a tree is killed, principally because the wood becomes too dry (Mielke 1950; Lowell and Willits 1998). Lowell and Willits (1998), regarding white and Sitka spruce in Alaska, stated “Once a tree has been killed by beetles, little further deterioration occurs from interior rot” (p. 58). Hinds et al. (1965), on the other hand, found moisture content in the heartwood of dead Engelmann spruce to be suitable for rot development for many years, especially near the ground level. They concluded that “some heart rots may continue to develop in the dead trees” (p. 538). It appears that in some cases beetle-killed trees dry sufficiently to stop decay, but not always. No study was found that quantified the relative occurrence of heart/sap rot and related them to time-since-death and moisture content.

Stain Fungi

Like the mountain pine beetle, spruce bark beetles vector a blue-staining fungus which is introduced into host trees, clogging the xylem and preventing water transport. The agent associated with *D. rufipennis* is most often *Leptographium engelmannii* (Davidson 1955). Infection by blue stain fungus typically begins immediately after the tree is attacked, and within a year the sapwood can be completely discolored (Hinds and Buffam 1971). In a study on lodgepole pine, almost 100% of sapwood was stained within ten months of attack (Harvey 1979). Blue stain is of little consequence in the current study, because it does not affect the structural properties of wood or cause de-grade in structural lumber classes (Snellgrove and Fahey 1977; Cahill 1980). On the contrary, niche markets can sometimes provide an opportunity for increased value of blue stain lumber (Hacker 2006). Blue staining does preclude the lumber from being graded in “appearance” classes or sold on the shelves of some large chain distributors.

Blowdown

Standing dead trees are inevitably subject to blowdown, also called windthrow. Once on the ground, they become more difficult to extract, are exposed to conditions favoring rapid rot (Brown et al. 1998), and their salvage life is very short (Hinds et al. 1965). Decay is almost always the main culprit in windthrow of beetle-killed spruce, causing breakage in either the lower bole or the roots (Mielke 1950; Hinds et al. 1965; Schmid and Frye 1977). Lodgepole pine reportedly has a faster fall rate than Engelmann spruce. Mitchell and Preisler (1998) found that in unthinned stands of lodgepole pine, 90% of the trees had fallen within 14 years. In contrast, Mielke (1950) reported that only 16% of the spruce trees had blown down 25 years after the southern Utah epidemic began. Mitchell and Preisler (1998) also observed that lower elevations were a significant contributor to blowdown in lodgepole pine. They hypothesized that the colder climates at higher elevation inhibited blowdown by slowing decay.

Markets and Industry

Scribner Scaling and Problems Associated with Beetle-Kill

The U.S. Forest Service defines scaling as "The determination of the gross and net volume of logs by the customary commercial units for the product involved" (USFS 2006). In order for mills to understand the value of logs, they must first be scaled; Scribner Decimal C is the common method in Region 2, where the study sites on the Rio Grande National Forest (RGNF) are located (USFS 2006). Gross Scribner scale is based on measurements of length and small-end log diameter, and does not take any defect into account. By ignoring defects, relying on gross scale for beetle-killed trees will lead to underrun, or lower than predicted yields at the mill. This may benefit the timber seller at the expense of the mill. To account for defect, scalers use a net scale value to communicate the expected final yield with the timber buyer. Problems associated with using net Scribner to predict yield from beetle-killed spruce have previously been identified in the literature (Cahill 1980; Snellgrove and Cahill 1980). Net Scribner tends to over-estimate defect due to surface checks and lead to excessive cull. If mills base their expectations on net Scribner, they may encounter overrun. This may benefit the mill at the expense of the land manager. Aligning these expectations and allowing better communication between these two entities is at the core of what this project seeks to achieve.

Potential Markets for Beetle-killed Spruce

According to Lynch and Mackes (2001), the largest wood market in Colorado is residential framing lumber (370.4 million dollars, 58.9% of lumber market or 35.3% of total wood market). Residential framing lumber is typically sold with a thickness of 2”, widths of 4”-12” in 2” increments, and lengths of 8 to 16 feet in two foot increments (Lynch and Mackes 2001). As of 2001, Up to 100% of this material was imported from out of state, despite having the resource and processing facilities in-state. The residential framing market was hit hard during the 2008 recession, where housing starts hit a record low (Keegan et al. 2012). However, housing starts in the west have shown a steady increase in the intervening years, from 132,000 in 2011 to 265,000 in 2015 (NAHB 2016).

Structural lumber is assigned grades which determine its market price (WWPA 2011). Unlike boards in the “appearance” class, these grades are entirely determined by strength, and are therefore not influenced by blue stain (Snellgrove and Fahey 1977; Cahill 1980; Lewis and Hartley 2006). “Splits”, which describe seasoning checks that are still present in the finished product, can serve to reduce grade (Cahill 1980), implying that checks do not necessarily render the affected portion useless. However, Scribner net scaling rules require season checks to be considered cull of the affected portion (Snellgrove and Cahill 1980). This is one of the reasons net Scribner is considered a poor scaling method for beetle-killed timber. In practice, many checks will lead to cull, but some will end up in the final boards and serve to reduce grade. Therefore the current study considers both yield and grade of the final product.

Residential framing lumber has the potential to be heavily affected by season checking. Therefore, several other markets provide opportunities.

- House Logs: Because some checking is allowed in house logs (Cahill 1980), logs of sufficient size can be put to this use. Colorado is one of the major producers of log homes in the country, using approximately 4.05 million linear feet of logs annually (Lynch and Mackes 2001). Spruce is the most important species in the production of house logs (Sorensen et al. 2016), and dead timber is actually preferred because it does not need to be further dried (Peckinpaugh 1978).
- Mine Props: Colorado has several underground mines, many of which require roundwood supports to be installed intermittently. Spruce logs too small for house logs might be suitable for this use, which had a 2001 market value in Colorado of 3 million USD (Lynch and Mackes 2001).
- Cut stock: Cut stock is defined as solid wood cut to a specified length, width, and thickness (Mackes and Eckhoff 2015). This can potentially maximize yield in heavily checked logs because it allows for varying sized boards to be cut.
- Pallet stock: Wood unsuitable for higher value uses often falls into the category of pallet stock. Cutting smaller-sized boards allows for the use of heavily checked logs, for similar reasons as cut stock. The pallet stock market in Colorado at the turn of the century was 11 million USD (Lynch and Mackes 2001).

Beetle-killed Engelmann spruce would also be suitable for non-solid sawn uses such as pulp (Scott et al. 1996), particle-board (Mueller 1959), and bio-energy, as season checking does not reduce their potential for use in these regards. However, high processing costs, low value, and a lack of facilities in the area make these options less viable. Several sawmills exist near beetle-kill hotspots in the southwest Colorado area, so solid-sawn use is the focus of the current study.

Local Timber Harvest Industry and Economics

How much could utilization of the timber resource actually contribute toward covering the cost of beetle-kill treatments? Logging costs are notoriously variable and difficult to predict (Keegan et al. 2002), but the results of a logger survey in the southwest Colorado area could give some indication (Licata 2015). Contractors providing logging services in the area charged between $1,000 and $3,000 per acre to remove trees for restoration purposes without the explicit intent of processing into lumber. Many of the same contractors also routinely worked jobs where money flowed the other way, where the contractor or a mill paid for the timber so that it could be processed and sold. In the latter case, the average price paid was $7.30/CCF (a CCF is defined as one hundred cubic feet of merchantable material). This indicates that timber sales could achieve similar objectives to service contracts while providing revenue rather than incurring a cost. This revenue could then go toward other restoration activities such as reforestation or erosion control.

There are several mills in southwest Colorado, the largest of which is a stud mill that processes 30 million board feet per year when running one shift. This mill has recently recorded underrun when processing dead spruce and commissioned a study to help predict yield of beetle-killed spruce. That study eventually grew into the current thesis. There are also several other mills in the five county area of San Juan, Dolores, Archuleta, La Plata, and Montezuma Counties (Licata 2015) and in the San Luis Valley to the east. Most of these mills are not currently operating at full capacity and could accept more logs. Many of these mills are familiar with processing beetle-killed spruce; in fact, in the five-county area, 25% of the material used for lumber production already comes from dead trees (Licata 2015).

Prior Studies on Beetle-Killed Wood Deterioration

There have been several studies focused on deterioration of beetle-killed spruce timber. However, unlike most other spruce beetle research, these findings have not been synthesized in any major review papers, including Schmid and Frye (1977) and Jenkins et al. (2014). The first round of studies occurred around the time of the White River National Forest (WRNF) outbreak of the 1940's, and included a longitudinal study whose results were not published until the 1960's (Mielke 1950; Nelson 1950; Nelson 1954; Hinds et al. 1965). Continuing insect mortality problems in the west led to a resurgence of interest in utilizing beetle-killed timber and a 1978 conference on the topic (Engineering Extension Service WSU 1978). Around this time, several papers were published (Snellgrove and Fahey 1976; Snellgrove and Cahill 1980; Cahill 1980; Aho and Cahill 1984). The mountain pine beetle epidemic in the Rocky Mountain region spurred more recent research on the topic, focused mostly on lodgepole pine (Lewis and Hartley 2006; Mackes and Eckhoff 2015).

White River Outbreak Studies

The earliest studies on spruce beetle-kill deterioration were conducted shortly after the White River outbreak of the 1940's. Arthur L. Nelson of the U.S. Forest Service published two articles in the *Journal of Forestry* regarding the extent of damage, need for control, and salvage opportunities of the epidemic. He reported that four billion board feet of Engelmann spruce had been killed by 1950, and that the timber would only be salvageable as sawlogs for "4 to 6 years". In his follow-up report, Nelson (1954) reported the killed timber to be unsuitable for lumber after just "2 or 3 years". The shelf life of 2 to 3 years was apparently drawn from two stories of attempted timber harvests in the latter 1940's, in which seasoning checks quickly rendered the timber unfit to be sawed. Quantitative information on the logs' deterioration was not given, so it is possible that mill technological improvements have proceeded in a way that would make sawing the material possible today.

Around the same time as Nelson, James L. Mielke (1950) reported results from his research on the deterioration of Engelmann spruce killed in an earlier epidemic in southern Utah lasting from 1916 to 1924. Unlike statements made by Nelson about the short salvage life of the timber, Mielke suggested that the material would stay viable for twenty years (Mielke 1950). On his study sites, he found little rot in standing trees, and it did not increase with time standing dead. Astonishingly, 84 percent of the killed trees remained standing approximately 25 years after attack, with rot being the leading cause of the little blowdown that occurred. This study did not present a quantitative analysis of surface checks; Mielke claimed "evidently checking practically ceases after the wood becomes well dried out" (p. 884). He noted that where checks exist they can be "slabbed off", and the loss is probably offset by the lower transportation costs in the dried logs. While potentially true, these statements are not supported by any deeper analysis, other than observations that after the Utah outbreak's end in 1924, loggers were cutting trees for sawtimber as late as 1944. Mielke's report may have inspired Combes (1978) to make the claim that "checking does not significantly affect lumber recovery" (p. 169).

Hinds et al. (1965) conducted a 12-year longitudinal study on trees killed in the White River Outbreak. They selected 25 1/10th acre plots in each of four study areas around the forest. At five year intervals, researchers entered five plots in each study area to fell and dissect all spruce trees larger than 5.1". On these samples, they measured total wood volume, decay, and blue-stain volume. On uncut stands, they made entries at two-year intervals to record blowdown trees. "Years since peak mortality" at the stand level was used to estimate Time-Since-Death, which is a reasonable proxy but likely not entirely accurate at the tree level. While the study still did not analyze seasoning checks, it added some quantitative information to Mielke's findings. Hinds et al. (1965) found a higher rate of decay than Mielke (1950), and noted that moisture conditions at ground level were often favorable to decay (50-100%). The authors concluded that rot initially increases and then levels off after about 12 years, but that the sap rot to heart rot proportion increases over time. In their examination of blowdown, they found 8% of the original volume was down after 10 years and 28% was down after 20 years. Because these numbers are reported as volume percentages, it is difficult to compare to them to the tree percentages reported by Mielke (1950). Either way, the findings indicate a much slower fall rate for Engelmann spruce than observed in studies on beetle-killed lodgepole pine (Lewis and Hartley 2006).

Large Scale Beetle Outbreaks in the West

James M. Cahill conducted a mill study on timber killed in the White River infestation in order to estimate both yield loss and value loss (Cahill 1980). Trees were either "dead" or "alive"; all trees were dead 20+ years and their time-since-death was neither measured nor estimated. 296 dead trees were selected and extracted from three stands, with 49 live trees serving as controls. After being measured for volume, logs were milled to dimensional lumber and graded by a certified grader. Researchers found that dead logs had significantly lower yield and value than live ones. Most of the value loss was due to "splits", which are acceptable in lumber but reduce the grade. Volume loss was due to especially severe surface checking and decay. One major oversight in the Cahill (1980) study is that standing trees were lumped together with blowdown. Literature has shown that logs on the ground deteriorate significantly more rapidly than standing trees (Hinds et al. 1965; Brown 1998), a confounding variable that could have obscured the source of the observed de-grade.

Lowell and Willits (1998) studied beetle-killed white and Sitka spruce (*Picea glauca* and *P. sitchensis*) deterioration on the Kenai Peninsula, Alaska. The authors grouped the trees into four deterioration classes, (1) live and recently attacked trees, (2) trees with fading needles, (3) trees dead with no needles, and (4) trees dead with bark sloughing. Statistically significant changes were found between classes 1 and all others, but not between 2-4, in both yield and value. As expected, both yield and grade was highest in class 1. This may indicate that trees quickly lose value, but do not continue to do so over time.

Lodgepole Pine Beetle-Kill Research

The mountain pine beetle (MPB) epidemic of the 2000's in the western U.S. and Canada has spurred considerable research into utilization of the dead timber resource. Lewis and Hartley (2006), in their excellent synopsis paper, reviewed much of the MPB research to provide a timeline of how standing trees deteriorate over time.

Trees are subject to an "initial rapid degrade" after being attacked, mostly driven by rapid drying. In a study on lodgepole pine in British Columbia, trees attacked in July recorded a sapwood moisture content of just 40% later the same summer, and fell below their fiber saturation point by the following summer (Reid 1961; Lewis and Hartley 2006). This resulted in considerable season checking in the trees, except in those where bark remained tight. Interestingly, moisture content of the heartwood was not changed appreciably by the following summer, remaining above 30% (Reid 1961). No similar studies were found on the rate of drying specific to Engelmann spruce. The spruce are likely subject to a similar rapid drying phase, but the effect of the higher elevation is not clear; dryer air and colder temperatures may have conflicting effects.

As for decay, Lewis and Hartley (2006) suggest that trees will succumb to blowdown before rot becomes an important contributor to cull. Support for this is given in a lodgepole pine study by Harvey (1986), where 226 cubic meters of beetle-killed trees were sampled. Results showed that less than 1% of the volume was lost to advanced decay 11 years after death, and decay was only present in 13.7% of the trees (Lewis and Hartley 2006). Lewis and Hartley concluded their review, similarly to Mielke (1950), by stating that salvage opportunities for beetle-killed trees may remain for 15-20 years as long as the trees remain standing. One gap in knowledge identified by Lewis and Hartley is whether or not seasoning checks continue to develop in years following the rapid drying phase, as ambient conditions cause wetting and drying in the wood.

Mackes and Eckhoff (2015) conducted a study on cut-stock recovery of beetle-killed lodgepole pine. They developed a model to predict a tree’s cut-stock recovery based on diameter at breast height (DBH) and TSD. Producing cut-stock allows cutting around individual checks and therefore maximizes yield relative to dimensional lumber. The authors found that TSD was an insignificant predictor of cut-stock recovery, but that diameter was highly significant. This implies that beetle-killed lodgepole pine may have a long shelf life for cut-stock recovery. However, this does not necessarily translate to dimensional lumber; cutting specified dimensions may require the inclusion of seasoning checks, which could lead to cull or degrade.

3. METHODS

Study Basics

Two separate studies were conducted: a field study and a mill study. Eleven plots (ten for the field study and one for the mill study) were selected on the Rio Grande National Forest (RGNF) to represent a variety of site conditions, elevations, and year of attack (Fig 3.1). Plot boundaries corresponded to polygons delineated by Colorado State Forest Service aerial forest insect surveys. These surveys identify the year that evidence of beetle attack first became apparent from aircraft, but are not always reliable in determining individual tree death (Webb 2015). Response and predictor variables were measured and used to develop regression models to answer questions identified in the objectives.

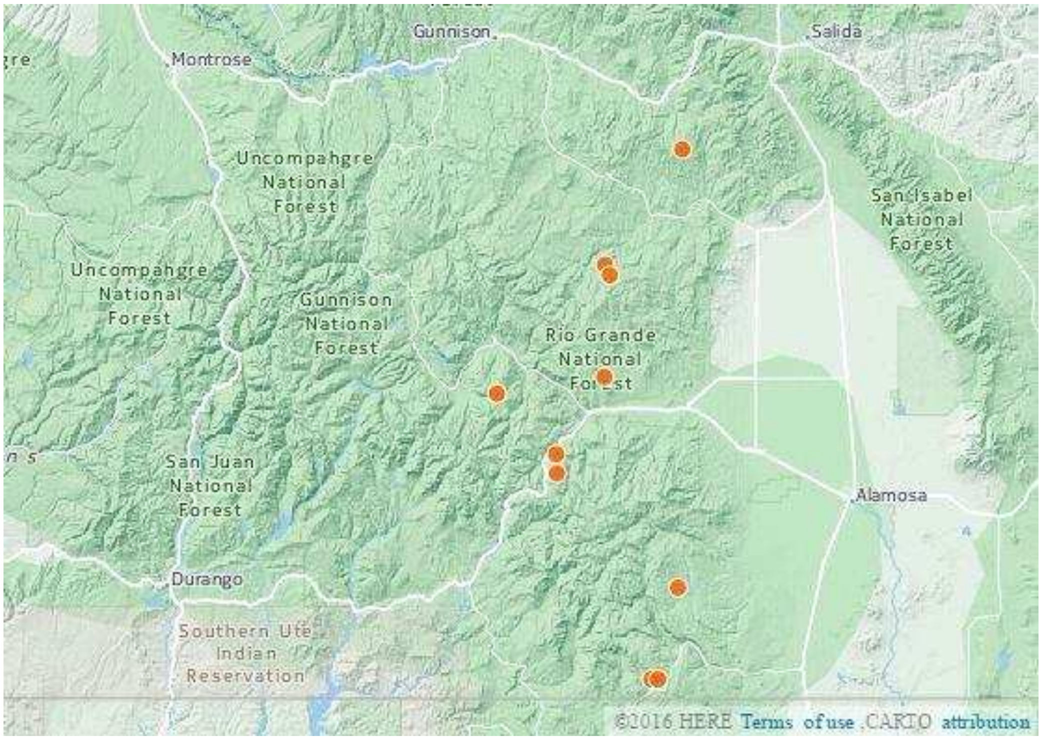


Figure 3.1 - Map of study area with plot locations shown. Map produced with Carto (https://carto.com/)

Plots range from 9,521’ to 11,346’ (2,902 to 3,458 m) in elevation, and receive between 23 and 48 inches (58 to 122 cm) of precipitation annually (Webb 2015). SNOTEL data from Wolf Creek Pass (11,000 feet in elevation) shows a 30 year mean daily temperature range from 9 to 26°F (-13 to -3°C) in the coldest month, December, and 44 to 66°F (7 to 19°C) in the hottest month, July. Temperatures are likely warmer in study sites at lower elevations, but information from the Wolf Creek Pass station is given because the station is centrally located and within the elevation ranges of the sites.

Variables: Descriptions and Measurement Methods

The field study consisted of felling, bucking, and measuring 86 trees on ten plots within the RGNF. This work was done in the summer of 2015 by Jim Webb of Forest Stewardship Concepts Ltd. On most plots, three beetle-kill trees were selected in each DBH class (8-11.9”, 12-16.9”, 17+”), for a total of nine per plot. Four plots had eight trees rather than nine because of time constraints. Measurements were made at the plot level, the tree level, and the within-tree level (see Appendix 1 for a complete list of measurements). The trees were felled and sectioned into sixteen foot logs. Logs were assessed for various properties including season checking, heart rot, and diameter. No differentiation was made in data collection between different species of fungus, nor between brown, white, and soft rot. A cross-section was taken from each tree so mortality year could later be determined through tree ring analysis (dendrochronology). Trees in this study had been attacked as recently as the previous season; therefore, all had been standing dead at least one year.

For the mill study, nine beetle-kill trees and two live “control” trees, all with a minimum DBH of 10”, were selected from a logging operation located in the vicinity of the field study. The trees were harvested and transported to Rocky Mountain Timber Products in Del Norte, Colorado for processing. All of the same predictor variables used in the field study were measured on trees in the mill study, including mortality year. The 11 trees yielded 33 logs, which were milled to two inch dimensional lumber with residual one inch boards. After milling, the boards were measured for volume and graded by a certified grader following the most recent Western Wood Products Association rules (WWPA 2011).

Predictor variables were all directly measurable and fell into one of three hierarchical levels: plot level, tree level, or within-tree level. The same predictor variables were used in all analyses; however, the response variables were different so they are presented later (see "Statistical Analysis"). Plot level measurements (including precipitation level, elevation, aspect, and more) were applied to all trees on the plot. Polygon mortality year was not used as a predictor. Instead, the more accurate tree-level dendrochronology analysis was used to indicate Time-Since-Death (TSD).

Tree-level measurements, with the exception of TSD, were taken before felling the tree. Because exploratory graphics indicated several interactions were occurring, TSD and DBH were treated as categorical variables ("TSDClass" and "DClass", respectively). TSD was grouped into three classes representing important phases identified in the literature (Table 3.1). Diameter was also grouped into three classes, shown in Table 3.2. Many other measurements were made at the tree level, such as moisture content, bark cover percentage, height, and snag class (Table 3.3).

Table 3.1 - Time-Since-Death Class information

TSDClass	Range	Median
New	1 Year	1 Year
Recent	2-6 Years	3 Years
Seasoned	6-11 Years	8 Years

Table 3.2 - Diameter Class information

DClass	Range	Median
Small	8-12"	11"

Medium	12-17”	14”
Large	17”+	19”

Table 3.3 - Summary of predictor variable measurements

Sampling Unit	**Measurement**	**Measurement Unit**
Plot	Polygon mortality year	Year
Plot	Latitude/Longitude	Decimal degrees
Plot	Elevation	Feet
Plot	Aspect	Categorical: N/NE/E/SE/S/SW/W/NW
Plot	Yearly precipitation	Inches
Plot	Logging Unit?	Categorical: Yes/No
Tree	Mortality Year	Year
Tree	Diameter at breast height (DBH)	Inches
Tree	Total Height	Feet
Tree	Height to 6” top	Feet
Tree	Snag class	Categorical: 1/2/3
Tree	Sap rot height	Feet
Tree	Sap rot depth	Inches
Tree	Bark retention	Percent
Tree	Diameter at butt	Inches
Tree	Butt moisture content	Percent
Within-Tree	Height	Feet
Within-Tree	Log	Location

Within-Tree level variables (response variables) were measured after the tree was felled and sectioned. These measurements were made at 1, 17, 33, 49, 65, and 81 feet, though not all trees were tall enough for every Height measurement. Because responses naturally change with the height in the tree, “Height” was considered an important predictor in the study.

Data Processing Methods- Dendrochronology and Scribner Scaling

Dendrochronology methods were used to determine mortality year for all trees in both studies. A core, taken from a live control tree, was used from each plot to establish a historical record of ring widths. Tree cross-section specimens, cut from the field and mill studies, were belt-sanded to improve the visibility of the rings. Specimens were then placed on a sliding track with a linear encoder for measuring distances. The linear encoder was connected to a Velmex Read-Out (Velmex Inc., Bloomfield, NY), which recorded the distances and printed to a computer. The researcher, looking through a microscope, lined up the start of each ring with crosshairs and pushed a button to print the measurement to the computer. He then turned a dial to move the sample along the track, lining up the next ring, repeating the process. This resulted in precise measurements for tree ring width going back several decades. Microsoft Excel 2013 was then used to create graphs of ring width vs. year. By comparing graphs of sample trees to control trees, year of death could be reliably determined. More information on this technique can be found in Mackes and Eckhoff (2015).

Net Scribner scale was used as both a response variable in the field study and a predictor variable in the mill study. First, gross Scribner was determined from tables by using the log's small-end diameter and length. Next, deductions for both rot and season check were calculated. Rot defect was calculated using either a length or squared defect deduction (Fig 3.2). Surface checking was typically more complicated. If only one check (non-spiral) was present, it could be removed with a pie cut. If multiple checks were present, the best strategy was typically a diameter reduction (Fig 3.2) based on the second deepest check and a pie cut to remove the remainder of the deepest check. Finally, these deductions were subtracted from gross Scribner to arrive at net Scribner. Logs with many defects sometimes scaled to a negative board foot value. To deal with this, rot was assumed to occur first and seasoning check deduction was reduced so the net became zero.

Statistical Analysis

Several distinct analyses were conducted for different response variables. Data analysis consisted of identifying the response variable of interest and building linear regression models to

Diameter reduction: The log is rescaled to the diameter of the unaffected inner core and the defect is calculated as the difference between the original scale and the new scale.

Pie-cut deduction: If defect is circumferential in nature, the gross Scribner is reduced by an appropriate proportion. For non-spiral season checks, the reduction is 1/8.

Length reduction: The log is shortened to remove defect and rescaled. Defect is calculated as the difference between the original scale and the new scale.

Squared defect: The defect is a volume measurement calculated by multiplying the height, width, and length of the defect.

Figure 3.2 - Methods used in calculating net Scribner defect, adapted from the National Forest Log Scaling Handbook (USFS 2006)

relate them to the predictors. Four responses were explored in the field study: “Checking”, “Sap Rot”, “Heart Rot”, and “Net Scribner”. Additionally, several responses were explored in the mill study. The software package ‘R’ was used to conduct analysis, build models, and prepare graphics. All mixed models rely on the “Kenward-Roger” method for approximating denominator degrees of freedom. All pairwise comparison p-values are corrected with a Tukey Adjustment for multiple comparisons. Pairwise comparisons use the adjusted means calculated by the ‘lsmeans’ package in R. Model assumptions were checked with residual diagnostics. All significance tests use alpha = 0.05 unless otherwise noted. Six models are presented in the results section; each is given an identifying number, and a summary can be found in Appendix 2.

Checking

At each Height, the depths of all checks were measured and combined with others within the cross-section to arrive at total checks/section in inches. In the analysis, only measurements up to the fourth cross section (49 feet) were included because shorter trees would have unbalanced the design. Therefore the response variable is “Checking” (inches, n=314).

These measurements were used to create a repeated measures mixed effects model (Fig 3.3). The top level factor is plot. Tree, the subject/experimental unit, is nested within plot. The within-subject factor is Height, allowing for a total sample size of 314. Because of a significant three-way interaction and issues with non-constant variance, the data were split by diameter class ("DClass"). This split resulted in three different models: Small, Medium, and Large. Pairwise comparisons were then investigated to look for significant contrasts.

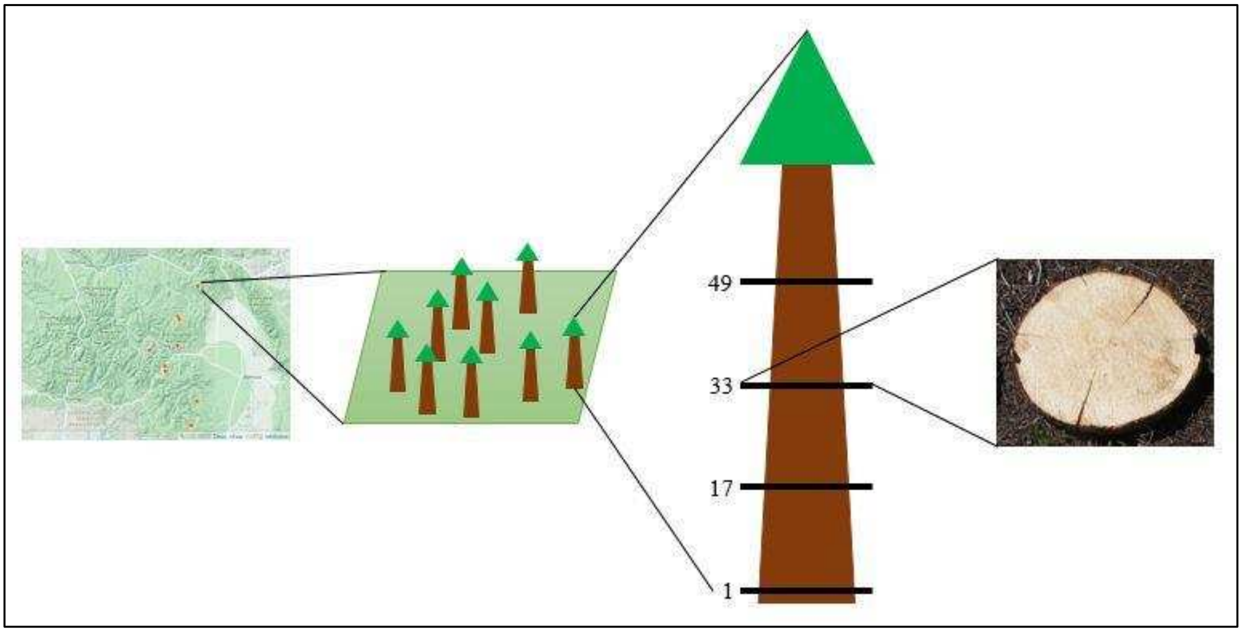


Figure 3.3 – Schematic of nested design. Reading from left to right: (a) Reproduction of Fig 3.1 showing ten study plots, (b) Close-up of the northernmost plot showing nine trees, (c) Close-up of the easternmost tree showing the four measurement heights, and (d) Cross-section at 33 feet.

Heart Rot

At each Height, the square area of heart or pocket rot was measured. If rot did not extend all the way to the end of the log, the tree was sectioned until the end was located and length of rot column could be measured. Cubic foot rot column was calculated by averaging the area of the two rot measurements and multiplying by the length of the rot. Rot columns were then aggregated by tree. Therefore, there were two response variables: “RotDisc” (Square inches, n=314) and “RotCol” (Cubic feet, n=86).

The rot analysis presented some problems because there was little rot in any of the study trees. First, “RotDisc” was used to develop a repeated measures analysis similar to “Checking”, but did not reveal any significant predictors. Next a nested mixed effects model for “RotCol” was developed with Plot as the random effect in which Tree was nested. All predictors were initially tested, including the three-way interaction of “Height” x “TSDClass” x “DClass”. A backwards elimination process was used to eliminate predictors not significant at the 0.05 level.

Sap Rot

Sap rot was measured and assessed at the tree level (height, depth, and circumference of rot), so a repeated measures model was not necessary. The proportion of trees with no sap rot was very high, and where sap rot was present it tended to be fairly uniform; typically 100% of the sapwood was infected to a height of 3-4 feet. For these reasons, sap rot was treated as a binary variable, where it was either present or absent. This approach makes practical sense because sap rot is typically dealt with by long-butting the tree (Cahill 1980) so there is 100% cull of the affected portion. Therefore, the response variable was “Sap” (Y/N, n=86). A Chi-square test was conducted to test the null hypothesis that sap rot occurrence is independent of “TSDClass”.

Net Scribner

Net Scribner is commonly used by the U.S. Forest Service and understood by mill operators, so measurements were used to calculate net Scribner yield on all logs in the study. Another advantage of this approach is that it accounts for both the higher yields and higher checking associated with diameter in one number to determine if they cancel out or if one eclipses the other. The response variable, determined through methods described above in “Data Processing Methods”, was “NetBF” (board feet, n= 233). “NetBF” was regressed over the predictors with a mixed repeated measures model similar to the “Checking” model. Rather than “Height”, “Log” was used as the within-Tree variable. Most trees included three logs, numbered consecutively from the butt log upward (“1”, “2”, and “3”). A backwards model selection process, beginning with all predictors and including the three-way interaction, eliminated all non-significant predictors. Once the final model was reached, the ANOVA table and pairwise comparisons were investigated to determine relationships.

Mill

Responses of interest in the mill study were the grade class breakdown, the proportion of yield with blue-stain, and the total board foot yield. All predictor variables were the same as in the other analyses, except “TSDClass”, which included green control trees. No trees in the mill study had been dead longer than six years; therefore the TSD levels in the mill study were “Control”, “New”, and “Recent”.

All boards were traced to their tree of origin, but because of difficulties encountered while milling they were not reliably associated with log position number. Therefore, all responses are aggregated by tree and the sample size is eleven. Linear fixed effects models were developed to analyze the effect that predictors have on blue-stain and grade composition of the finished products. Additionally, three methods of predicting yield were tested for accuracy against the final lumber tally, and the method with the highest Pearson correlation was determined. These methods were gross Scribner, net Scribner, and product potential cubic. Scribner scaling methods followed the protocol described above for the field study. Product potential cubic is described in Snellgrove and Cahill (1980) and USFS (1991), and is a method to predict merchantable cubic foot yield with defects removed. The difference between gross log volume and log volume reduced by average check depth is first used to estimate defect. This defect is then halved and subtracted from gross volume to calculate the final cubic scale. It is important to note that this method predicts the cubic volume suitable for product rather than actual board foot yield, because it does not account for waste in the form of kerf, edges, and slabs.

4. RESULTS

Field Study

Checking

The initial checking model indicated a significant “Height” x “TSDClass” x “DClass” interaction (p = 0.0458), meaning that each of these factors had a different effect on the response depending on the level of the other factors (Fig 4.1). The co-variates “Elev” (elevation in feet) and “BarkCover” (percent of bark remaining on tree) were also significant (p = 0.0067 and p = 0.0048, respectively), so they were included in subsequent models.

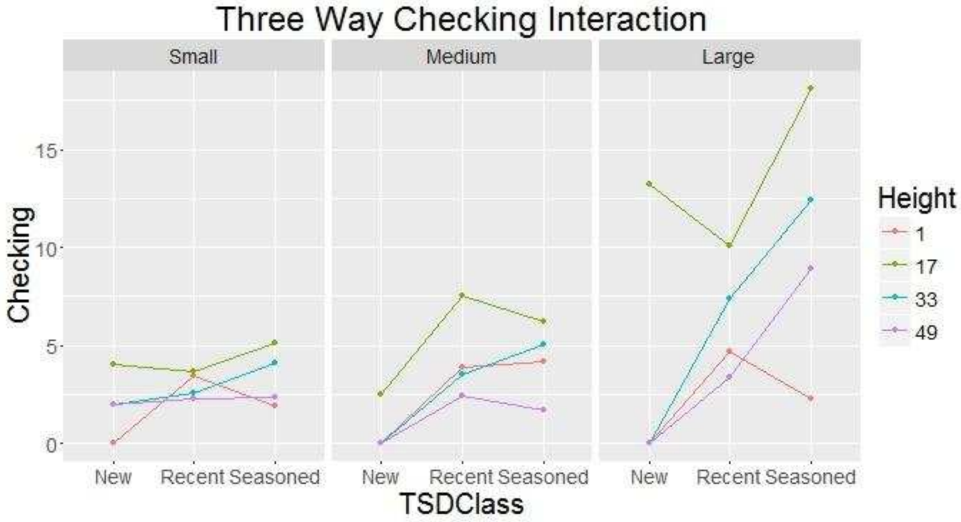


Figure 4.1- Interactions between factors affecting the Checking response. Each panel represents a diameter class, the x-axis shows TSD class, and results are grouped by height (feet).

Splitting the model by diameter class helped to interpret the different effects of TSD class within each diameter class. The model for the small trees (Model 1) contained no significant predictors of “Checking” (Table 4.1). The model for the medium trees (Model 2) indicated that both “DClass” and “TSDClass” were significant, but the covariates “Elev” and “BarkCover” were not. The pairwise comparisons of “TSDClass” showed a significant increase in “Checking” as trees move from New to Recent (p = 0.0032), but not as trees move from Recent to Seasoned (p = 0.7925; Table 4.2). The large tree model (Model 3) revealed that all main effects and the interaction were significant predictors of “Checking” (Table 4.3). Because the interaction was significant, pairwise comparisons of “TSDClass” were examined at different heights (Table 4.4). At Height 1, no “TSDClass” contrasts were significant. At other Heights, the only “TSDClass” contrasts that approached significance were the Recent-Seasoned classes. This effect was most pronounced at Height 17 (p = 0.001). This indicates that above ground level, large trees experience an increase in “Checking” as they move from TSD classes Recent to Seasoned. This is a different pattern than observed in the medium trees, and will be touched on in the discussion.

Table 4.1 - Small trees (Model 1): ANOVA table

	Sum Sq	Mean Sq	NumDF	DenDF	F.value	Pr(>F)	Significance
Height	67.772	22.5906	3	58.237	2.36465	0.08029	.
TSDClass	17.524	8.7621	2	22.793	0.91717	0.4139	
Elev	24.823	24.8225	1	7.248	2.59827	0.14955	
BarkCover	20.165	20.165	1	20.248	2.11076	0.16159	
Height:TSDClass	51.965	8.6609	6	57.216	0.90657	0.49677	

Table 4.2 - Medium trees (Model 2): Pairwise comparisons of “TSDClass”, averaged over levels of “Height”

	Estimate	SE	DF	t.ratio	p.value	Significance
New-Recent	-4.0542047	1.095144	23.18	-3.702	0.0032	**
New- Seasoned	-4.7387205	1.419977	24.05	-3.337	0.0075	**
Recent- Seasoned	-0.6845158	1.0481	23.32	-0.653	0.7925	

Table 4.3 - Large trees (Model 3): ANOVA table

	Sum Sq	Mean Sq	NumDF	DenDF	F.value	Pr(>F)	Significance
Height	586.21	195.403	3	69	11.2039	4.46E-06	***
TSDClass	137.83	68.917	2	12.82	3.9515	0.046036	*
Elev	289.08	289.079	1	5.025	16.575	0.009525	**
BarkCover	181.29	181.288	1	20.998	10.3946	0.00407	**
Height:TSDClass	391.69	65.281	6	69	3.7431	0.002783	**

Table 4.4 - Large trees (Model 3): Pairwise comparisons of “TSDClass” at different heights

Contrast	**Estimate**	**SE**	**DF**	**t.ratio**	**p.value**	**Significance**
			Height = 1			
New-Recent	-1.25879847	4.775889	82.88	-0.264	0.9624	

New-Seasoned	1.74077994	4.90058	82.06	0.355	0.9329	
Recent-Seasoned	2.99957841	1.932252	47.92	1.552	0.2761	
			Height = 17			
New-Recent	6.60057653	4.775889	82.88	1.382	0.3549	
New-Seasoned	-0.81477561	4.90058	82.06	-0.166	0.9849	
Recent-Seasoned	-7.41535215	1.932252	47.92	-3.838	0.001	**
			Height = 33			
New-Recent	-3.96192347	4.775889	82.88	-0.83	0.6858	
New-Seasoned	-8.34255339	4.90058	82.06	-1.702	0.2105	
Recent-Seasoned	-4.38062992	1.932252	47.92	-2.267	0.0704	.
			Height = 49			
New-Recent	0.03807653	4.775889	82.88	0.008	1	
New-Seasoned	-4.87033117	4.90058	82.06	-0.994	0.5828	
Recent-Seasoned	-4.9084077	1.932252	47.92	-2.54	0.0376	*

Heart Rot

Heart rot was not common in the samples, and when present it was typically only found near the ground level. Therefore, the responses were aggregated by tree to investigate the total rot column (“RotCol”). The five number summary for “RotCol” is (0, 0, 0.01, 0.51, 37.96), showing a distribution of mostly zero with a very long right tail. A backwards selection process was undertaken to find significant predictors of “RotCol”. All predictors eventually dropped out, leaving none of significance. Therefore, there is not enough evidence to reject the null hypothesis that “RotCol” is not dependent upon “TSDClass” or “DClass” (p = 0.9366 and p = 0.2404, respectively; Table 4.5). This finding, regarding the lack of increasing rot with time-since-death, is in line with other findings in the literature (Hinds et al. 1965; Lewis and Hartley 2006).

Table 4.5 - Heart rot analysis ANOVA table

	Sum Sq	**Mean Sq**	**NumDF**	**DenDF**	**F.value**	**Pr(>F)**	**Significance**
TSDClass	5.22	2.61	2	30.682	0.06245	0.9396	
DClass	121.36	60.68	2	77.524	1.45198	0.2404	

Moisture content was also measured at stump level in both the sapwood and heartwood, to determine if conditions were suitable for decay. Many trees had a high enough moisture content in both sapwood and heartwood for decay, and the heartwood tended to have a higher moisture content than the sapwood (Fig 4.2).

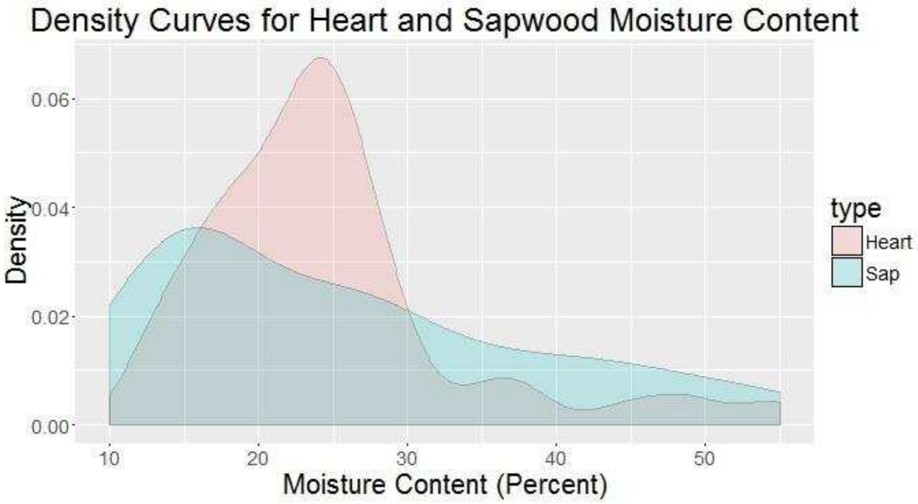


Figure 4.2 - Distribution of moisture content in both sapwood and heartwood.

Sap Rot

There was a clear relationship between “TSD” and the occurrence of sap rot (“Sap”). As shown in Figure 4.3, trees containing sap rot had generally been standing dead longer than those without sap rot.

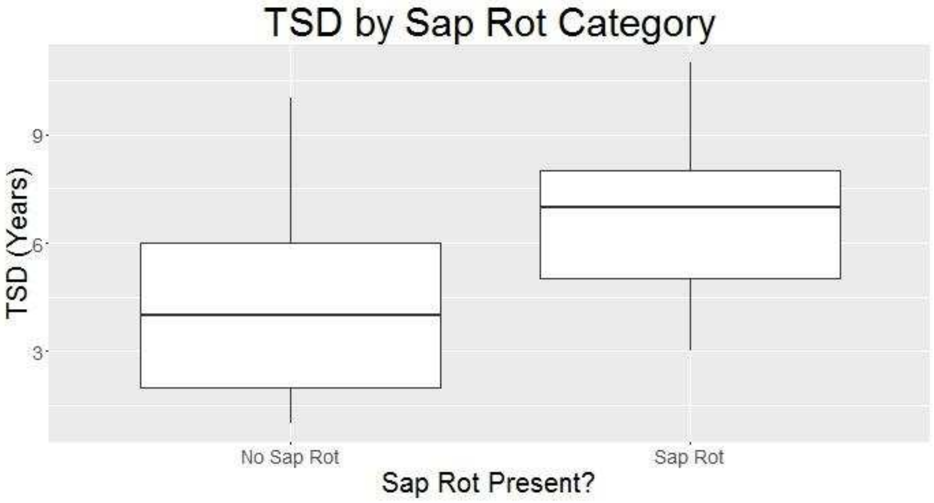


Figure 4.3 - TSD comparison for trees without sap rot vs those with sap rot

A Chi-Square test was conducted to formally test the null hypothesis that “Sap” is independent of “TSDClass”. Results from the test support rejecting the null and concluding that sap rot occurrence and “TSDClass” are not independent (P= 0.0070; Table 4.6). The longer a tree stands dead, the more likely it is develop sap rot.

Table 4.6 - Contingency table for Chi-Square analysis of sap rot

	New	**Recent**	**Seasoned**	**Totals**
No Sap rot	8	50	15	73
Sap rot	0	5	8	13
Totals	8	55	23	86

Net Scribner

The final net Scribner model included “DClass” and “Log” (Model 4) after eliminating insignificant predictors such as “TSDClass” (p = 0.1502). Pairwise comparisons of “Log” showed an insignificant difference from Log 1 to 2 (p = 0.0730) and a highly significant decrease in yield from Log 2 to 3 (p < .001; Table 4.7). Without considering any defect, we would expect Log 1 to show significantly more yield than Log 2 because of its larger size. These results indicate that, according to Scribner scaling rules, the defects on the lower portion of the bole counter these effects. Diameter comparisons show a significant contrast moving from Small to Medium (p = 0.0071), but not Medium to Large (p = 0.1086; Table 4.8). This result is also contrary to what would be observed without considering defect, and could indicate that the higher yields in larger trees are offset by higher rates of checking.

Table 4.7 - Net Scibner Model: Pairwise comparisons by Log Number, averaging over “DClass” and “TSDClass”

	Estimate	**SE**	**DF**	**t.ratio**	**p.value**	**Significance**
1-2	5.582541	2.53	146.97	2.209	0.073	.
1-3	19.139147	2.81	151.8	6.822	<.0001	***
2-3	13.556606	2.81	151.13	4.824	<.0001	***

Table 4.8 - Net Scribner Model: Pairwise comparisons by "DClass", averaging over "TSDClass" and "Log"

	Estimate	SE	DF	t.ratio	p.value	Significance
Small-Medium	-13.13365	4.2155	80.89	-3.116	0.0071	**
Small-Large	-21.72217	4.426	81.83	-4.908	<.0001	***
Medium-Large	-8.58852	4.1968	71.91	-2.046	0.1086	

Mill Study

Overall, 182 boards measuring 1,743 board feet were produced from 33 logs from 11 trees. The grade breakdown of the lumber tally was: 58.4% Select Structural (SS), 3.6% Grade 1, 17.3% Grade 2, and 20.7% Grade 3. In total, blue-stained boards accounted for 64.5% of the lumber tally. Of the SS tally, 67.1% contained blue stain, showing that having blue stain did not prevent a board from achieving the grade of Select Structural. Most of the lumber tally was split-free (93.6%); of the ten boards that contained splits, eight made Grade 3, one made Grade 2, and one made Select Structural.

Blue Stain

As expected, blue stain increased tremendously between Control and New TSD classes, but did not significantly change between New and Recent (Fig 4.4).

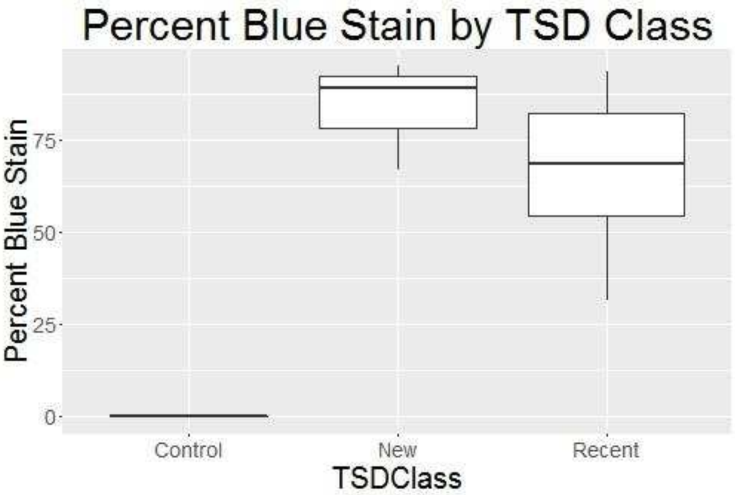


Figure 4.4- Percentage of yield with blue stain increased from Control to New but not from New to Recent.

A model (Model 5) was developed to predict percentage of yield with blue stain from TSD class. One-way ANOVA showed a statistically significant relationship (p = 0.0040). Pairwise comparisons reveal, as expected, that transitioning from Control to New showed a significant increase in blue stain (p = 0.0040) but moving from New to Recent showed no significant change (p = 0.4590).

Scaling Method Comparison

Three methods of scaling were tested in regards to their accuracy to predict lumber tally (Table 4.9). Gross Scribner was far better than net Scribner for predicting yield, indicating that net Scribner assigns too much defect for surface checks. Cubic recovery is defined as the final yield volume in cubic feet (board foot yield divided by 12), making it an appropriate comparison for cubic predictors. Product potential cubic does not account for kerf, slabs, and edges, and thus over-predicts the yield. However, it is well correlated with the cubic recovery so a correction would allow it to be used as a relatively accurate scaling method.

Table 4.9 - Comparison of various scaling methods in the mill study. Correlations with yield are indicated in the bottom row (Pearson product-moment correlation coefficient)

Tree	**Gross Scrib (Bd ft)**	**Net Scrib (Bd ft)**	**Lumber Tally (Bd ft)**	**PPCubic (ft^3)**	**Cubic Recovery (ft^3)**
A	90	88	112.83	19.56	9.40
B	150	79	169.34	26.66	14.11
C	170	104	216.15	26.56	18.01
D	75	74	105.65	16.56	8.80
E	310	26	267.99	21.11	22.33
F	60	65	71.99	13.70	6.00
G	75	75	91.66	19.61	7.64
H	100	100	141.01	22.54	11.75
I	130	130	131.00	31.55	10.92
J	120	112	137.50	16.38	11.46
K	220	200	298.00	38.70	24.83
R	0.92	0.35	1.0	0.68	1.0

Select Structural Prediction Model

Overall, grade declined with increasing TSD class (Fig 4.5). To formally test this, a model was developed to predict Select Structural Percent (SSPercent) from “TSDClass” (Model 6). The one-way ANOVA showed this relationship to be just barely above the threshold for significance (p = 0.0677), likely because of the small sample size. The model coefficients, displayed in Table 4.10, can be used to predict loss of SSPercent as time progresses.

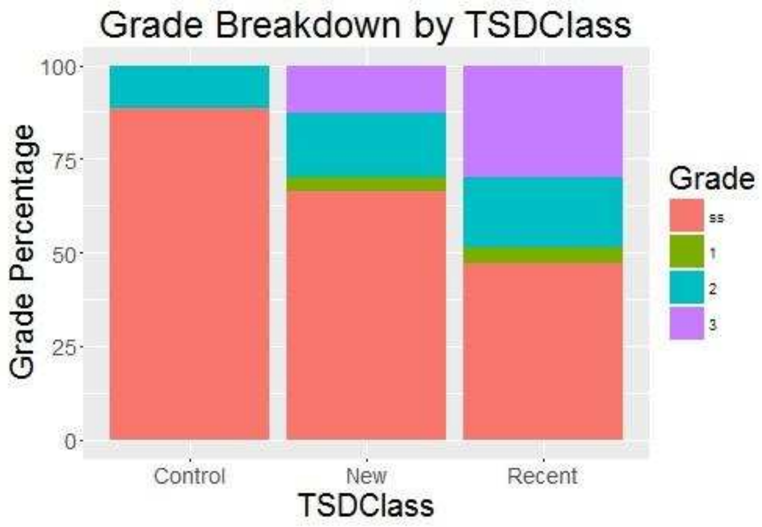


Figure 4.5 - Percentage of board feet in the four grade classes, grouped by TSD Class.

Table 4.10 - Model 6 Summary, including co-efficient estimates

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	87.19661	12.33032	7.071722	0.000105
TSDClassNew	-23.2488	15.91838	-1.4605	0.182282
TSDClassRecent	-38.8285	14.23783	-2.72714	0.02596

5. DISCUSSION

Deterioration Types and Associated Predictors

Season Checking

Season checking has been identified as the principal mechanism of deterioration after beetle attack (Cahill 1980; Snellgrove and Cahill 1980; Lowell and Willits 1998) and therefore was the most important response in this study. In the past, season checking has been attributed to everything from making trees completely unmerchantable (Nelson 1950) to being a relatively insignificant problem that can be "slabbed off", with its negative effects being cancelled out by a reduction in transportation costs (Mielke 1950). The reality is most likely somewhere in the middle of these two extreme views. The conclusion reached by Snellgrove and Fahey (1977) is that beetle-kill causes continuing deterioration in the wood of affected trees, but valuable products can still be recovered until the trees blow down.

One major question, identified by Lewis and Hartley (2006), is whether or not checking continues to progress over time. After the initial rapid drying phase, do trees continue to develop additional checks through wetting and drying? Lowell and Willits (1998) found that the first year of deterioration in southeast Alaska spruce was by far the most detrimental, and significant deterioration did not occur after that. The current study has found that season checking in Colorado Engelmann spruce can increase with time-standing-dead, but this occurrence is variable and largely influenced by tree diameter. Larger diameter trees tend to check more heavily than smaller diameter trees, and the effect of TSD is different across the diameter ranges.

Three models were developed to predict the occurrence of season checks, one for each diameter class. Small trees (8-11.9") were less affected by checks than larger trees. However, no predictors, including TSD, were statistically significant (α=0.05). The lack of TSD significance suggests that after one year of rapid drying, additional checking may not develop in the small trees. With medium trees (12-16.9”) in this study, checking continued into TSD class Recent, representing three years dead. This suggests that either the trees take longer than one year to dry below Fiber Saturation Point or that continuing moisture fluctuations can lead to additional checking. With large trees, checking continued to increase into TSD class Seasoned, representing 8 years dead. These trees showed an interesting pattern: checking did not increase between New and Recent, but did increase from Recent to Seasoned. The “New to Recent” conclusion may not be fully supported, however, because the response from the Large New class is based on a single tree (see discussion in “Outliers”).

Elevation and bark cover were also significant predictors of checking in some of the models. Elevation serves as a proxy for climate; higher elevations tend to be both cooler and dryer, conditions that could have conflicting effects on the rate of drying. In Model 3 (large trees), higher elevations were associated with reduced checking. It appears that the cool temperatures inhibited checking despite the dryer air. This effect is probably aided by the frequent rain events that occur during the summer, when warmer temperatures would otherwise have the potential to promote drying. Bark cover was also a significant predictor in Model 3. Trees with a higher percentage of remaining bark were less likely to have severe checking. Bark retention is not solely determined by TSD; Woodpecker forage is the main factor in bark loss of beetle-killed Engelmann spruce in the study area (Webb 2015).

Diameter’s Effect on Surface Checking

These results show that diameter increases have a disproportionate effect on check formation. To understand why this is the case, it is important to emphasize the exponential relationship that basal area has with diameter. Diameter is the most common way to measure a tree, mostly because it is much easier for people to visualize than area (Curtis and Marshall 2000). It is easier to pick out a 10" diameter tree in a forest than one with an area of 78.5 in^2. Despite this, basal area rather than diameter often determines the properties of interest. In this case, shrinkage area in a tree cross-section is proportional to the square of the tree's diameter. Every time the diameter of a tree doubles, its cross-section area quadruples. Lowell et al. (2010), in a thorough review of findings on wood deterioration after disturbance, reported that smaller logs deteriorate "faster" than larger ones. Smaller logs have a higher proportion of sapwood and are quicker to dry. Results from the current study indicate that, in Colorado Engelmann spruce, larger logs have an absolute deterioration that is greater than smaller logs, but their deterioration takes place over a longer time period.

Heart Rot

Heart rot is not considered a beetle related defect, but it becomes important in predisposing trees to blowdown after an infestation. Literature has indicated that spruce beetle killed trees will blow down before significant cull from rot is seen (Mielke 1950; Hinds et al. 1965). This study's results support these statements with the extremely low incidence of heart rot found in the trees. Most trees had no decay; however, there were a few notable exceptions, where up to 100% of a tree was decayed.

This study found no difference in heart rot among the three TSD classes, which is not surprising considering results from past studies. More interesting is the fact that no other predictors of heart rot proved to be significant at any reasonable alpha level. Other predictors considered included the presence of wood borers, moisture content, and DBH- none of which were found to be significant. There are two possible explanations for the low occurrence of heart rot found in the study trees: heart rot ceases with death, or trees with heart rot tend to blow down and thus avoid sampling. Evidence exists against the former and in favor of the latter. First, heart rot likely does not cease with death, because this study found many trees with moisture content readings over 20%, and even over 25% (Fig 4.2). Beetle-kill may not cause rot to cease, but it likely serves to slow it down by worsening the conditions for fungal development. Second, findings by Worrall and Nakasone (2009) indicate that stand defect in Colorado Engelmann spruce can range from 7-26%. Overall defect in the field study trees was 5.3% of the merchantable volume. One potential reason for this number being outside the proposed range is that decayed trees had already blown down before stands were sampled.

The issue of blowdown might have skewed this study's results and under-represented the importance of decay as a factor in cull. Therefore, these study's findings cannot be used to conclude that rot does not increase with TSD class. What is actually occurring is likely a mixture of two outcomes: trees dry out, which inhibits colonization by decay fungi, and tree blowdown accelerates, removing evidence of what decay there is. This study is not the first to observe the confounding effect of blow down. Hinds et al. (1965) commented that "Butt and trunk rots seem to be declining in relative importance, possibly because the most decadent trees are being windthrown" (p. 538). To truly test the change in heart rot of standing trees over time, blowdown trees must be taken into account. This would require a specialized design to account for these trees; simply determining TSD of blowdown trees and measuring rot would not solve the problem, because decay would be significantly expedited by the blowdown.

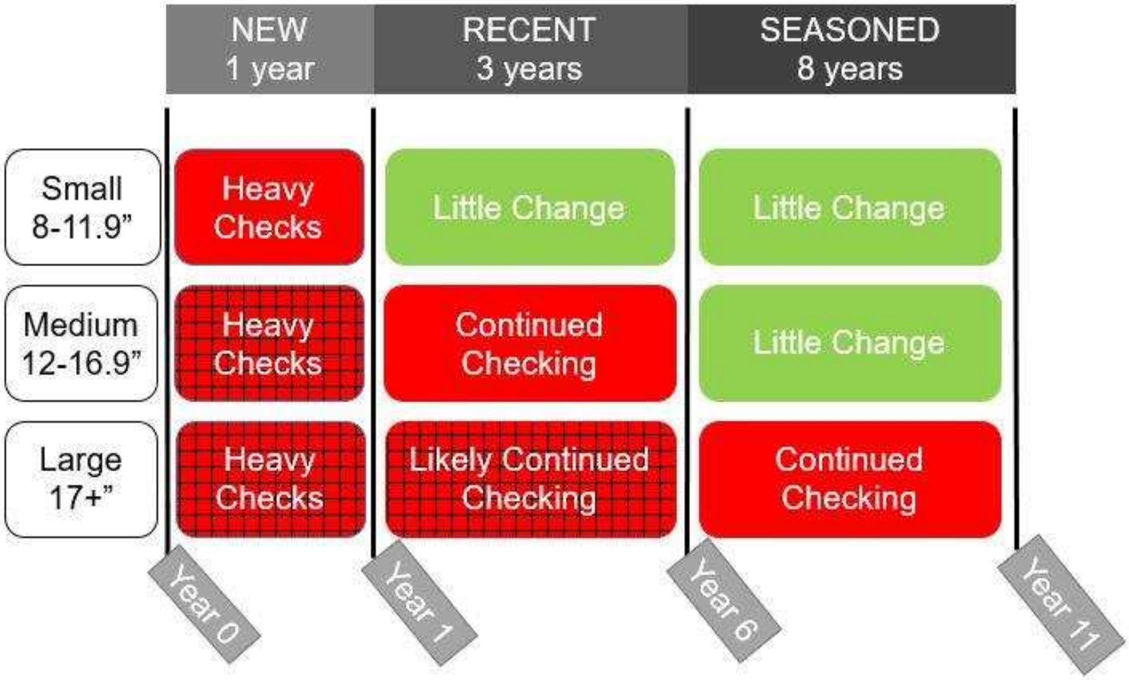
Sap Rot

As with heart rot, there was a fairly low occurrence of sap rot in the study trees; only 13 of the 86 trees were effected. Treated as a binary response variable, sap rot had no association with diameter and the most significant predictor was Time-Since-Death. A Chi-square test found significant evidence to conclude that sap rot occurrence did increase with TSD class, which supports claims made previously in the literature (Hinds et al. 1965; Cahill 1980). Sapwood in live trees has a high moisture content that precludes fungal colonization, but when mortality causes the tree dry out, its sapwood becomes susceptible. The length of time standing dead increases the chances of the tree coming into contact fungi, which are typically vectored by beetles or wind (Castello et al. 1976). Additionally, surface checks may allow moisture to penetrate deeper into the wood and promote the development of decay (Lowell et al. 2010). If harvested before blowdown, sap rot is typically dealt with by leaving the affected trunk portion in the woods, losing the largest diameter portion of the butt log but avoiding a diameter reduction (Cahill 1980).

Deterioration Timeline

If maximizing sawtimber recovery is a land management objective, responses can be prioritized by tree diameter and Time-Since-Death. Because of constraints associated with planning, budgeting, and contracting, it is assumed that managers will not be able to respond in the same season as beetle attack, and trees will be subject to significant deterioration in the first year. With regards to season checking, the sooner a project can be implemented the better, although there are certain stand types that are a higher priority than others due to risk of deterioration. Chief among these are recently killed stands with larger sized trees.

Figure 5.1 presents a generalized visual timeline that is supported by findings in this study. In blue cells, checks are not actively developing so there is little pressure to respond with haste. Red cells indicate worsening checks in the trees. Hatched cells indicate where a quick management response may be desirable to stay ahead of developing checks. Meanwhile, there



	NEW 1 year	RECENT 3 years	SEASONED 8 years
Small 8-11.9”	Heavy Checks	Little Change	Little Change
Medium 12-16.9”	Heavy Checks	Continued Checking	Little Change
Large 17+”	Heavy Checks	Likely Continued Checking	Continued Checking

Figure 5.1 - Timeline of season checking after beetle attack, based on information obtained in the field study. Red squares indicate that the trees continue to check through the time period. Hatched squares indicate priority cells for a management response that is focused on timber recovery. “Likely Continued Checking” indicates a non-significant change (alpha = 0.05).

are still some concern about increases in sap rot, risk of blowdown, and grade reduction (Fig 5.2), but these problems are not as imminent as season checking.

	NEW 1 year	RECENT 3 years	SEASONED 8 years
Grade Reduction	-23.25% SS	-38.83% SS	No data

Figure 5.2 - Percent Select Structural reduction with increasing TSD class. Changes indicated use year zero as a base.

Implications for Buyers and Sellers in Timber Sales

Sellers and buyers of timber should agree on the value of material in question, otherwise mistrust and bad relations could develop. In beetle-killed timber, this means having some way to translate in-woods defect into product yield loss. Valuing timber in terms of its potential forest products can be difficult- the USFS log scaling handbook describes a log rule as “an arbitrary measure” (USFS 2006, p. 13). A log rule’s utility is in its consistency and repeatability- theoretically, two completely independent scalers would assign the same scale to a given tree. It is up to the judgment of mill operators to make adjustments to the log scale based on technology, end product, and experience.

The numerous circumferential defects inherent in beetle-killed trees complicate the matter of scaling. Surface checks spread out the defect and can cause boards to fall apart in ways that are more difficult to predict than an interior defect such as heart rot (Fig 5.3). Therefore, it is especially important that the methods for measuring this defect are consistent and do not vary. That way accurate comparisons can be made and all parties involved can develop a frame of reference for what to expect.

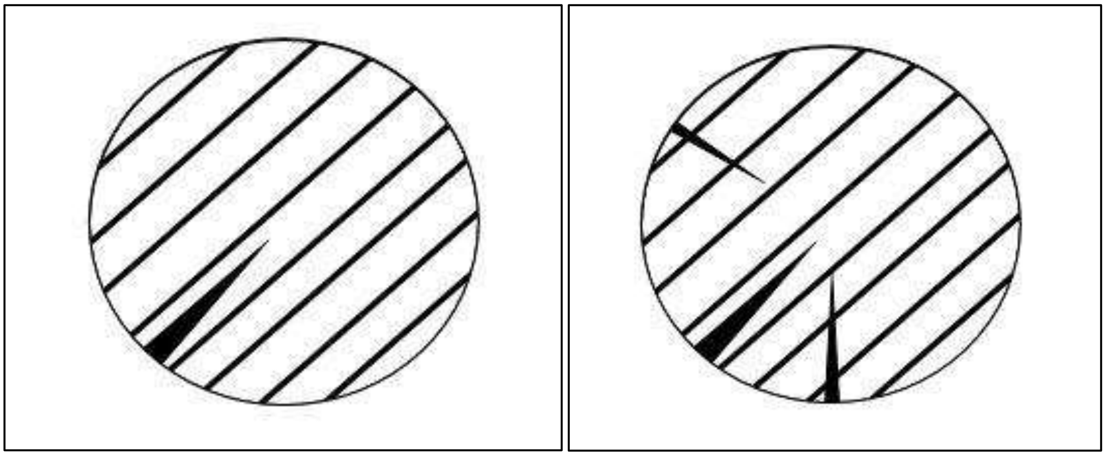


Figure 5.3 - If cuts are made parallel to a single check, minimal losses would occur (left). With multiple checks, it is difficult to isolate them, and boards may fall apart.

There are many options for communicating the scale and defect to the buyer:

1. Gross methods: Gross cubic and gross log scale are the easiest method for appraisers, as timber cruisers do not need to measure seasoning checks or any other defect. However, it leaves the most room for interpretation by the buyer; gross methods give no indication of the defect contained in the logs. Buyers can potentially use TSD and DBH to approximate beetle-caused deterioration. This information can be obtained through site visits, a working knowledge of the units in question, and/or CSFS aerial insect surveys.
2. Net cubic methods: “Product potential cubic” was proposed by Snellgrove and Cahill (1980) as a useful way to account for surface checks and other defects in standing beetle-killed trees. Where checks are concerned, scalers measure the volume of the unaffected core of the tree. This can be done with a thin probe, such as a cut section of a Logger’s tape, to measure surface check depth. The defect is the difference between the volume of the unaffected core and the gross log volume; defect is then reduced by 50% (USFS 1991, p. 55). There are other ways to report net cubic, including a “cubic perimeter defect”, which only considers the circumferential portion of the log effected by checks (K. Stagner, USFS Region 2 Measurement Specialist, personal communication, July 12, 2016).
3. Net log scale: Using net Scribner allows for much flexibility in how defect is calculated. Results can be drastically different depending on whether pie-cut deductions, diameter reductions, or a combination are used. Diameter reductions based on the deepest check will result in the heaviest defect, and simply using pie cuts will result in the smallest. Neither are likely to be accurate; diameter reductions over-estimate waste and multiple pie-cuts could not be realistically achieved at the mill (Fig 5.3).

Many of the larger dead spruce may find their highest use in house logs. Fahey (1980) reported house logs to have a higher value per oven-dry ton than dimension lumber in dead lodgepole pine. Marketing decisions regarding a tree's end product are based on individual tree characteristics, and are more likely to be made by the purchaser than the seller. Because non-spiral surface checks do not reduce a logs suitability as a house log (Peckinpaugh 1978; Cahill 1980), mills could set aside such logs for purchase by log home manufacturers.

Although this study was not designed to specifically test beetle related deterioration in terms of proportion of value loss to volume loss, some insights can be gained from the mill study. Very few of the finished boards in the mill study exhibited de-grade due to splits. Seasoning checks in the logs led to some volume loss in slabs and edges, and splits caused several finished boards to be culled, and were thus not counted in the board foot tally. The implication of this is that checking led mostly to volume loss and contributed little to value loss. In general with beetle-killed timber, the ratio of volume loss to value loss is likely to be highly variable and dependent on factors such as mill technology, final product specification and mill operator decisions. Therefore, it is probably safest for a purchaser to assume that checking will result in cull and any lower grade boards that can be recovered are a bonus.

Limitations of Results

Results of this study can be useful in understanding the factors that influence deterioration over time in standing trees, but do not provide predictions in actual lumber tally. The main benefit of having a lumber tally prediction would be the ability of combining all defects into one standard unit of measure and using it to adjust predicted yields. An example of this problem is apparent in the field study: it is difficult to tell whether or not the increased yield in large trees compensates for the increased checking when it comes to board foot output. The net Scribner analysis was conducted to address this problem, but is not a perfect solution due to noted deficiencies in the Scribner method concerning dead timber.

The mill study did provide actual lumber tally, but the sample size was much smaller than that of the field study. Because of this, the statistical power may have been too low to identify significant yield predictors and provide reliable model coefficients. A larger sample size would have likely resulted in more significant findings, but studies of this nature are very expensive to conduct. Felling trees as in the field study is not too difficult, but getting them out of the woods, transported to the mill, and processed can be costly.

Another limitation of this study is the lack of data about tree deterioration immediately following beetle attack. All trees in the field study were sampled during the summer following attack, and thus had been standing dead for at least one year. This suited the study objectives well, as longer-term changes were of primary interest to aid management decisions. However, a large portion of the deterioration from surface checking comes in the first few months after attack, as the tree quickly loses the majority of its moisture and approaches fiber saturation point. This study does not provide any resolution at the month level, which would be very interesting information to know.

TSD class was used to group trees into meaningful categories based on how long they had been standing dead. This provides some advantages over treating TSD as a continuous variable, most notably by increasing the sample size used in comparisons. It also allows for studying the general trends over time, and examining interactions. The disadvantage is that models based on categorical predictors don’t take into account the full numerical range of the predictors. Also, there is some subjectivity in assigning groups to the TSD years. Groups were identified very early on in the process based on reasonable patterns, but another researcher may have decided to define them differently.

Because TSD of the trees was unknown before they were felled and subjected to dendrochronology analysis, there was one missing cell from the mill study and one very unbalanced cell in the field study (Figs 5.1 and 5.2). The missing cell is in the mill study; the sample did not contain any trees in the "Seasoned" class. Therefore it cannot be said if grade continues to be lost into this class, or if grade loss ceases in the first few years. The unbalanced cell is in the field study and is also discussed in "Outliers and problem trees". This is the "large new" class, which had only one tree and led to the strange pattern observed in Figure 4.1.

Issues with Plot-Level Variables

Plot level variables proved to be poor predictors in all models; aspect and precipitation were the first to drop out of every model, without exception. Elevation, on the other hand, was a strong predictor in a few cases (see "Checking" discussion). One potential reason for this is that these variables were measured at the plot level and applied to individual trees, which didn't work perfectly in practice. The sites were subject to natural variability, and likely had a variety of microclimate conditions that prevented generalization. For example, applying a "North" aspect to all trees on a plot may not have accurately captured the aspect of each individual tree. Precipitation measures may not have been directly represented by the trees because of microclimate conditions such as depressions, ridges, or surrounding vegetation. However, elevation is more reasonably applied to all trees on a plot because the within-plot ranges are much smaller than the broad study-wide ranges in elevation.

Another reason these plot variables may have dropped out is that the difference between the plots was not very strong relative to other variations. In other words, the variability among the trees was similar to the variability among the plots, and both were much smaller than the overall variability in the models. An examination of the model summaries reveals that in most cases the variance component associated with plot was comparable to that of the tree and much lower than the residual (Table 5.1).

Table 5.1 - Variance components (σ^2) of mixed models used in Checking analysis. Values computed by the 'lme4' package in R.

Model	**Plot**	**Tree**	**Residual**
1: Small	2.4967	0.1443	9.5535
2: Medium	1.5539	0.1616	10.2847
3: Large	0.00	2.372	17.441

Outliers and Problematic Trees

Field Study: Tree 3C

Tree 3C from the field study was unique in that it was the only tree that was simultaneously in the "Large" diameter class and the "New" TSD class. Spruce beetles generally attack the largest trees first, so it was not surprising that most large trees were in older TSD classes than smaller trees of the same stand. Tree 3C also exhibited a very high level of checking at the 17 foot level (Fig 4.1). This high checking level contributed to the conclusion that large trees do not develop surface checks between New and Recent TSD classes. However, this conclusion is drawn from a single tree, which should be taken into consideration. It is possible, and in fact more likely, that large trees develop checks at a steady rate into the "Seasoned" TSD class. The effect of Tree 3C was amplified in the Scribner analysis, where the high checking at 17 feet affects 2 of 3 logs rather than just 1 of 4 heights. As a point of comparison, the Mill Study also contained one "Large New" tree, which exhibited very little checking. If it were grouped into the larger dataset, which was not done due to the study design, it would have smoothed out the rough line seen in Fig 4.1.

Mill Study: Tree I

Tree I from the mill study threw off the grade measurements by producing an extremely low proportion of select structural boards, despite having been killed relatively recently (two years standing dead). Originally, mill study data were used to develop a quadratic model in which SS percent was explained by the continuous TSD variable rather than categorical (as in Model 6). Tree I pulled the line down strongly and resulted in an unrealistic pattern. An outlier test was conducted in R, but the tree showed a Bonferroni-adjusted p-value of 0.23, meaning there was not enough evidence to drop it from the model. The most likely reason for the loss of grade in Tree I was that it contained a significant portion of an unknown coffee-colored stain. Therefore its inclusion in the final model is justified; it illustrates that there can be other contributors to loss of grade than splits caused by seasoning checks. The relationship between the “coffee stain” and TSD is unknown.

6. CONCLUSIONS

Summary of Main Findings

As trees stand on the stump following beetle attack, they are subject to continuing deterioration that can affect the potential yield and grade of forest products. However, opportunities remain for salvage operations to recover merchantable logs until the trees blow down. Knowledge of these deterioration processes is critical in marketing products from these trees and in improving seller/buyer communications. The following bullets highlight the main findings from this study:

- The most important predictors of season checking in standing trees are diameter, Time-Since-Death, bark retention, and elevation. Larger diameter trees check more heavily than smaller ones. Bark retention helps control moisture loss and reduces checking. Cooler temperatures associated with higher elevations also reduce checking.
- Season checking continues to increase with TSD in larger trees, but may cease after the first year in small trees.
- TSD is the most important predictor of sap rot, which is more likely to develop the longer the tree stands on the stump.
- Net Scribner is a poor predictor of lumber yield in beetle killed trees. In the mill study, net Scribner had a very low correlation with actual lumber tally.
- The proportion of lumber containing blue stain increases drastically one year after attack but does not continue to increase with time.
- As trees stand on the stump, the proportion of structural lumber grade boards contained in logs is reduced, and the proportion of lesser grades are increased.

Opportunities for Future Research

Almost all research conducted on surface checking to date has focused on the lumber recovery potential; there is very little research on the mechanisms for and process of checking itself. A better understanding of these processes would help to interpret the results of these studies. Some unanswered questions are: What factors determine the location of the surface check (e.g., ray cells)? Does surface checking happen all at once, similar to frost crack, or gradually? A lab study set up to analyze tree cross sections in drying could provide answers to these questions. Tree cross-sections would be dried at different rates by controlling temperature, allowing researchers to make observations on surface checking patterns.

Another great opportunity exists to study the development of checks immediately following insect attack. As mentioned in the “Limitations” section, the current study does not provide any information about the monthly or weekly deterioration that happens following attack. If a stand can be identified that has been recently attacked, trees can be tagged and subjected to repeated sampling over the course of a season. Check depths can be measured with a probe, and lengths with a clinometer. Changes in the checks can then be understood and related to time.

Because of the confounding effect of blowdown, heart rot in beetle-killed trees has not been accurately tracked over time in a scientific study. Moisture content could be used as a proxy; if moisture content is suitable, there is no reason fungal colonization would be prevented by mortality. Repeated measurements of moisture content through time following insect attack would give information on how often the MC is above the 20% threshold suitable for decay, if it tends to waver around this number, or permanently drops below. These measurements could also give more information on what drives continued checking, based on whether or not the MC fluctuates around the 30% general FSP and results in shrink/swell.

Revisiting the Objectives

This study was guided by the four objectives identified in the Introduction section. To meet Objective 1, the significance of Time-Since-Death was tested for the various forms of deterioration. TSD was found to be influential in everything except heart rot, and therefore the null hypothesis of $\beta_{TSD} = 0$ was rejected. Objective 2 focused on identifying other significant predictors of deterioration. Several models were developed that showed significant relationships and patterns (see Discussion) with predictor variables such as diameter, elevation, and bark cover. Objective 3 was set in the hopes of developing a model to predict net Scribner from TSD and other measurements. Only diameter and log position remained in the models after backward elimination, which is not surprising considering diameter is the main measurement used in calculating Scribner. Because TSD was not itself significant, the model could not be used to propose Scribner modifications based on TSD. Objective 4 was met by testing various scaling methods against the lumber tally from the mill study. This led to the finding that net Scribner assigns an unrealistically high defect and gross Scribner or product potential cubic is a better predictor.

Results from the field study reveal more about the contributing factors of deterioration than any previously published studies. Interactions are demonstrated between diameter, Time-Since-Death, and tree height as they relate to season checking. Sap rot is shown to increase in prevalence with TSD. Results from the mill study can be used to predict how lumber grade and defect will change with TSD, to illustrate better scaling methods than net Scribner, and to demonstrate that quality lumber can be milled from trees standing dead for several years.

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APPENDIX 1: MEASUREMENTS

Table A1.1 – All measurements from the field study

Sampling Unit	Measurement	Measurement Unit
Plot	Polygon mortality year	Year
Plot	Latitude/Longitude	Decimal degrees
Plot	Elevation	Feet
Plot	Aspect	Categorical: N/NE/E/SE/S/SW/W/NW
Plot	Yearly precipitation	Inches
Plot	Logging Unit?	Categorical: Yes/No
Tree	Mortality Year	Year
Tree	DBH	Inches
Tree	Total Height	Feet
Tree	Height to 6” top	Feet
Tree	Snag class	Categorical: 1/2/3
Tree	Sap rot height	Feet
Tree	Sap rot depth	Inches
Tree	Bark retention	Percent
Tree	Diameter at butt	Inches
Tree	Butt moisture content	Percent
Tree	Wood borers?	Y/N
Within-Tree	Total number of checks	Count
Within-Tree	Number of checks per quad	Count
Within-Tree	Depth of each check	Inches
Within-Tree	Spiral check?	Categorical: Yes/No
Within-Tree	Boring insects?	Categorical: Yes/No
Within-Tree	Heart Rot	Square inches
Within-Tree	Diameter	Inches

Table A1.2 - Measurements from the mill study

Sampling Unit	Measurement	Measurement Unit
Plot	Polygon mortality year	Year
Plot	Elevation	Feet
Plot	Aspect	Categorical: N/NE/E/SE/S/SW/W/NW
Plot	Yearly precipitation	Inches
Tree	Mortality year	Year
Tree	DBH	Inches
Tree	Diameter at butt	Inches
Log	Heart Rot	Cubic feet
Log	Total number of checks	Count
Log	Checks per quad	Count
Log	Depth of each check	Inches
Log	Diameter	Inches

Log	Length	Feet
Log	Moisture content	Percent

APPENDIX 2: MODEL DESCRIPTIONS

Model 1
Description: Season checking model for small trees
Type: Repeated measures mixed effects model
Call: Check~(1|Plot/Tree)+Height*TSDClass+Elev+BarkCover
Data: Repeated measures, Small tree subset

Table A2.1- ANOVA table for Model 1

	Sum Sq	Mean Sq	NumDF	DenDF	F.value	Pr(>F)	Significance
Height	67.772	22.5906	3	58.237	2.36465	0.08029	.
TSDClass	17.524	8.7621	2	22.793	0.91717	0.4139	
Elev	24.823	24.8225	1	7.248	2.59827	0.14955	
BarkCover	20.165	20.165	1	20.248	2.11076	0.16159	
Height:TSDClass	51.965	8.6609	6	57.216	0.90657	0.49677	

Model 2
Description: Season checking model for medium trees
Type: Repeated measures mixed effects model
Call: Check~(1|Plot/Tree)+Height*TSDClass+Elev+BarkCover
Data: Repeated measures, Medium tree subset

Table A2.2 - ANOVA table for Model 2

	Sum Sq	Mean Sq	NumDF	DenDF	F.value	Pr(>F)	Sig
Height	179.738	59.913	3	80.371	5.8254	0.001183	**
TSDClass	152.924	76.462	2	23.705	7.4345	0.003117	**
Elev	41.993	41.993	1	6.952	4.083	0.08333	.
BarkCover	23.197	23.197	1	23.255	2.2555	0.146599	
Height:TSDClass	36.509	6.085	6	80.482	0.5916	0.736097	

Model 3
Description: Season checking model for large trees
Type: Repeated measures mixed effects model
Call: Check~(1|Plot/Tree)+Height*TSDClass+Elev+BarkCover
Data: Repeated measures, Large tree subset

Table A2.3 - ANOVA table for Model 3

	Sum Sq	Mean Sq	NumDF	DenDF	F.value	Pr(>F)	Significance
Height	586.21	195.403	3	69	11.2039	4.46E-06	***
TSDClass	137.83	68.917	2	12.82	3.9515	0.046036	*
Elev	289.08	289.079	1	5.025	16.575	0.009525	**

BarkCover	181.29	181.288	1	20.998	10.3946	0.00407	**
Height:TSDClass	391.69	65.281	6	69	3.7431	0.002783	**

Model 4
Description: Net Scribner response predicted by diameter class and log position.
Type: Repeated measures mixed effects model
Call: BFNet~(1|Plot/Tree)+Dclass+Log
Data: Scribner

Table A2.4 - ANOVA table for Model 4

	Sum Sq	Mean Sq	NumDF	DenDF	F.value	Pr(>F)	Sig
DClass	6605.867	3302.933	2	77.7961	12.22936	2.41E-05	***
Log	12812.92	6406.461	2	149.7585	23.7204	1.12E-09	***

Model 5
Description: Blue Stain percent by TSDClass one way ANOVA
Type: Linear fixed effects model
Call: BSPercent~TSDClass
Data: Mill

Table A2.5 - ANOVA table for Model 5

	Sum Sq	DF	F value	Pr(>F)	Sig
(Intercept)	0	1	1.38E-29	1	
TSDClass	9114.566	2	11.85859	0.004047	*
Residuals	3074.418	8			

Model 6
Description: Select Structural Percent by TSDClass one way ANOVA
Type: Linear fixed effects model
Call: SSPercent~TSDClass
Data: Mill

Table A2.6 - ANOVA table for Model 6

	Sum Sq	DF	F value	Pr(>F)	Sig
(Intercept)	15206.5	1	50.00925	0.000105	***
TSDClass	2336.727	2	3.84237	0.067679	.
Residuals	2432.59	8			