AN ABSTRACT OF THE THESIS OF

Daniel W. D. Norlander for the degree of Master of Science in Forest Science presented on July 10, 2008

Title: Effect of Site and Silvicultural Treatment on Insect Pests and Diseases of Young Ponderosa Pine.

Abstract approved:

David C. Shaw

Ponderosa pine is an important species both commercially and ecologically in western North America. This study considers the incidence of insect and disease pests on a series of replicated ponderosa pine research plantations in northern California. The studies were situated on an environmental gradient and contained a series of silvicultural treatments including vegetation control, fertilization application and insecticide application/thinning. The mean annual temperature and total precipitation were used as climatic variables and the site index was considered as an environmental site variable. Needle retention was negatively correlated with site productivity, with no treatment effects. Estimates of mean needle retention were consistent with those found in the literature. Total foliar herbivory was the lowest at the highest productivity site, but no treatment effects were not significant. The gouty pitch midge had the highest level of branch infestation lowest productivity sites. Drier, warmer and higher sites were likewise more susceptible. Sequoia pitch moth attacks were highest at the drier and warmer sites while treatments with vegetation control experienced higher levels of attack. Total foliar pathogen infection was significantly lower on the installation with highest site index. There was no significant difference between the other five nor between silvicultural treatment. Western gall rust incidence was highest on the most productive sites and on treatment units that were fertilized and had vegetation control. The peak year of gall infection corresponded to the occurrence of El Niño events.

Effect of Site and Silvicultural Treatment on Insect Pests and Diseases of Young Ponderosa Pine

by
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APPROVED:

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Daniel W. D. Norlander, Author

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Chapter 1: Introduction

Forest management has a large potential impact on the incidence of pests and pathogens on trees (Powers 1999). Forested ecosystems are a complex landscape of plants and animals, producers and consumers, hosts, pathogens and pests. This is true in an old growth forest with hundred year old trees and in young industrial plantations. Other factors like weather, geographic location and stand history all play important roles in the relationships between biotic actors (Burns and Honkala 1990). Forest management interacts with many of these factors by altering the vegetative constituents, thus potentially affecting pests and pathogens.

Silvics of ponderosa pine:

Pinus ponderosa (ponderosa pine) is one of the most abundant forest trees in western North America. It ranges from northern Mexico, around 33º north, in the south to southern British Columbia, around 52º north, in the north and from the coast of the Pacific eastward to the Great Plains (Figure 1.1). The species is found from sea level to more than 3000 meters in elevation (Burns and Honkala 1990). The diversity of habitats in which *P. ponderosa* can be found and its ability to grow to large sizes with long life spans make it an economically and ecologically important species. This range in geography also allows for a diversity of forest pathogens and pests.

Ponderosa pine is made up of three varieties, each with their own adaptations to a specific geographic region. Starting in the east there is *Pinus ponderosa* var. *scopulorm*

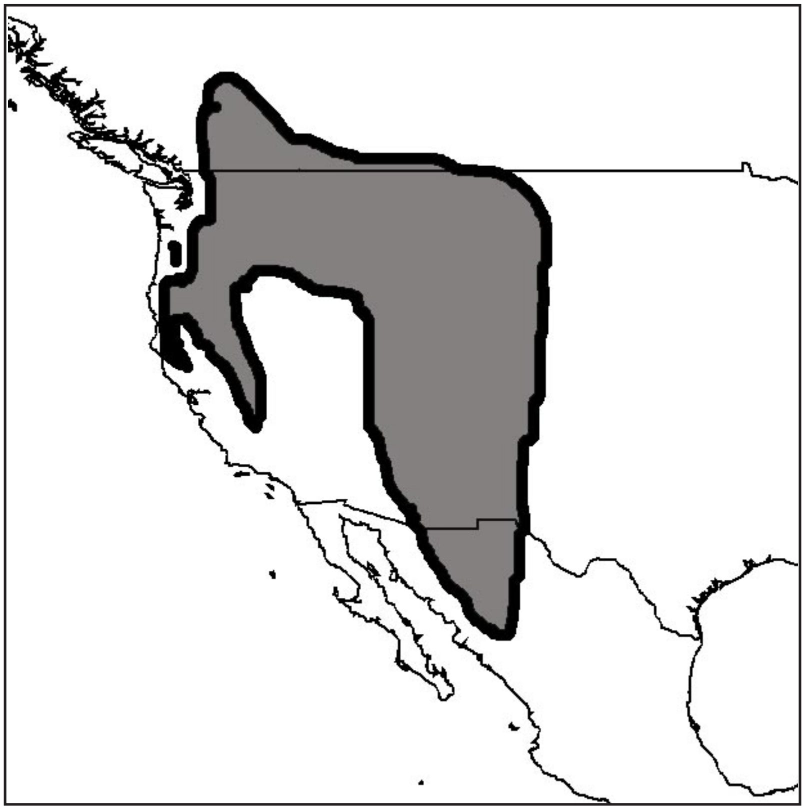

Figure 1.1: The general distribution of ponderosa in western North America.

which reaches east of the continental divide into the Plains states in the north and in the south from Texas west to the eastern edge of the Great Basin and Arizona. *Pinus ponderosa* var. *arizonica* inhabits the mountains of the extreme southern portion of the overall range: southern New Mexico and Arizona and northern Mexico. The variety found along the west coast and in to the Pacific Northwest is *Pinus ponderosa* var. *ponderosa* (Burns and Honkala 1990). The latter variety is the focus of this research.

Ponderosa pine is a long-lived three needle hard pine with thick bark on older trees that is able to withstand high temperatures, insects, and pathogens quite well (Burns and Honkala 1990, Perry 1994, Sugihara et al. 2006). These aspects allow individual trees to grow to large stature and dominate a forest overstory. Historic fire return intervals of 10 to 20 years were common among the ponderosa forest type. This short interval kept tree stocking at low levels and allowed trees to flourish and become well established (Sugihara et al. 2006).

With the introduction of anthropomorphic fire suppression, many of the pine forests in western North America have become much denser by increasing the number of smaller trees. The result has often been a shift from open stands with large old trees to denser stands with new understories of younger, smaller and often times stagnant trees that are said to be more susceptible to insects and pathogens (Kaufmann 1996). The low tree vigor has allowed many insects and pathogens to become increasingly abundant (Powers 1999). Differences in silvicultural treatments can influence the impact of forest pests and pathogens (Furniss and Carolin 1977, Hansen and Lewis 1997), and as these systems are managed in the future it will be important to understand the dynamics that are at play.

Biotic influences:

Throughout the range of ponderosa pine the primary limiting factor to growth is soil moisture (Burns and Honkala 1990). This is especially true in the drier areas of the Southwest, eastern Rocky Mountains and the Great Basin. Precipitation levels vary greatly, from as low as 205 mm in the Southwest and Black Hills to as high as 1750 mm in the northern Sierra Nevada mountains of northern California. Typical average annual temperatures range between five and ten degrees Celsius throughout the range and there are between 90 and 200 frost free days. Mean annual temperatures are between 5°C to 10°C with extremes below -40°C to over 45°C (Burns and Honkala 1990).

Ponderosa pine has a varied successional role in its habitats, representing either a climax or a seral species. It is one of the primary species in several forest types, including the Interior Ponderosa Pine, Pacific Ponderosa Pine, and Pacific Ponderosa Pine-Douglas-fir types (Burns and Honkala 1990). With such a wide range of habitats, ponderosa pine is found in approximately 65 percent of all forest types in western North America, south of the boreal zone (Burns and Honkala 1990).

Throughout the range of ponderosa pine, shrubs compete aggressively with pine regeneration, reducing both height and radial growth of young trees (Burns and Honkala 1990, Powers and Ferrell 1996). Regeneration is sporadic and occurs when a variety of conditions coincide. This includes ample moisture over several seasons (cones take more than one year to mature), low levels of competing vegetation, relatively low levels of herbivory by the many small animals that consume the seed, and a heavy seed crop (Burns and Honkala 1990). Regeneration is enhanced by the ability of seedlings to grow a deep taproot that can reach deep moisture very rapidly (up to 50 cm within a few months of germination) and by its ability to withstand extremes in both temperature and moisture stress, down to -8.0 MPa for short periods (Burns and Honkala 1990).

While the range of ponderosa pine is extensive, the inherent variation in environmental conditions found in this range allows for a great diversity of insect pests and pathogens to attack the species. Insects of primary concern include the red turpentine beetle (*Dendroctonus valens*), the mountain pine beetle (*Dendroctonus ponderosae*) and at least four other *Dendroctonus spp.* bark beetles. Twelve species of *Ips* can often be found naturally occurring in stands throughout the west, and several other bark beetles all impact the survival of ponderosa pines (Furniss and Carolin 1977).

Many mining and boring insects affect the growth and reproduction of young trees. Among the more common species are pine tip moths (*Rhyacionia spp.*), gouty pitch midge (*Ceciomyia piniiopis*), and the western pineshoot borer (*Eucosma sonomana*). Reproduction is hindered by several insects including the ponderosa pine cone beetle (*Conophtorus ponderosae*), the pine reproduction weevil (*Cylindrocopturus eatoni*), and several species of cone borers in the *Ernobius* genus.

Foliage insects are also common in natural stands and are capable of reducing the amount of photosynthesizing foliage, in turn impacting tree and stand growth and yield. The very common, but relatively benign, sequoia pitch moth (*Synanthedon sequoia*) causes masses of pitch to be exuded from the large stems, resulting in minor damage that could result in some wood defects and/or wind breakage in small stems (Furniss and Carolin 1977).

Forest pathogens infect all parts of ponderosa pine, from the roots to the tip of the growing leader. Dothistroma needle blight (*Mycosphaerella pini*) has afflicted tens of thousands of hectares of lodgepole pine in western Canada in recent years (Woods et al.

2005), but can also affect ponderosa pine. Lophodermella and Lophodermium needle casts, caused by *Lophodermella morbida* and *Lophodermium seditiosum*, cause premature loss of needles on ponderosa in the Pacific Northwest and can reduce tree vigor. Elytroderma needle blight, caused by *Elytroderma deformans*, causes brooms, branch death and can result in a decrease in volume growth.

Stems and branches are susceptible to western gall rust (*Endocronartium harknessii*) which can kill branches and increase breakage of boles (van der Kamp et al. 1995). There are many different heart rots and wound decays including *Phellinus pini* and *Fomitopsis pinicola*. Root rots often cause damage in stands and are not uncommon in stands that have been disturbed by thinning and harvest activities. Common root rots are several species of *Armillaria*, Black stain root disease (*Leptographium wagneri*), and Annosum root disease (*Heterobasidion annosum*) (Burns and Honkala 1990). The most important pathogens of ponderosa pine are the warf mistletoes *Arceuthobinm campylopodium* and *A. vaginatum subsp. cryptopodum* (Burns and Honkala 1990).

<u>Growth impacts:</u>

Conifer needle retention has been shown to be greater on installations that are less productive (Reich et al. 1996), such as those at higher latitudes and elevations (Reich et al. 1996, Pouttu and Dobbertin 2000). For several conifer species, greater resource and nutrient availability correspond to shorter leaf retention periods (Reich et.al. 1992). This trend persists across different scales ranging from riparian to up-slope, and across the broadleaf dominated eastern forests or conifer dominated western forests.

Foliar herbivory can have dramatic impacts on the ability of a tree to photosynthesize. This has been seen many times as invasive or endemic insect species defoliate large areas of forests. Examples include the Douglas-fir tussock moth, gypsy moth, western spruce budworm and pandora moth (Furniss and Carolin 1977, Goheen and Willhite 2006).

Foliar pathogens have been causing significant growth decline and even mortality in conifer populations, from Swiss needle cast on Douglas-fir in the Pacific Northwest (Hansen et al. 2000) to dothistroma needle blight on pines in western Canada (Woods et al. 2005). Foliar diseases often result in a decrease in the length of time that a tree will hold its needles (Goheen and Willhite 2006), reducing its photosynthetic capacity, carbon assimilation, and tree growth. Foliar pathogens may also predispose trees to attack by bark beetles and accelerate mortality (Burns and Honkala 1990).

Gouty pitch midge:

The gouty pitch midge is a small fly that feeds on and lives in pitch pits formed by the larvae. Found throughout North America, the midges are often found in young, open grown stands of pines. Attacked trees are distinguished by deformities in the branches (Furniss and Carolin 1977). Some degree of resistance is conferred by increased waxy bloom and smoothness of the branches (Hoff 1988).

Sequoia pitch moth:

The sequoia pitch moth attacks several different pine species and Douglas-fir, but does not attack sequoias. Sequoia pitch moths attack the boles and branches of two and three needle pines, burrowing into the cambial layer and causing a mass of pitch to be exuded from the entry point (Goheen and Willhite 2006). The pitch masses (Figure 1.2) and pitch stem flow can increase the fire hazard of heavily infected trees (Furniss and Carolin 1977). Rocchini et al. (1999) have also found an association between some pitch moths and certain rust diseases including western gall rust.

Figure 1.2: Mass of pitch caused by the larval feeding of sequoia pitch moths on ponderosa pine.

Western gall rust:

Western gall rust is a pine-pine autoecious rust of hard pine in western North America (Hansen and Lewis 1997). It infects current year shoots and needles (moving to the shoots) and produces globose galls one to two years following infection, then sporulates and re-infects other hard pines.

Branches and boles can be weakened and become more susceptible to breakage by wind and snow. The galls also cause a deformity in the wood, decreasing its value. Eventually very small trees and branches can become girdled and die. As trees mature there appears to be a reduction in susceptibility possibly caused by a change in the microclimate of the crown as it increases in height above the ground (Zagory and Libby 1985).

Western gall rust is dependent on appropriate climatic conditions and appears to respond to certain combinations resulting in a wave year pattern of infection (Peterson 1971). In several studies there has been a key year that had a substantially higher level of infection than surrounding years (Peterson 1971, Bella and Narvatil 1988, van der Kamp 1988 and 1994, and van der Kamp et al. 1995). This is evidence that wave years are a common pattern throughout western North America.

Objectives:

The primary objectives of this research were to determine whether the incidence of insect pests and diseases in ponderosa pine plantations of northern California was impacted by geographical location and/or silvicultural treatment. I investigated the influence of installation location, weather, and the complex of installation characteristics represented by site index. I also identified gradients in needle retention, the amount of total foliar herbivory by arthropods, and the level of infection by foliar pathogens. Branch herbivory by the gouty pitch midge, incidence of western gall rust, and bole and branch herbivory by the sequoia pitch moth were investigated in more detail.

The objectives of this study was to test the following hypotheses:

1) Needle retention will increase as the installation productivity decreases.

2) Treatments that increase the growth of trees will decrease needle longevity, so a decrease in elevation will decrease the length of time that needles are held on the trees.

3) The amount of herbivory will increase as installation productivity increases, so will decrease with lower precipitation, higher elevation, and colder temperatures.

4) The summed frequency of all foliar pathogens will increase with environmental conditions that increase tree growth (i.e. higher site index, lower elevation, higher precipitation, and mean annual temperature) because these same conditions increase fungal growth.

5) Gouty pitch midge will be more prevalent at installations with higher growth due to an increase in resin availability and photosynthate production.

6) Sequoia pitch moths will be greater at higher productivity installations due to greater amount of phloem.

7) Incidence of gouty pitch midge and sequoia pitch moth will be highest at mid-elevations with the high precipitation and moderate mean annual temperatures, conditions that will not kill the larvae extreems in temperature.

8) Silvicultural treatments that increase the growth of trees (fertilizer, herbicide) will increase the number of attacks.

9) Western gall rust will have the highest number of infections: a) under greater precipitation and higher temperatures that favor western gall rust; b) after silvicultural treatments that increase shoot growth due to an increase in the susceptible surface area of the tree.

10) Infection by western gall rust will fluctuate with global climate cycles (particularly El Niño cycles), as proposed by Peterson (1971).

Table 1.1: Summary of study hypotheses.

Needle Retention	Increases as site productivity decreases, treatments increasing growth decrease needle retention.
Total Foliar Herbivory	Increases with site productivity, increases with higher volume growth treatments, decreases with cool temperatures, lower precipitation.
Sequoia Pitch Moth	Increases with site productivity, increases with higher volume growth.
Gouty Pitch Midge	Increases with site productivity, mid elevation sites will have the highest infestation.
Total Foliar Pathogens	Warmer, wetter sites will have higher infection rates; crowded, brush filled treatments will have higher infection
Western Gall Rust	Highest infection rate between 1200m and 1400m; increased volume growth treatments will have more galls; wave years will coincide with El Nino events

Chapter 2: Methods

Study Area:

The study installations (Figure 2.1) used in this project are all part of a long term ponderosa pine plantation study initiated by the USDA Forest Service, Pacific Southwest Research Station Silviculture Unit based in Redding, California. The study, coined the Garden of Eden study, set out to determine the effect of all possible

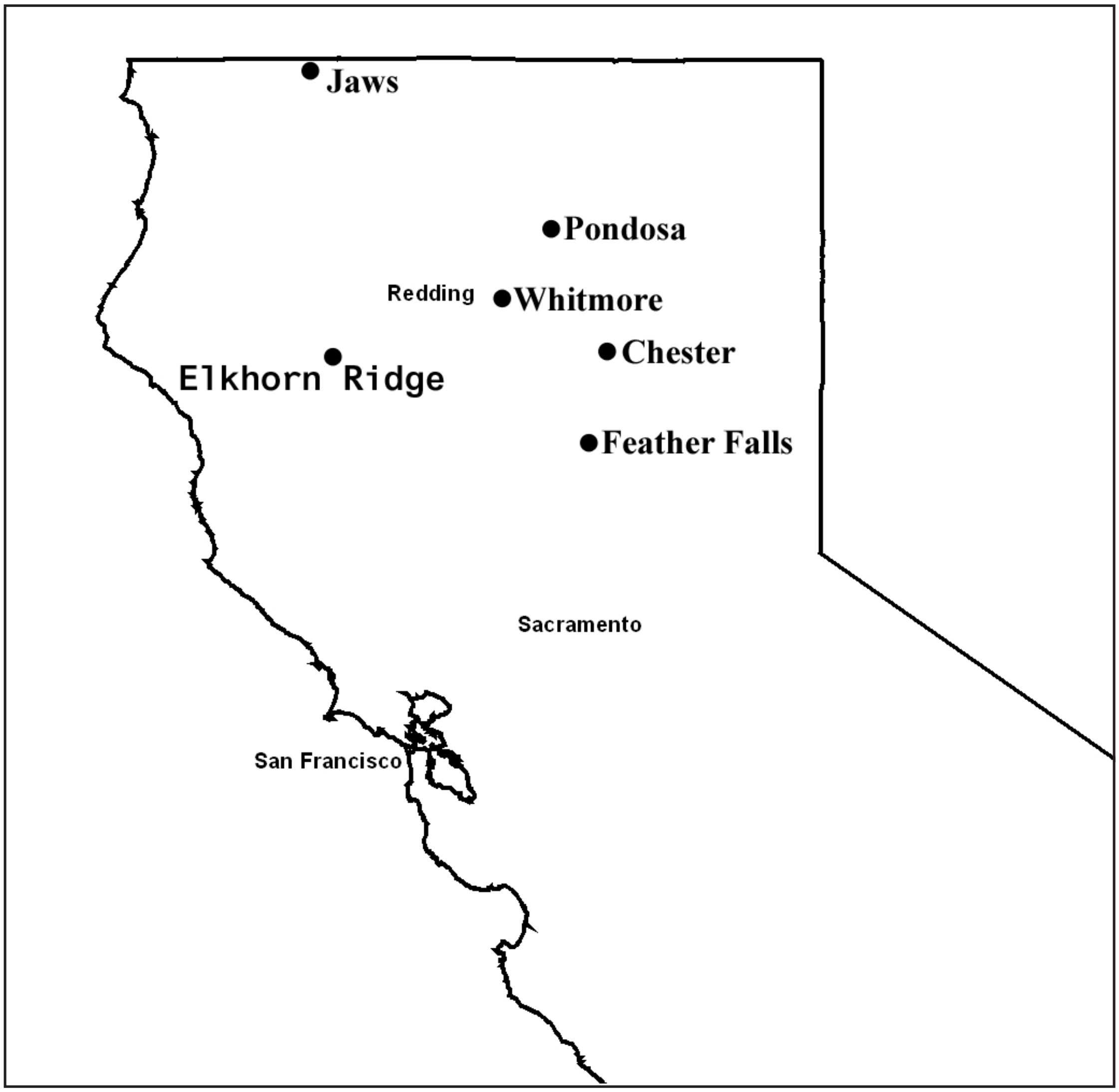

Figure 2.1: The six Garden of Eden study site locations in northern California.

herbicide, fertilizer and insecticide applications on the growth and yield of ponderosa pine. Initially there were eight installations all located on private industrial forest land. Over time, two of the installations were abandoned, leaving six. Initially started in 1986, the study has been monitored for the last 22 years (Powers and Ferrell 1996). All of the installations are located in the Sierra Nevada, Cascade, and Klamath mountains of northern California. The study was situated across an environmental gradient of latitude, elevation, temperature, and precipitation, so is well suited to determining silvicultural treatment effects that persist among differing environmental conditions.

Table 2.1: Fifty year site index, elevation, mean annual temperature from 1985 to 2007, mean annual precipitation between 1985 and 2007, and year of planting for the six study sites.

Site	Site Index (m/50 years)	Elevation (m)	Temperature (°C)	Precip. (mm)	Year Planted
Elkhorn Ridge	17	1490	11	840	1988
Pondosa	20	1175	10.5	1180	1988
Chester	20	1465	8	1035	1987
Whitmore	23	730	14	882	1986
Jaws	23	1005	8	1311	1988
Feather Falls	30	1220	11	2094	1988

The Garden of Eden study pertains to the xeric, Mediterranean climate of northern California (Powers and Ferrell 1996). The eight initial installations were located to meet the following criteria: minimum size of two hectares, slope less than 20 percent, aspect within 45 degrees, same soil family, adjacent stands with common insect pests of ponderosa pine, and

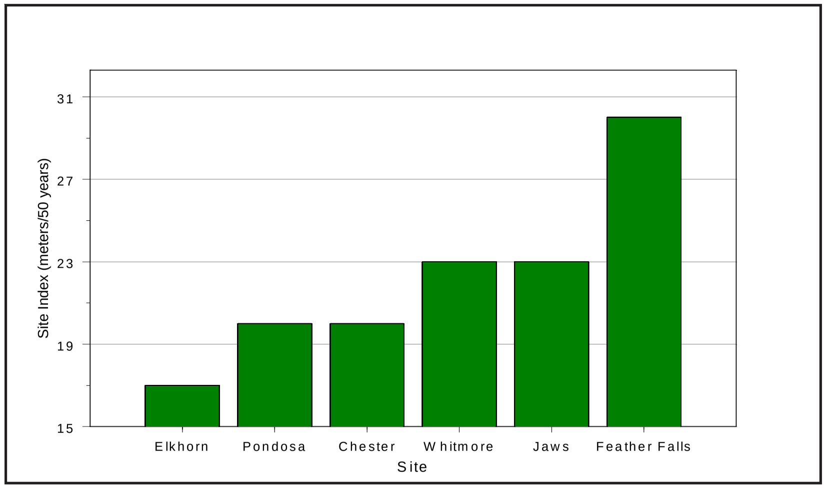

Figure 2.2: 50 year site index (m)

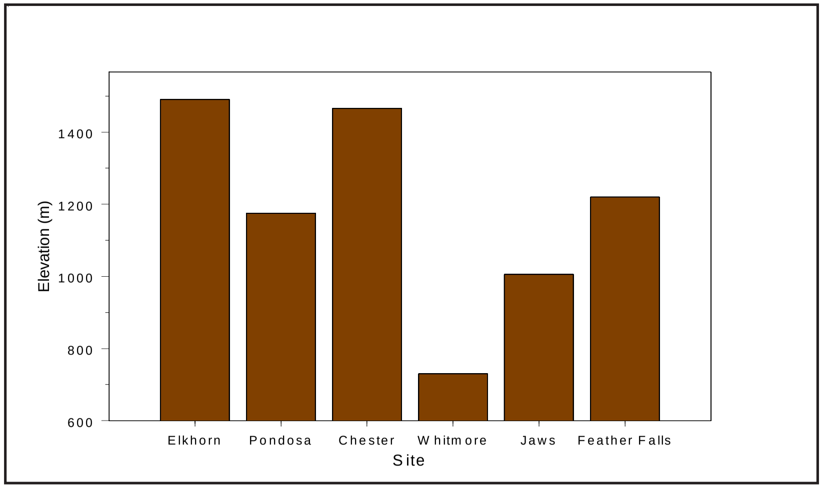

Figure 2.5: Elevation (m) of the six study sites.

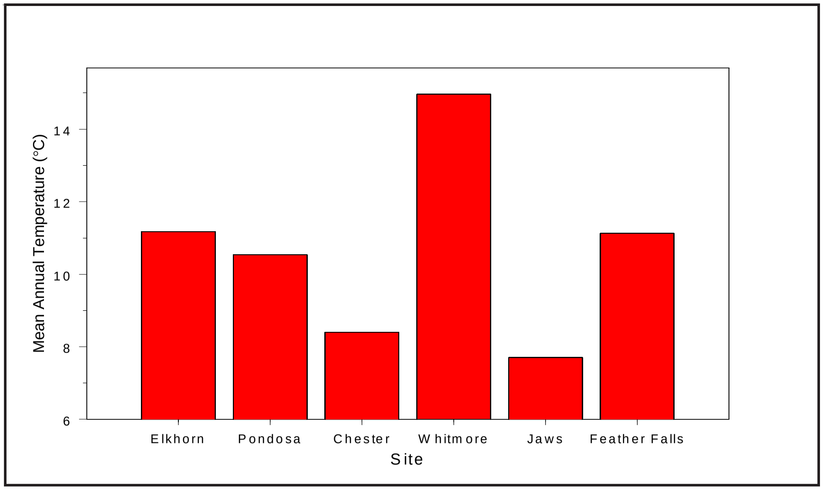

Figure 2.4: Mean annual temperature (°C) by site between 1985 and 2007.

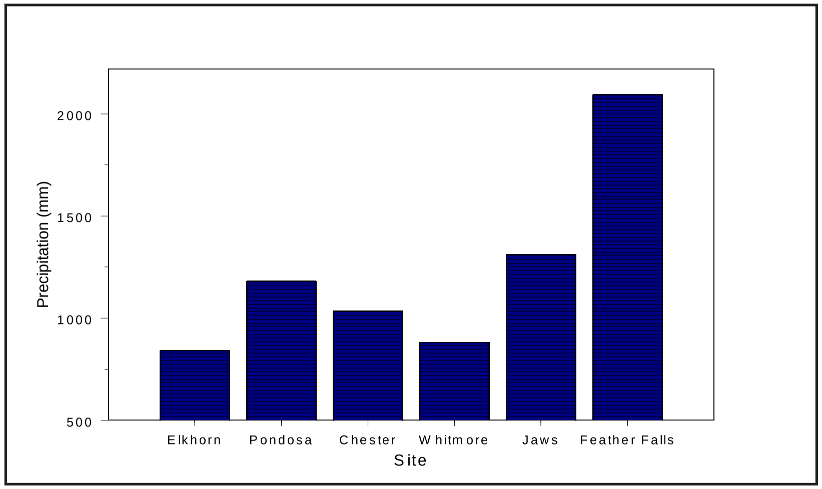

Figure 2.3: Mean annual precipitation (mm) by site between 1985 and 2007.

no signs of soil pathogens. The locations chosen were in four different geologic ranges: the southern Cascades, the Northern Sierras, the Klamath Mountains and the California Coast Range (Figure 2.1). The installations were located on an environmental gradient meant to capture the range of ponderosa pine growing environments (Figures 2.2-2.5). All installations are located on land owned by five different companies.

The lowest elevation installation was Whitmore, located approximately 40 miles east of Redding, California. Precipitation falls primarily during the winter months. There are 250 frost free days per year on average. Whitmore was the first installation of the study (1986) and was previously a brushfield. The volcanic parent material (Haplohumult) originates from the southern Cascade Mountains. Furthest north, Jaws is located on metasedimentary soils of the Klamath Mountains (Haploxeralfs). Jaws is the steepest of the six installations and was previously a natural stand. Pondosa is located near the town of McCloud (in the shadow of Mount Shasta), like Whitmore, Pondosa is located on volcanic soils (palexeralfs) of the southern Cascades. Established in 1988, the installation was converted from a brushfield. Feather Falls is the most productive installation (site index of 30 m), and is located in the volcanic parent material (haploxeralfs) of the Sierra Nevada Mountains east of Oroville, California. Feather Falls was also established in 1988 from a natural stand. Chester is very similar to Pondosa but higher and was also converted from a brush field (1987). Located just south of Chester, California and Lake Almanor, the installation is at the extreme south end of the Cascade Mountains. The underlying soils are volcanic in nature (xerochrepts). The highest and final installation is Elkhorn Ridge, located in the foothills of the Klamath range. The soils were derived from metasedimentary parent materials and are in the xerochrept great group. The installation was planted in 1988 and was previously a plantation.

Each of the installations has an identical set of treatments under the same layout. The three base treatments were herbicide, fertilizer, and insecticide, each with two levels (i.e. application vs. no application) giving a 2^3 factorial design. All possible treatment combinations were tested, with three replications at each site. The experimental units at each site were 19.5 m by 21.9 m and contained rows of six trees spaced 2.4 m apart. The measurement plot comprised the inner five rows of four trees, allowing for a two-row buffer. Treatments were randomly assigned to the experimental units, but the same assignment was applied to all sites.

The herbicide vegetation control treatment was an annual spring application of glyphosate, hexazinone, or triclopyr at the manufacture's recommended levels for the type of vegetation. Application was done with backpack sprayers and all vegetation except planted trees was sprayed. Herbicide was applied until all competing vegetation was eliminated from the treatment plot.

Insecticides acephate or dimehoate were applied directly to the trees until the crowns were saturated and dripped. Application was done annually in the spring after the new years' needles had emerged from the bundle sheaths. As in the herbicide treatments, insecticides were applied at the manufacturer's recommended levels for anticipated insects. Insecticide treatment was discontinued after the eighth year due to a lack of insect herbivory and attack in any treatment. Following this, the treatments containing insecticide application were converted to thinning treatments where ten of the 20 core trees were removed.

Each fertilizer plot received a mixture of macro and micro nutrients that were thought to give each tree all required nutrients. Each nutrient was applied as a salt during the dormant season and was applied at an increasing rate to account for the increase in size of the trees and increasing demand for nutrients. Fertilizers were applied in the spring of years one, three, five, and the fall of year six. The first three applications were made in soil holes at a distance from the tree equal to two-thirds of its length, on four sides. Year six application was made in bands between each row of trees during the fall due to the large amount of fertilizer prescribed. The fertilizers included: nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, zinc, copper, and boron. Application rates were determined

Table 2.2: Application rates for all fertilizers applied to fertilization treatments. Application of dry salts was made at 2-year intervals for the first six years of the study.

Nutrient		Amount applied (kg/ha)			
	Planting	Year 2	Year 4	Year 6	Total
Nitrogen	15.6	46.6	213.7	798.7	1074.6
Phosphorus	7.9	23.2	103.4	395.2	529.7
Potassium	7.7	23.2	109.6	399.4	539.9
Calcium	10.1	23.6	118.6	264.0	416.3
Magnesium	5.5	16.8	61.7	137.2	221.2
Sulphur	5.2	28.3	16.0	62.4	111.9
Zinc	1.1	3.2	14.0	55.1	73.4
Copper	0.5	1.6	6.8	26.9	35.8
Boron	0.5	1.6	6.8	29.8	38.7

for an average site and increased with estimated growth of this theoretical site (Table 2.2).

Measurements:

Measurements of needle retention, foliar herbivory and foliar pathogens were made from a branch mid-crown from five randomly selected trees on each plot in summer 2007. A random number generator was used at each plot to determine from the tree from which a branch was harvested. When a selected tree was not present (either dead or removed) a different tree was randomly selected until five were measured. Plots that had fewer than five trees had every tree measured.

Variation in the amount of light, temperature and microenvironment of the sample branch was controlled by selecting a mid-crown branch on the south side of the tree. By standardizing in this way, variation in light and temperature, and potentially leaf wettness and relative humidity, were minimized. The branch was collected by pole pruner when the mid-crown was above arms' reach. When mid-crown was above 6.5 m the highest reachable branch was collected. Needle retention was recorded as the number of annual needle cohorts that were present on a branch from the mid-crown on the south side of the tree, to the nearest tenth of a cohort.

Foliar herbivory was ocularly estimated as the amount of dead leaf tissue or missing foliage from the 2005 and 2006 cohorts (Figure 2.6). When insects were present, the area that was covered was assesed as feeding and included in the herbivory percentage. Current year foliage was not recorded unless there was a dramatic amount of herbivory.

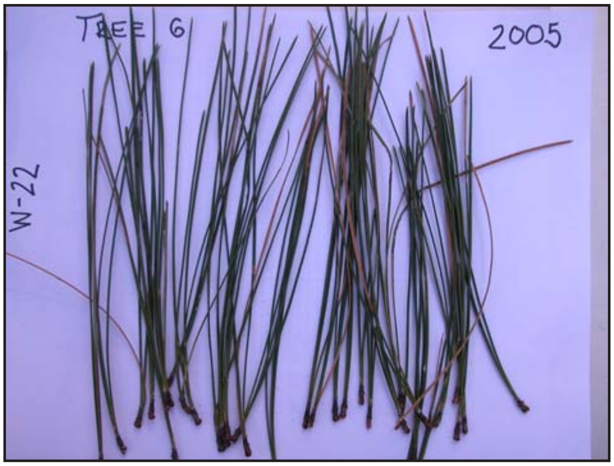

Figure 2.6: The 2005 cohort of needles from a sampled tree. Estimation of herbivory and pathogen infection was made by considering the proportion of needles that were consumed or displayed symptoms of infection.

Identification of the damaging agent was made in the field with the aid of field guides and references.

Foliar pathogens were measured in the same manner and using the same branch sample as the foliar herbivory. Ocular estimation of the chlorotic or dead foliage as well as the presence of fungal fruiting bodies were made for the 2005 and 2006 cohorts. Field identification of the causal agent was made using field guides, hand lenses and a stereo microscope when needed. When the agent was unidentifiable it was listed as “other pathogens.”

Branch herbivory was estimated by looking at the entire tree and ocularly estimating the percentage of the branches that were impacted by a variety of insects. Much of the time identification was made by finding the damaging agent and identifying it using field guides. The proportion was recorded for each tree on the measurement plot.

Any visible pathogens or insects on exposed roots were also recorded. When a tree looked unhealthy or was dead the root crown was exposed to look for any pathogens or insects. If any were found, they were identified and recorded.

The tree base and root crown area (butt) were assessed on every tree for any kind of biotic and abiotic damage. Causal agents were identified and any damage was photographed. The bole of every tree on the measurement plot was examined for any damage, including fungal agents such as western gall rust and insects like sequoia pitch moths and bark beetle. The search started at approximately 0.5 meters from the ground surface and extended to the point that foliage was consistently present on the main axis of the tree. Each infection or attack was tallied, and these tallies were summed for each tree.

The clear winged, sequoia pitch moths feed on the phloem in the trunks and branches of trees, causing large pitch masses where their larvae feed and mature. These pitch masses were counted on each tree. Each contiguous site of infestation was counted as a single attack even if it appeared that the pitch may have been exuded in different years.

The terminal of each measurement plot tree was assessed to identify any insect attacks (i.e. tip moths, shoot borers). Tall trees that were beyond the point of study for ocular estimation were reviewed either by using binoculars with an 8x magnification or were climbed if evidence of attack needed closer examination. Infections or attacks were tallied on each tree.

Western gall rust infections were studied in greater detail than other types of infection or attack. Each measurement plot trees was first searched for galls, and the total number was counted and recorded. Each buffer tree also was surveyed for the number of galls to give a total for the buffer. All galls in the measurement plot classified as a hip/bole gall if it was on the main stem of the tree or a branch gall. The height of each gall was measured using a laser hypsometer to the nearest hundredth of a meter. The gall age was determined either by counting the annual shoots to the gall when the branch was alive or counting the branch nodes and bole whorls to the ground when the branch was dead.

Weather data were gathered from the Western Regional Climate Center in Reno, Nevada and Scripps Institute of Oceanography in La Jolla, California. The weather station was identified for each installation that was nearest and had continuous data dating back to 1985. The California Climate Data Archive on-line database contains data from National Weather Service Cooperative sites, Snotel sites, RAWS stations, and several other stations. For this study only NWS COOP and RAWS sites were used because they were the nearest and the most consistent data sources.

Statistical Analysis:

After all of the data were compiled and input, summary statistics were generated and explanatory analysis was done graphically. Where initial analysis (scatter plots, residual plots from ANOVA and simple linear regression) showed their necessity, transformations were made. Transformations included arcsine square root transformations of proportion data (foliage herbivory and pathogens and gouty pitch midge data). Analysis of variance (ANOVA, S-Plus 2005) explicitly recognized installation replication, treatment effect, and installation by treatment interactions were considered, but retained only if statistically significant (alpha=0.05). Transformed dta was used in all ANOVAs.

Regression analyses (S-Plus 2005) determined if continuous covariates explained variation in responses. Count data for the butt, bole, sequoia pitch moth and western gall rust were analyzed with Poisson log-linear regression to match the discrete nature of counts and variance proportional to the mean. Stepwise regression and all subsets analysis (S-Plus 2005) identified relevant variables representing effects of weather, elevation and site index. The model that was determined to be appropriate was determined using adjusted R^2, Akaike's Information Criterion, and drop in deviance tests.

The year of infection was compared to years of known El Niño Southern Ocean Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) to determine the influence of large scale weather patterns on wave year occurrence. An one-way ANOVA with the count of galls as the response variable was run to test for the effect of year on infection level. A Tukey multiple comparison test identified the years with significantly greater or lesser infection level. Precipitation was then added to this model as a covariate.

Chapter 3: Results

The six installations were stocked with healthy trees growing at rates that would be expected for these sites (Powers and Ferrell 1996). There were no major forest health issues noted previously, and an observer walking through the plots would not see anything remarkable, with only a few exceptions. The Feather Falls installation had a noticeable number of western gall rust infections present and the Pondosa installation had evidence of pineshoot borers presence. However, on closer inspection, there were several other insects and pathogens on the installations.

During the summer of 2007 I found 13 different insect pests and six different pathogens that were identifiable in the field (Table 3.1). Most of these, however, were present in extremely low levels and may have been present only at one installation, on one plot, or even one tree.

Although 19 insect pests and diseases were identified, I focused on the most abundant insects, the gouty pitch midge, and sequoia pitch moth, and western gall rust. Foliar herbivory and total foliar pathogens were also analyzed in detail. Needle retention was assessed because it interacts with insect and disease agents and was known to be affected by fertilization and site productivity.

Growth responses were shown to be positively correlated to the site productivity. With volume growth higher in some treatments than values previously reported similar sites. Treatments also contributed significantly to the volume growth of the plots. Vegetation

Table 3.1: Diseases and insects found on study plots during the 2007 field survey. Frequency on sample trees is noted as a percent of the trees that had the organism present.

Common Name	**Scientific Name**	**Frequency on sample trees (%)**
Insects		
Leaf hopper	Family *Cicadellidae*	0.5
Aphids	Family *Aphididae*	1.0
Scale	*Chionaspis spp., Nuculaspis spp.*	5.7
Sequoia pitch moth	*Synanthedon sequoiae*	7.6
Western pineshoot boarer	*Eucosma sonomana*	2.5
Tip moth	*Rhyacionia spp.*	2.5
Sugar pine tortrix	*Choristoneura lambertiana*	0.1
Needle miner	*Coleotechnites spp.*	1.0
Weevil	*Magdalis gentilis, Scythropus spp.*	12.2
Bark beetles	*Ips spp., Dendroctonus spp.*	0.6
Gouty pitch midge	*Cecidomyia piniinpis*	20.5
Saw fly	*Neodiprion spp., Acantholyda spp.*	0.2
Pathogens		
Armillaria	*Armillaria ostoyae*	0.1
Western gall rust	*Endocronartium harknessii*	10.3*
Dothistroma needle blight	*Mycosphaerella pini*	12.6
Elytroderma needle blight	*Elytroderma deformans*	0.2
Lophodermella/ Lophodermium needle cast	*Lophodermella spp., Lophodermium spp.*	0.1
Diplodia	*Sphareopsis sapinea*	0.3

(*) Rare to Very Common depending on the site

controlled and fertilized treatments had much higher growth rates than on just herbicide or just fertilizer plots and much higher than on control plots (Powers and Reynolds 1999)

Needle Retention:

Initial analysis and evaluation of needle retention suggested that there was a difference between the installations but little treatment effect. Table 3.2 shows the different means between installations and between treatments. Figures 3.1 and 3.2 graphically demonstrate the differences between installations and treatments. The site by treatment

Table 3.2: Mean needle retention by site and treatment in 2007. Standard error of the mean is reported in parentheses. Grand means for sites and for treatments are reported on the far right and bottom.

	Treatment								
Site	C	F	FI	H	HF	HFI	HI	I	GRAND MEAN
Chester	4.6 (0.09)	4.2 (0.19)	4.3 (0.17)	4.7 (0.07)	4.4 (0.19)	4.8 (0.30)	4.6 (0.18)	4.8 (0.34)	4.5
Elkhorn Ridge	3.6 (0.27)	3.9 (0.20)	3.8 (0.07)	3.6 (0.34)	4.0 (0.27)	2.8 (1.38)	3.8 (0.38)	3.7 (0.14)	3.6
Feather Falls	2.6 (0.09)	2.4 (0.17)	2.5 (0.19)	2.6 (0.21)	2.3 (0.19)	2.7 (0.25)	2.7 (0.10)	2.5 (0.16)	2.5
Jaws	2.5 (0.05)	2.7 (0.17)	2.5 (0.15)	2.8 (0.15)	2.7 (0.17)	3.0 (0.06)	2.8 (0.05)	2.7 (0.04)	2.7
Pondosa	3.4 (0.06)	3.7 (0.01)	3.7 (0.15)	3.9 (0.15)	3.8 (0.05)	3.9 (0.08)	3.7 (0.10)	3.6 (0.11)	3.7
Whitmore	3.0 (0.13)	2.9 (0.14)	2.8 (0.15)	2.7 (0.18)	2.6 (0.11)	3.2 (0.50)	3.0 (0.13)	3.0 (0.06)	2.9
GRAND MEAN	3.3	3.3	3.2	3.4	3.3	3.4	3.4	3.4	3.3

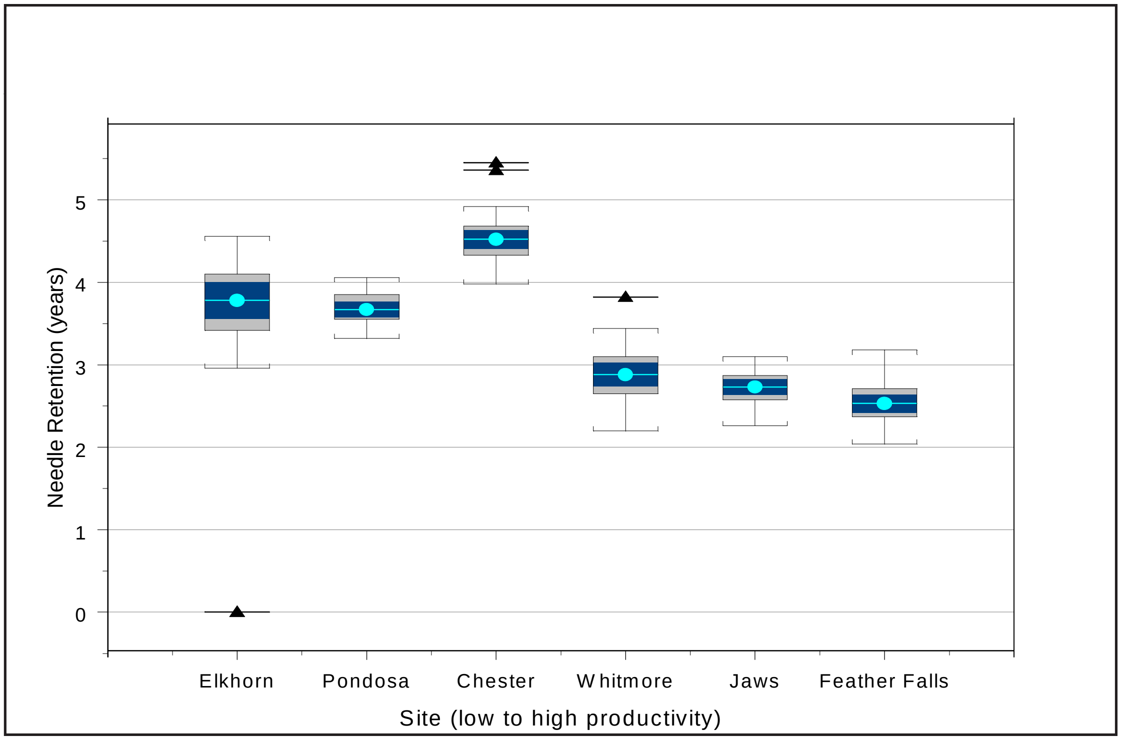

Figure 3.1: Mean needle retention (circle) by site with 95% confidence bounds (dark color), quartiles (light color), outliers (triangles) and max/min (whiskers).

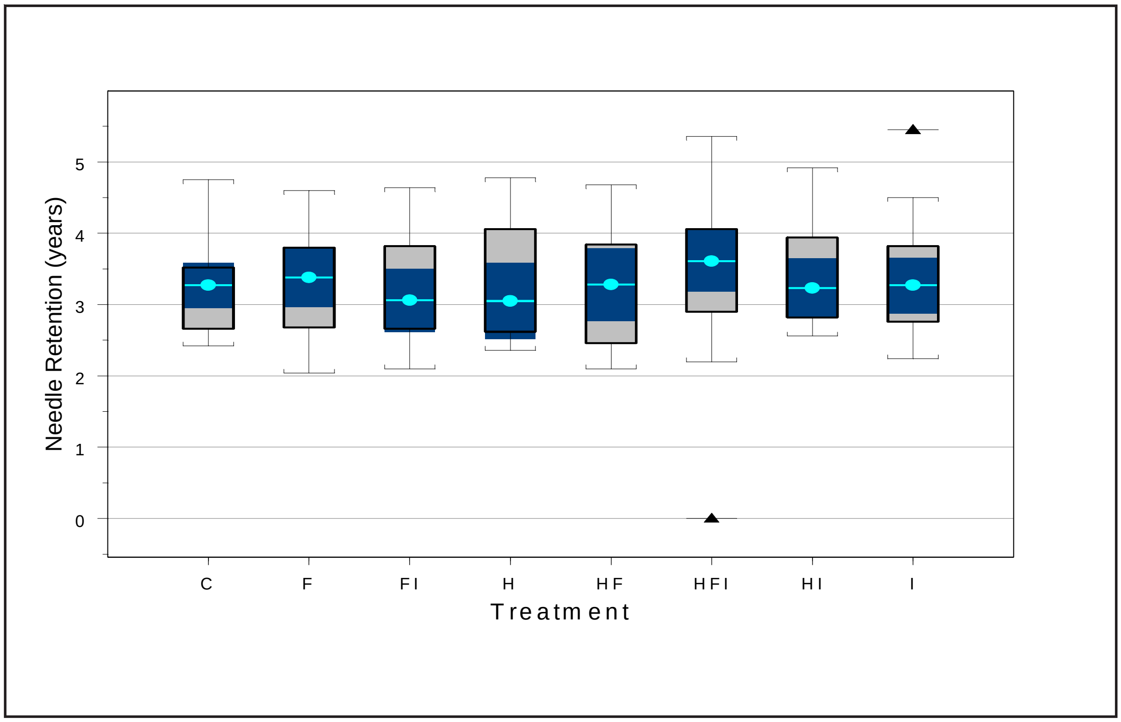

Figure 3.2: Mean needle retention by treatment (circle), 95% confidence bound, quartiles, outliers and max/min.

interaction was not significant (p-value 0.8670) nor was the treatment effect (p-value 0.9606); however, retention differed significantly between sites (p-value <0.001). Excluding the installation by treatment term lowered the treatment terms p-value but not to a significant level (p-value 0.5548). The final ANOVA model (Table 3.3) of Needle Retention=Installation had a final p-value <0.001.

Table 3.3: ANOVA for needle retention and site.

	Df	Sum of Sq	Mean Sq	F Value	Pr(F)
Site	5	69.3616	13.8723	69.9419	0
Residuals	137	27.1726	0.1983		

Residual standard error: 0.4453

Regression analysis resulted in a final model with elevation and mean annual precipitation as predictors and a weighted residual S.E. of 0.6725. When the Installation term was added and the stepwise regression rerun, the final model was the same as the ANOVA test (N.R.=Installation) with a residual S.E.=0.5371. When treatment was added to the model it was nonsignificant (p-value=0.8274).

The analysis showed a trend of decreasing needle retention with increasing site productivity. Mean needle retention at Chester was the highest at 4.54 years (C.I. 4.25 to 4.82) followed by Pondosa at 3.70 (3.42 to 3.99), Elkhorn Ridge 3.48 (3.19 to 3.76), Whitmore at 2.88 (2.60 to 3.17), Jaws at 2.71 (2.43 to 3.00), and the most productive installation, Feather Falls at 2.54 years (2.25 to 2.82). About 63% of the variation in retention was explained by site (R^2=0.63) with a residual standard error of 0.5371. Elkhorn Ridge and Pondosa were not significantly different (p-value 0.16), nor were Feather Falls, Jaws, and Whitmore (p-value 0.26 for Whitmore and Jaws, 0.0537 for Whitmore and Feather Falls, and 0.26 for Jaws and Feather Falls; Table 3.4, Figure 3.3).

Regression analysis indicated that needle retention decreases by 0.08 years for each 10-cm increase in mean annual precipitation (p-value <0.001, C.I. -0.10 to -0.06) holding elevation fixed Needle retention increases 0.16 years with each 100-m gain in elevation (p-value <0.001, C.I. 0.12 to 0.20), keeping precipitation constant

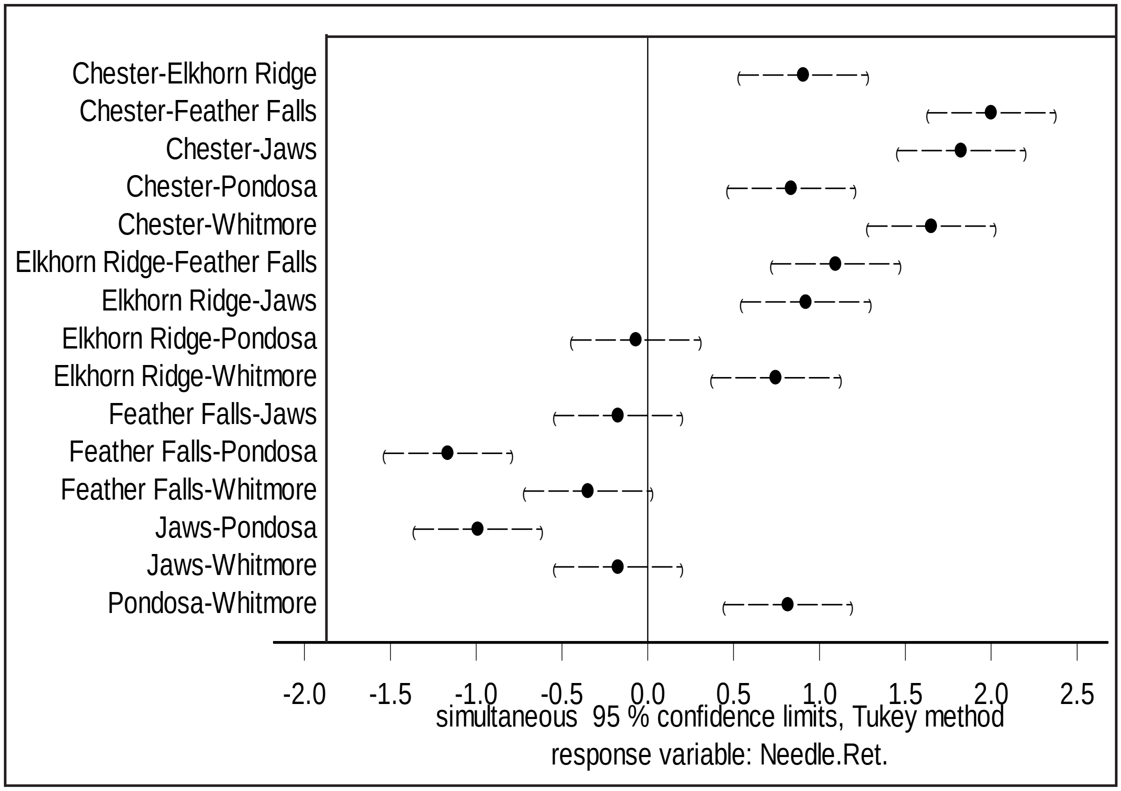

Figure 3.3: Simultanious 95% confidence intervals of needle retention for all site comparisons.

Table 3.4: Mean needle retention by site with standard error and upper and lower Tukey 95% simultanious confidence limits.

	Estimate	Std.Error	Lower Bound	Upper Bound
Chester	4.54	0.11	4.25	4.82
Elkhorn Ridge	3.48	0.11	3.19	3.76
Feather Falls	2.54	0.11	2.25	2.82
Jaws	2.71	0.11	2.43	3.00
Pondosa	3.70	0.11	3.42	3.99
Whitmore	2.88	0.11	2.60	3.17

Gouty Pitch Midge:

Gouty pitch midge occurred at all installations (Figure 3.4). Because gouty pitch midge (GPM here after) level was expressed as a percentage of branches with signs of GPM attack, the response data were transformed to arcsine square root (Ramsey and Schafer 2002). The mean GPM infestation rate for individual plots was 1.77 percent with a minimum of 0.00 and maximum of 13.95 percent. Installation means ranged from 0.3 percent to 5.2 (Table 3.5, Figure 3.4).

The installation by treatment interaction was not significant (p-value=0.3294). The treatment effect was nonsignificant in the reduced model (p-value 0.6757), leaving the installation as the only significant effect (p-value <0.001). Levels of infestation between Chester and Jaws (p-value 0.0001), Feather Falls and Jaws (p-value <0.001) and Elkhorn Ridge and all other installations (p-values <0.05).

Regression analysis showed that, excluding treatment and installation terms, elevation, mean annual precipitation, and mean annual temperature were all

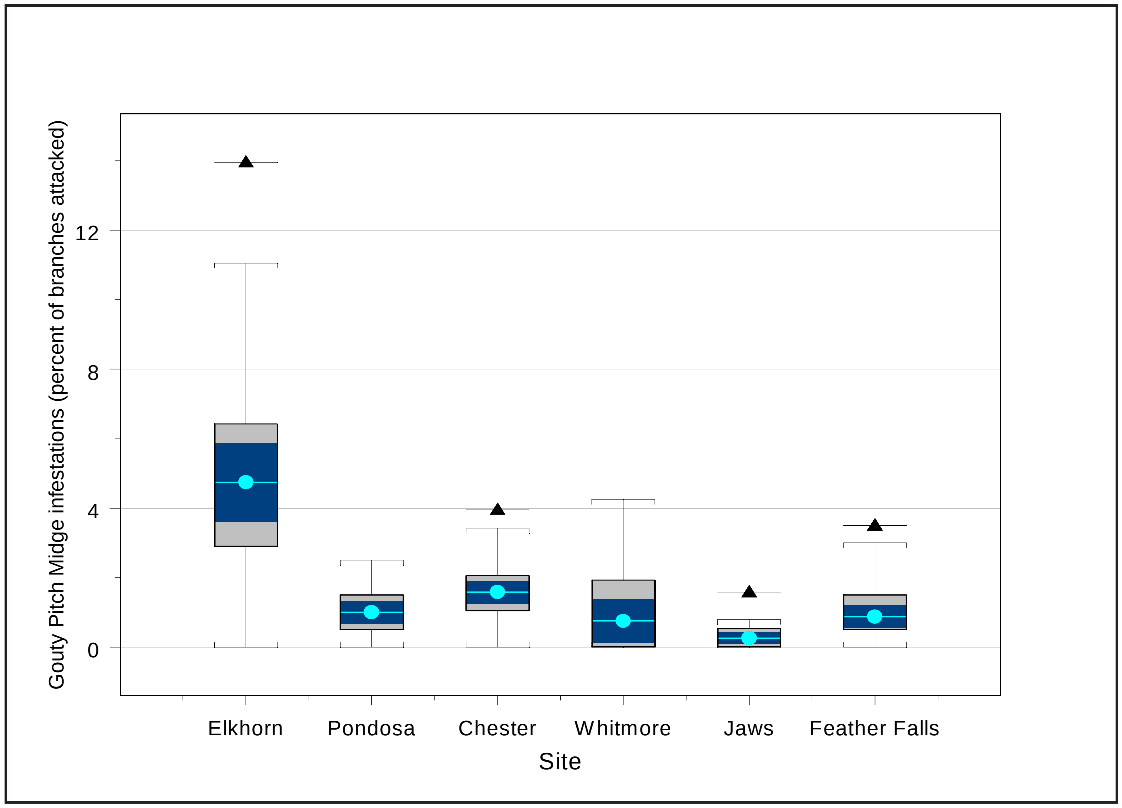

Figure 3.4: Mean proportion of branches attacked by the gouty pitch midge with 95% confidence intervals (dark color), quartiles, outliers (triangles) and min/max.

significant predictors of gouty pitch midge frequency. Relative frequency increased by 18 percent for every 100-m increase in elevation (p-value <0.001, arcsine sqrt data: 0.0002, C.I. 0.000191 to 0.000226), 273 percent for every 1-cm increase in mean annual precipitation (p-value 0.0172, arcsine sqrt data: -0.0003, C.I. -0.00038 to -0.00018), and an increase of 13 percent for each one degree Celsius increase in temperature (arcsine sqrt data: 0.0143, C.I. 0.0122 to 0.0163). Approximately 49 percent of the variation in the gouty pitch midge frequency was explained by the regression model.

Table 3.5: Mean proportion of branches infested by gouty pitch midge with simultaneous 95% confidence intervals.

	Estimate	Std.Error	Lower Bound	Upper Bound
Chester	1.640	0.325	0.798	2.49
Elkhorn Ridge	5.210	0.325	4.370	6.06
Feather Falls	1.270	0.325	0.426	2.12
Jaws	0.329	0.325	-0.517	1.17
Pondosa	0.979	0.325	0.134	1.82
Whitmore	1.160	0.325	0.317	2.01

Total Foliar Herbivory:

The total amount of foliar herbivory was measured as the proportion of needle that was missing due to insect activity. Herbivory was analyzed using scatter plots (Figure 3.5), linear regression and ANOVA. Herbivory was first transformed by the function arcsine square root.

The first analysis was an ANOVA test with installation, treatment, and the installation by treatment interaction terms all present. The interaction term between site and treatment was not significant in the initial ANOVA (p-value 0.8950), so was dropped. Treatment was not significant in the reduced model (p-value 0.8638). Herbivory did differ significantly by site (p-value <0.001). Feather Falls had significantly less herbivory than all other installations (p-values <0.05, Figure 3.6).

All subsets analysis and stepwise regression showed that installation would explain about 18 percent of the variation in herbivory, with a residual standard error of 0.0888. The

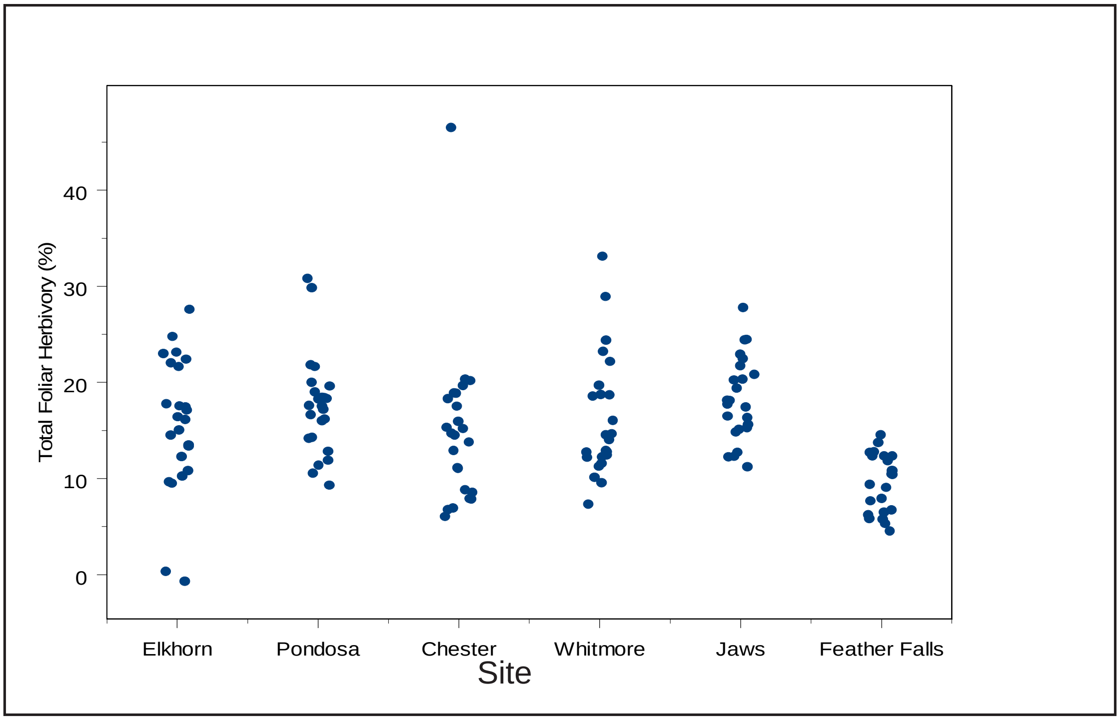

Figure 3.5: Total foliar herbivory (%) by site. Jittered in on x-axis to show spread among plots.

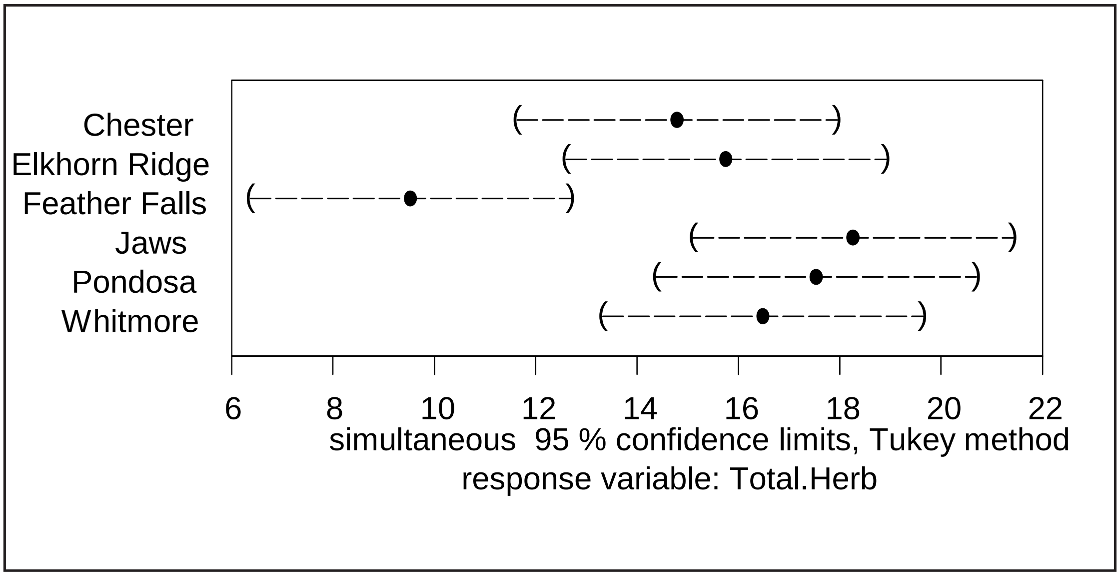

Figure 3.6: Simultaneous 95% confidence intervals for the proportion of consumed foliage from the six study sites.

model with continuous environmental variables had a similar residual standard error (0.884) and explained a similar proportion of the variation in herbivory (R^2=0.186).

Herbivory decreased as elevation, site index, and mean annual temperature increased. For each 100-m increase in elevation, herbivory decreased about 4 percent (arcsine sqrt data: 0.01556 C.I. -0.0225 to -0.0086, p-value <0.016). Herbivory decreased by 2.4 percent for each 1-m increase in 50-year site index (C.I. -0.0134 to -0.0056, p-value <0.014), and decreased by 2.4 percent for each one degree increase in mean annual temperature (C.I. -0.0166 to -0.0021, p-value 0.047).

Total Foliar Pathogens:

Activity of foliar pathogens was measured as the proportion of needle that was discolored and showing signs of infection. Scatter plots (Figure 3.7), ANOVA, and regression analysis confirmed the need for arcsine square root transformation. The pathogen data before transformation are summarized in Table 3.6.

Table 3.6: Site summary for mean foliage pathogens. Data is percentage of foliage with infection symptoms and is non-transformed.

Site	Mean	Standard Error
Elkhorn Ridge	11.8	1.4
Pondosa	9.4	1.1
Chester	5.1	0.6
Whitmore	23.3	2.8
Jaws	23.5	2.5
Feather Falls	11.4	1.1

The interaction of installation and treatment was not significant (p-value 0.9653), and the main effect of treatment was likewise not significant (p-value 0.9853). Only installation had a significant effect on total pathogen activity (p-value <0.001). Multiple comparison by

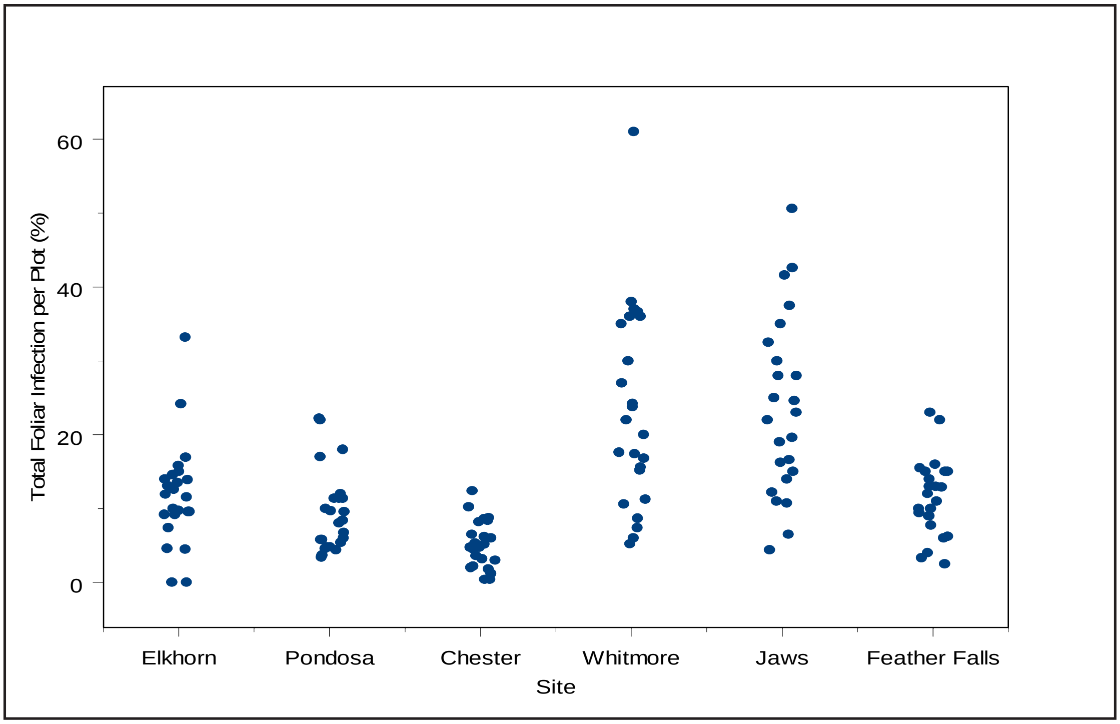

Figure 3.7: Mean foliar pathogen infection per plot (%). Values jittered in the x-axis.

Tukey method (Table 3.7) showed significant differences in the amount of pathogen infection between Elkhorn Ridge and Chester, Jaws, and Whitmore. As well as Pondosa and Jaws and Whitmore. Chester and Feather Falls, Jaws, and Whitmore were different. And lastly Feather Falls was different from Jaws and Whitmore (all p-values <0.05). The highest level of pathogen symptoms occurred at Jaws, followed by Pondosa, Whitmore, Elkhorn Ridge, Chester, and Feather Falls.

Regression analysis suggested that only elevation explained a significant amount of variation in pathogen activity. Residual standard error and R-squared were 0.1204 and 0.4185 respectively for the installation only regression versus 0.1306 and 0.2955

Table 3.7: Estimated means of foliar pathogen infection (arcsin sqrt%) with simultaneous 95% confidence intervals. Significant site differences marked with (*).

	Estimate	Lower Bound	Upper Bound
Chester-Elkhorn Ridge	-0.1140	-0.2150	-0.0139 *
Chester-Feather Falls	-0.1210	-0.2210	-0.0203 *
Chester-Jaws	-0.2780	-0.3790	-0.1780 *
Chester-Pondosa	-0.0863	-0.1870	0.0141
Chester-Whitmore	-0.2720	-0.3730	-0.1720 *
Elkhorn Ridge-Feather Falls	-0.0064	-0.1070	0.0940
Elkhorn Ridge-Jaws	-0.1640	-0.2640	-0.0636 *
Elkhorn Ridge-Pondosa	0.0280	-0.0724	0.1280
Elkhorn Ridge-Whitmore	-0.1580	-0.2580	-0.0574 *
Feather Falls-Jaws	-0.1580	-0.2580	-0.0572 *
Feather Falls-Pondosa	0.0344	-0.0660	0.1350
Feather Falls-Whitmore	-0.1510	-0.2520	-0.0510 *
Jaws-Pondosa	0.1920	0.0916	0.2920 *
Jaws-Whitmore	0.0062	-0.0942	0.1070
Pondosa-Whitmore	-0.1860	-0.2860	-0.0854 *

respectively for the model with only elevation. For each 100-m increase in elevation foliar pathogen activity decreases by 8.9 percent (p-value 0.036).

<u>Sequoia Pitch Moth</u>:

Over the entire study, 346 infestations were identified with a maximum of 16 in any one plot and a mean of 2.4 per plot. Ordered from low to high productivity, Elkhorn Ridge had mean of 4.17 pitch nodules per plot, Pondosa 2.92, Chester 0.79, Whitmore 2.5, Jaws 3.75, and Feather Falls only 0.29 (Figure 3.8).

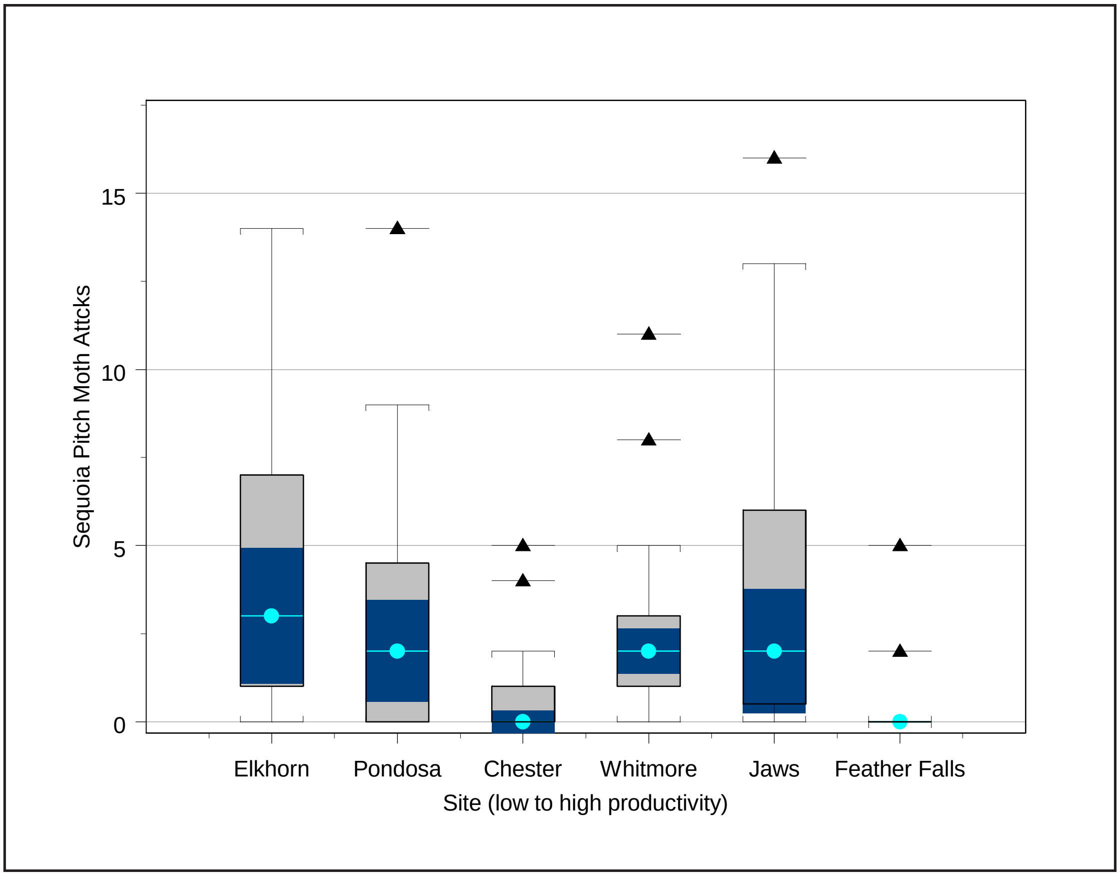

Figure 3.8: Mean sequoia pitch moth attacks per plot with 95%. confidence intervals (dark box), quartiles (light boxes) and min/max (whiskers).

Analysis of variance found significant effects of installation, treatment and the installation by treatment interaction (p-values <0.001 for installation and treatment and 0.017 for the interaction). Elkhorn Ridge had significantly more attacks than Pondosa, Chester, Whitmore, and Feather Falls. Pondosa had significantly more attacks than Chester and Feather Falls. Chester had significantly more attacks than Feather Falls. Whitmore had significantly more attacks than Feather Falls and Chester. Jaws was significantly higher than all but Elkhorn Ridge. Feather Falls was significantly lower than all other installations. There was a significant difference between the C and H, F, HF, HI, and HFI treatments (Table 3.8,

Table 3.8: Sequoia pitch moth treatment simultaneous means (simulation-based method) with 95% confidence bounds. Treatments with a number of attacks significantly greater than zero marked with (*).

Treatment	Estimate	Lower Bound	Upper Bound
C	0.8	-1.250	2.80
F	2.2	0.195	4.25 *
FI	0.7	-1.360	2.69
H	4.4	2.420	6.47 *
HF	4.4	2.420	6.47 *
HFI	3.2	1.140	5.19 *
HI	2.4	0.417	4.47 *
I	1.1	-0.972	3.08

Figure 3.9). Of the plots that were significantly different from the control, F was significantly lower than the others, H was significantly higher than all but HF, HFI was lower than H and HN, but higher than F and HI, and HN significantly higher than all others.

With count data there is often a large number of zero counts in the data. Poisson analysis suggested that installation explained a significant amount of variation in sequoia pitch moth attacks (residual s.e. 0.5371). Mean annual temperature, elevation and site index were all significant predictors in the final regression model. An increase in mean annual temperature by one degree Celsius corresponded to a decrease in pitch moth infestation of 14.7 percent (p-value <0.001, C.I. 9.8% to 19.3%). Infestations decreased 2.7% (p-value <0.001, C.I. 1.9 to 3.5) for every 100-m gain in elevation, and 18% (p-value <0.001, C.I. 12.0 to 24.4) for each 1-m increase in 50-year site index.

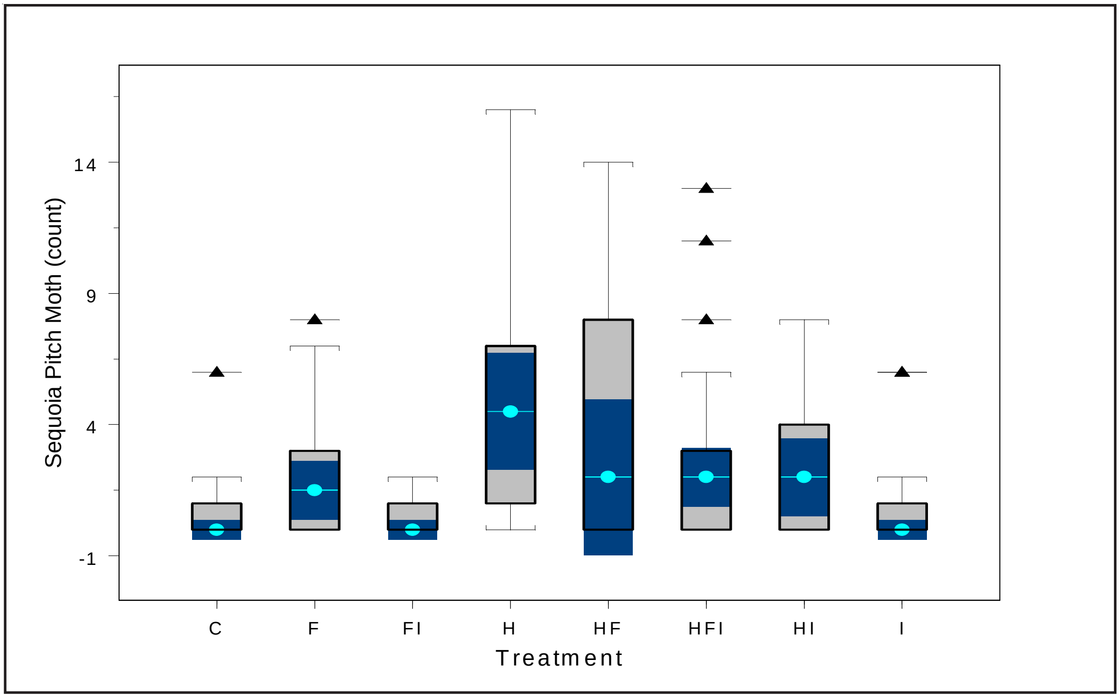

Figure 3.9: Sequoia pitch moth plot means by treatment. Dark boxes are 95% confidence intervals, light boxes are quartiles, whiskers are max/min values.

Western Gall Rust:

A total of 586 galls were counted, with a mean of 4.1 galls per plot over the entire study. Feather Falls had the highest level of galls at 477 (averaging 19.86 per plot), followed by Chester with 74 galls (3.08 per plot), Pondosa with 18 (0.75 per plot), Jaws with 11 (0.458 per plot), Whitmore with 5 (0.21 per plot), and finally Elkhorn Ridge had one gall (0.041 per plot) (Figure 3.10). Treatment averages ranged from 2.7 per plot under HI to 6.2 under HF (Table 3.9).

Analysis of variance showed that both the installation-by-treatment interaction and the treatment effect were not significant (p-value 0.92 and 0.18 respectively) . Gall rust infections did differ significantly among installations (p-value <0.001). Significant differences

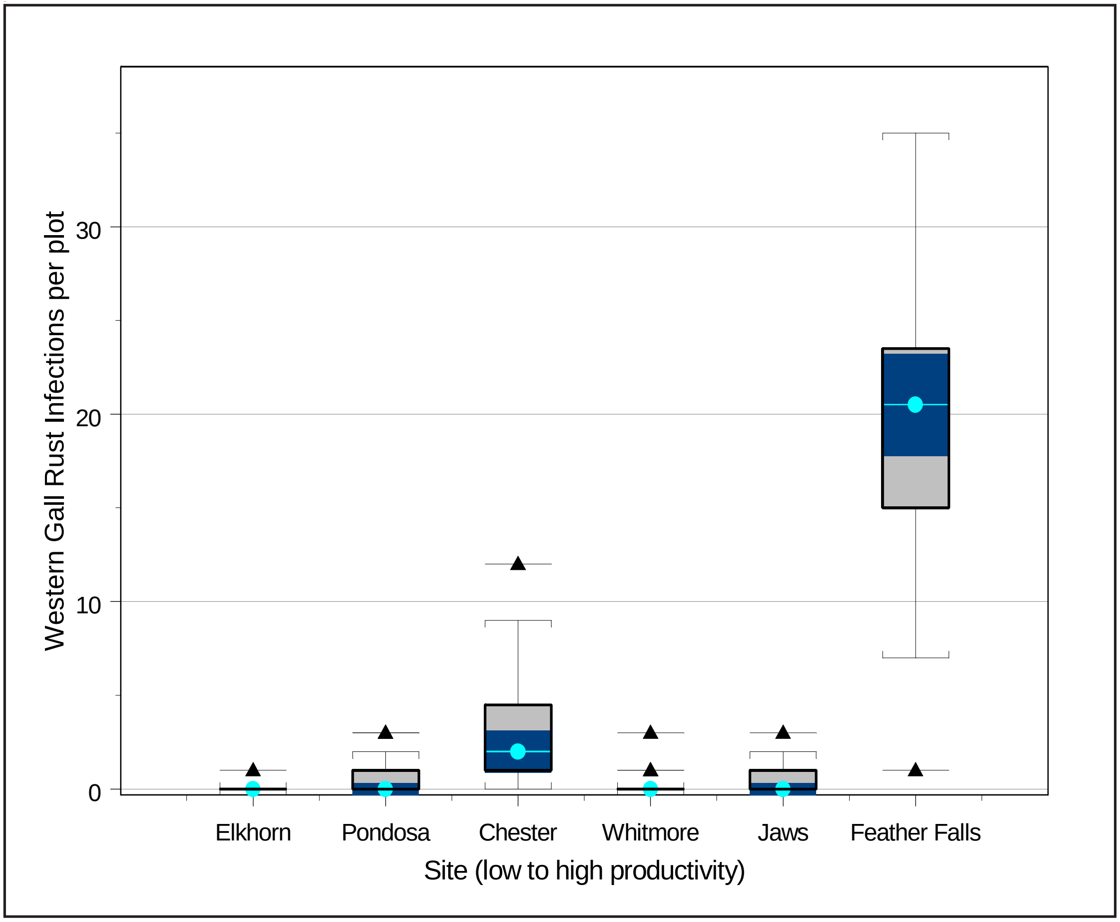

Figure 3.10: Western gall rust infections per plot on each plot. Dark boxes are 95% confidence intervals, light boxes are quartiles, whiskers are max/min values.

Table 3.9: Mean and total gall count on treatments throughout the entire Garden of Eden study.

Treatment	Mean # of Galls	St. Err.	Total galls
C	3.7	1.8	67
F	3.6	2.2	65
FI	4.8	2.1	87
H	3.8	1.7	69
HF	6.2	2.4	111
HFI	4.1	1.4	73
HI	2.7	1.4	48
I	3.7	2.0	66

are found between Feather Falls and the other five installations but not between any of the other installations.

All subset analysis and stepwise regression analysis showed that installation accounts for the greatest amount of variability in gall rust incidence. Mean annual temperature, elevation and site index were all significant predictors and resulted in only a slightly greater residual standard error (3.669 vs. 3.667 for installation only). Poisson regression analysis also suggested that several of the treatments were significantly different. Only the treatment with herbicide and fertilizer was significantly greater than the control (p-value <0.001).

Environmental variables included site index and elevation. There was and increase of one gall as elevation doubles on an installation average (C.I. 1.0-1.1, p-value=0.024). A doubling in the 50-year site index corresponded to a 1.4 gall increase per installation (C.I. 1.2-1.6, p-value<0.001).

Chapter 4: Discussion

The importance of site characteristics and their relationship to forest health management was strongly demonstrated by results from this study. In each response examined, installation was either the only or the best descriptor. This result indicated that location is very important and that other variables, such as silvicultural treatment or weather, did not fully explain the pattern of insect and disease incidence. Unexpectedly, the eight silvicultural treatments had very little impact on the amount of pests and pathogens. While there may be differences in the amount of growth that the treatments experience (Powers and Ferrell 1996, Powers and Reynolds 1999), these difference did not translate into measurable forest pest incidences.

Needle Retention:

Needle retention was strongly influenced by installation, with approximately one year difference in the retention of needles between the highest productivity site and the lowest productivity site. While the seedlings planted at each installation were produced from local sources (Powers and Ferrell 1996), the differences among installations are probably related more to phenotypic response by the trees to their environment than to a genotypic determined trait (Reich et al. 1996). In previous studies trees of both Scots pine and Norway spruce from different latitudes and elevations were grown in a common garden, but no correlation was found between latitude or elevation of origin and the time needles were retained (Reich et al. 1996).

While it is difficult to separate any latitude variation in the small spatial scale used in this study, there was a 760 meter difference in elevation. With this increase in elevation there was an 82 percent increase in the length of time that needles are retained. Needle retention in the *Pinus* genus tripled along a 3000 meter elevational gradient (Ewers and Schmid 1981). While a 3000 meter increase in elevation would be above the ponderosa pine habitat, expanding the 82 percent increase observed over 760 meter to 3000 meter would be more than three times the needle retention seen at the lowest installation. Elevational differences have also been observed in lodgepole pine in Colorado (Schoettle 1990), with higher needle retention at higher elevations. However, needle retention characteristics do not appear to be inherited in ponderosa pine, as judged from comparison among many sites in the western United States (Weidman 1939).

Growth rates were increased with the addition of fertilizers and the control of competing vegetation (Powers and Reynolds 1999), however, there was no significant impact on the level of needle retention. While I hypothesized that the more stressed treatments (those with higher levels of competing vegetation and lower nutrient availability) would have longer needle longevity, this hypothesis was not supported. Other studies that have found foliage retention decreases several years following fertilization in lodgepole pine (Amponsah et al. 2005). Amponsah et al. (2005) state that the needle retention decreased 23 to 30 percent seven to eight years following fertilization, but they also note that other studies refute this result. Although their contradicting studies were short term, the current study addresses a relatively long term response of ten years.

Larger trees in the Garden of Eden study had lower needle longevity, contradicting Schoettle (1994) who asserted that needle longevity was longer for larger trees (older trees) in *Pinus aristata* and *Pinus contorta*. While there are significant differences in the tree ages between Schoettle (1994) and the Garden of Eden study, the differences are applicable because trees under 20 years of age have been recorded as having lower levels of needle retention compared to older age classes in the same environments (Grulke and Retzlaff 2001). While some have suggested that inherent site characteristics, such as soil fertility, play a role in determining needle retention, the present study would refute this as there was no significant difference in the amount of needle retention between treatments that approached ideal growing conditions.

Decreases in needle retention with increasing site productivity could be related to crown closure, as the highest site trees were at crown closure and the mid crowns were intermingled with each other. A decrease in light availability in the mid crown would be expected to lower needle longevity especially as the plot reaches crown closure (Amponsah et al. 2005). While no measure of the crown closure was taken, observation of the plots suggests that plots at Feather Falls had reached crown closure while the other installations had not.

As precipitation increases, the amount of needle retention decreases. Adaptation to more arid environments has been shown to increase needle retention (Ewers and Schmid 1981). Reich et al. (1996) determined that variation in needle longevity was a phenotypic response to environmental condition and not related to seed origin. Because the installations that received more moisture were more productive in the study (Powers and Ferrell 1996), we would expect that these would be the installations with lower needle retention. The reported values showed that the highest precipitation installations had the lowest levels of needle retention and the installations receiving the least precipitation had the highest values (Figure 4.1).

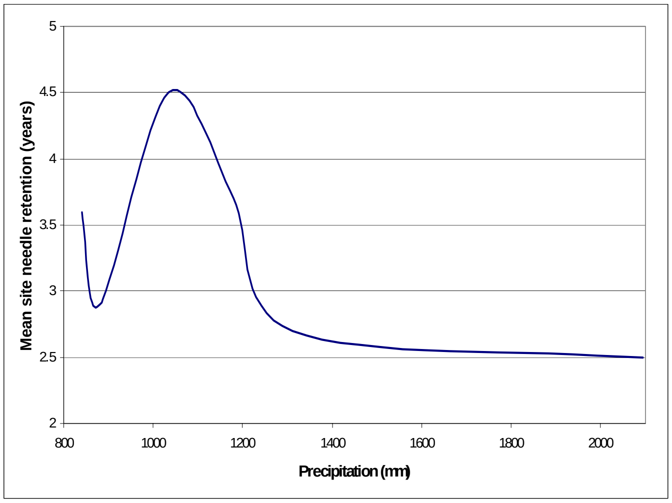

Figure 4.1: Mean needle retention in relation to mean annual precipitation.

One drawback in measuring needle retention is that there is no way to account for the amount of biomass that is held on the branch from year to year. A more appropriate measure may have been the total dry mass of the needles held. This could also be useful in estimating the amount of photosynthetically active area and total leaf area.

Total Foliar Herbivory:

The only installation that was significantly different from any other installation was Feather Falls, the highest productivity installation, with a significantly lower percentage of herbivory.. A possible explanation is that the surrounding stands may have lacked a high enough level of ambient infestation to infest the study installation. Alternately, there may be a lower percentage of foliage consumed but equal or higher biomass of needles consumed.

Muzika and Liebhold (2000) have suggested that high vigor trees would be better suited to cope with insect attacks. The evidence in this study would support this because the highest productivity had the lowest proportion of defoliation by insects (Figure 4.2). While Muzika and Liebhold (2000) consider the silvicultural actions that can alter the amount and persistence of forest defoliators, the concept that trees with all the nutrients and water

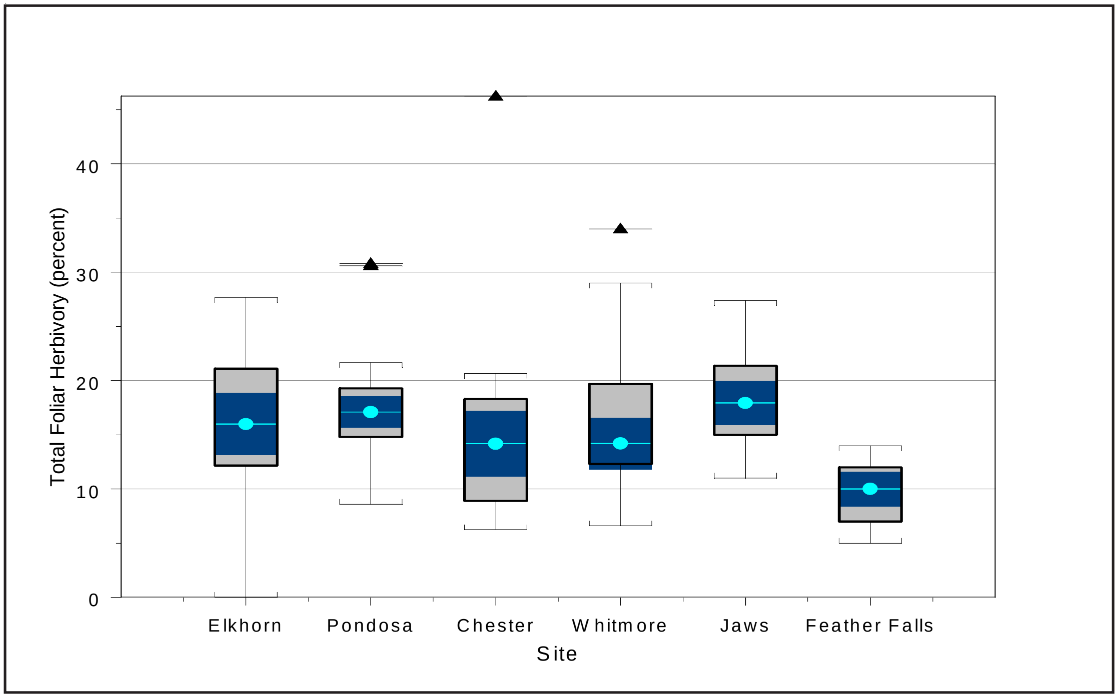

Figure 4.2: Foliar herbivory by site. Site productivity increases left to right. Feather Falls has a statistically significant mean from all other sites ($p<0.05$).

needed would be more resilient to insect attack would lead to a hypothesis that the treatments receiving fertilizer would increase the trees’ ability to withstand attacks through secondary metabolites. Additionally, plots where vegetation is controlled would be under less water stress and would therefore be more likely to respond to attacks. However, there was no treatment effect observed in the herbivory data.

While Alfaro et al. (2001) found that medium productivity sites (15m-25m/50 yrs) were more susceptible to spruce budworm, Wagner and Zhang (1993) found that lower soluble nitrogen levels increased sawfly resistance on ponderosa pine. Higher levels of nitrogen are found in the higher productivity installations in the Garden of Eden study (Powers and Reynolds 1999). This would suggest that an increase in the amount of nutrients in the foliage, caused by fertilization, may cause the foliage to become more desirable to defoliators and increase the level of herbivory. The findings in the current study do not support this. While the higher productivity installations had a greater level of foliar nitrogen (Powers and Reynolds 1999), they also had a lower percentage of herbivory. Herms (2002) surveyed available literature and concluded that fertilization does not enhance a plants’ ability to cope with defoliator attacks. Increased foliage desirableness and redistribution of plant nutrients related to increased growth would suggest that the fertilized trees would have increased amounts of defoliation.

Some studies show that fertilizer increases resilience and others suggest that it is decreased, but the current study shows that there is no statistical effect of fertilization.

Björkman et al. (1991) also showed that herbivory did not respond significantly to fertilization.

The insecticide treatment, which was converted to a thinning treatment, had no effect on the amount of defoliation. This is probably due to the length of time that passed between the final insecticide treatment and the time that assessment took place.

To make the insecticide a valid treatment there was an attempt to locate the installations in areas that had background populations of tree-feeding insects. While some arthropods were present, they were never in large quantities sufficient to affect plant growth. In fact, the insecticide-containing treatments produced no significantly different growth than the related treatments (i.e. HI vs. H, C vs. I) at any of the installations, thus suggesting that the growth was not related to the historical insecticide treatment. Even when the thinning treatment is considered, the short time span and general lack of crown closure would limit the effect of a thinning and change in resource availability in these plots.

Gouty Pitch Midge:

Of the arthropods that were observed and quantified in the Garden of Eden study, the gouty pitch midge was among the most prevalent and visually obvious. The midge attacks trees at lower site index installations. This is further supported by the environmental variables that were analyzed, showing that drier, warmer and higher installations were all attacked more than more moderate areas. The percentages of infection were close to those found by Hoff (1988) in his study of pitch midge impacts on province trials in northern Idaho. The maximum percentage found in the current study was five percent as a plot mean at Elkhorn Ridge; Hoff observed that the mean damage level was five percent in his northern Idaho study. Additionally, Hoff found that there was minimal relationship between the height of the trees and the amount of attack, indicating that it was possible to have attacks at the various installations given the right conditions.

Other observations of plantation studies have shown that stands with higher level of brush competition have higher levels of attack (McDonald and Fiddler 1989). Oliver (1984) also found that the midge was positively correlated to the amount of brush with up to 60 percent of the branches and leaders affected in northern California. In contrast, the present study did not reveal a significant difference in the amount of infestation among different treatments. Given previous findings it would be expected that the control and non-vegetation-controlled plots would have had the highest levels of attack. In the current study, the highest level of impact was found at Elkhorn Ridge, which had very short trees, densely crowded by shrubs.

Resistance to the midge has previously been associated with new shoot characteristics, with more viscid, resinous shoots attacked more often (Duffield 1985, Hoff 1988). Previous studies have suggested that this is a genetic trait in ponderosa pine passed on from parent to offspring (Hoff 1988). Further investigation of this would be appropriate in common garden studies at various environmental conditions and levels of shrub competition.

Overall, there is a very limited amount of previous research on the impact of gouty pitch midge despite its ability to cause a significant amount of branch death during an outbreak. Future research should investigate conditions that are favored by the insect and what tree traits are the most likely to influence the level of attack. Research into the basic biology, habits, and preferences of the midge would be appropriate since there is a limited amount of literature on the subject and much of what is available focuses on resistance of the host.

Sequoia Pitch Moth:

Pitch moths cause globules of pitch to be exuded from injuries to the cambium of branches and boles of two- and three-needle pines (Furniss and Carolin 1977). The larvae feed on the phloem and can cause points of stem breakage in small trees. In the present study a difference was observed between the installations and between treatments and treatment installation interactions. In a comparison of the installations, the Sierra Nevada installations were less attacked than those in the Cascade or Klamath mountains. More attacks were observed in treatments that had higher tree volume growth. Trees that have optimum growing conditions have higher radial growth rates (Powers and Reynolds 1999), indicating that there would be higher phloem produced and more pitch in the trees which would favor the pitch moth larvae. Open grown trees in plantations and on forest edges appear to be more susceptible (Wu and Ying 1997), which is consistent with observations of the canopy structure in this study. The installations with the least crown closure had the highest incidence of pitch moths. These installations also had a higher level of gouty pitch midge incidence. While no link has been made between these two cambium feeding insects, there may be an association.

Several studies have seen correlations between pitch moths and injuries to the trees from pruning (Powers and Sundahl 1973) and also rust and pitch moth resistance (Wu and Ying 1997). Dix et al. (1996) found a negative correlation between the infection of western gall rust and the occurrence of pitch moths, proposing that the gall rust might alter the physiology of the tree in a way that would discourage the impact of pitch moths. This is supported by the current study; the installation with the highest level of rust infection had the lowest levels of sequoia pitch moth (Figure 4.3). Both Feather Falls and Chester had the lowest levels of pitch moth and the highest levels of gall rust. This contradicts results reported by Rocchini et al. (1999) who found a strong association between rust infections and the occurrence of pitch moths in British Columbia, Canada.

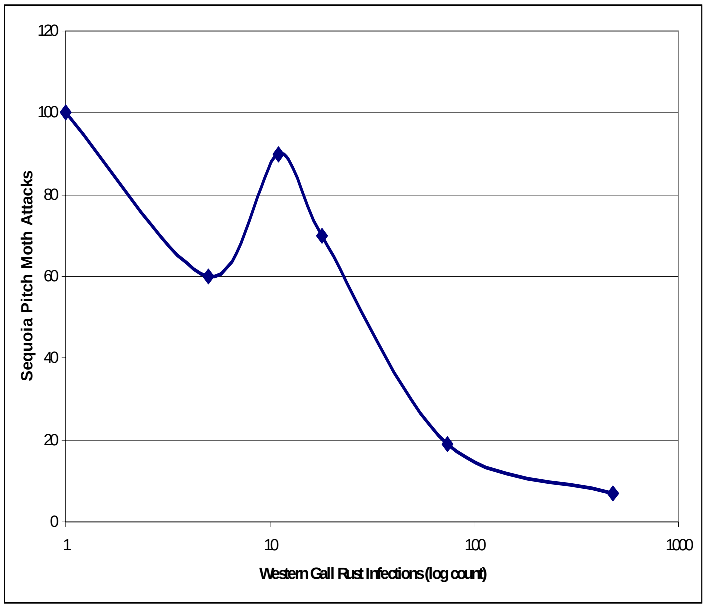

Figure 4.3: Sequoia pitch moths attacks plotted against western gall rust infections. Gall rust is presented on a log scale. Diamonds represent study sites.

The significance of treatment differences should not be understated, since this is the only study variable considered that had strong treatment effects ($p<0.05$). The treatments that were attacked most intensively were those with vegetation control. This may be because the decrease in moisture stress in these plots would allow stomata to remain open longer and increase the amount of moisture movement through the tree. It appears that the best growing trees at each installation are also the most likely to have a high level of pitch moth attack even though the pitch moth was most abundant at the lowest productivity installation. The treatment with the herbicide, fertilizer and thinning had the highest occurrence, while the herbicide alone treatment had the highest mean occurrence of pitch moth indicators.

Environmental variables that were important in the pitch moth analysis were the mean annual temperature, elevation, and site index. As each of these variables increased, the level of pitch moth occurrence decreased. Installations on or near the valley floor may experience temperatures that are high enough to be detrimental to the pitch moth larvae (Furniss and Carolin 1977), while high elevations with significant periods below freezing may have had an adverse impact on the larvae due to the two-year life stage. As site index increases the larvae may be pushed out of the cambium due to excessive pitch flow. Additional research that would be helpful would be an exploration of the relationship between sap flow and pitch moth attack, as this would illuminate the conditions that the larvae prefer.

Management of stands to control pitch moths is seemingly difficult because their occurrence appears to contradict the general goals of most forest management (to grow trees quickly and large). Where managers may want to use fertilizers, thinning, or pruning to increase growth, they should be aware that these are actions that may increase the levels of pitch moths. Where fire breaks are being constructed the combustible pitch on the boles of the trees, especially around pruning wounds can become a major issue (Power and Sundahl 1973). Efforts such as applying insecticides to pruned trees or using pheromone traps to decrease the level of moths would be possible actions to take. Pruning in the late fall to early winter would also allow time for the wounds to heal and decrease the attraction to the tree.

Total Foliar Pathogens:

Foliar pathogens are a concern throughout the world. Whether it is Swiss needle cast in the Pacific Northwest on Douglas-fir (Hansen et al. 2000) or dothistroma needle blight on lodgepole pine in British Columbia (Woods et al. 2005) they reduce productivity and are capable of killing trees. With this in mind it is important to determine the impact of installation and treatment on infection by foliar pathogens. The results from this study show that the site productivity is important in the amount of foliar pathogens, but treatment was not statistically significant. This leads to the conclusion that fertilization, vegetation control and thinning/insecticide do little to ameliorate foliage infection. This is in contrast to previous studies that have shown thinning to be an appropriate method for controlling foliar pathogens (Hansen and Lewis 1997). While treatment may not be important, the higher productivity installations had higher levels of infection in contrast to the gouty pitch midge and sequoia pitch moth.

Dothistroma needle blight has had large and significant impacts throughout the world, including large scale impacts in British Columbia on lodgepole pine (Woods et al. 2005). In this study, installations that are at the lowest elevations and had higher temperatures had an increased incidence of infection than higher elevation, drier installations. There appears to be a location effect on foliar pathogen that may be related to the precipitation patterns and topography. The installations that are in a rain shadow had lower levels of infection while those that are on the windward side or centrally located had a higher proportion of infected needles, up to 23 percent in the Klamath Mountains. An increase in elevation resulted in decreasing infection levels, indicating that there is an aspect of the difference in elevation that is not captured by the precipitation amount or mean temperature.

Foliar pathogens are often closely related to weather. Woods et al. (2005) found a relationship between an increasing amount of warm rain events and an epidemic of dothistroma needle blight in British Columbia. While northern California is a xeric climate, current models of the global climate predict that warmer, wetter winters will be likely and that summer months may be droughtier. If this is the case, foliar pathogens may respond with a large increase due to a constant growing season and an ability to produce even more inoculum (Kliejunas et al. 2008).

The disease triangle is a good model to consider when there are many different variables, placing the pathogen in one corner, climate and environment in the other corner, and the host in the last (Schumann and D’Arcy 2006). The environment is likely becoming more favorable to foliar pathogens (Woods et al. 2005) and the pathogens are present, if only at low levels. The final corner is the predominance of forest plantations as monocultures in modern forestry. It is very difficult to control outbreaks of foliar pathogens that do not require alternate hosts and are spread easily from tree to tree in monoculture stands. Forest managers who are concerned about the threat of foliar pathogens should use mixed species forestry and resistant planting stock.

Western Gall Rust:

While often not considered to be a major forest pathogen on ponderosa pine in northern California, western gall rust has a much larger impact on lodgepole pine in western Canada (van der Kamp 1994) and has become a concern in Australia and New Zealand where a substantial amount of susceptible radiata pine is grown but where the rust is not currently present (Old 1981, Ramsfield et al. 2007). Western gall rust is autoecious and does not require an alternate host. Many other rusts require an alternate host (i.e. comandra blister rust, white pine blister rust), but gall rust moves from pine to pine without a secondary host. The result is that western gall rust is able to spread quickly and effectively through a stand under the right climatic conditions.

Installation had a strong relationship with the amount of infection. Feather Falls had the highest number of galls with 477. This was 414 more than the next highest installation (Figure 3.9). There appears to be a set of environmental variables that makes this area a higher risk for gall rust. Observations of other research plots near Feather Falls indicates that gall rust is common in the area (personal observation).

The degree of infection by gall rust has been reported to be associated with a period of leaf wetness, spore density and temperature (Old 1981), and in particular environmental gradients including elevation and topographical aspect changes (Bella and Navratil 1988). This is an important consideration because the results of Bella and Navratil (1988) and Hoff (1990) indicated that the elevation band between 1200 meters and 1400 meters had the highest level of infection in west-central Alberta, Canada. In the current study, there was a higher level of infection at Feather Falls, 1220 meters, than at any of the other six installations. While aspect was not a variable in this study, it may play an important role, especially considering orographic lifting and differences in microclimate features.

Treatments had a mixture of effects on the amount of gall rust. While the control had a plot mean of 3.7 galls, the FI, HF and HI treatments all significantly increased the amount of galls per plot. These treatments may have had greater infection because of greater air movement resulting from a decrease in understory vegetation in the "H" plots and a more open structure in the "I" plots. Other studies that describe micro climate and air flow as an important variable in the incidence of the disease support this idea (Old 1981, Blenis et al. 1993). Biologically, the increase was rather small, an increase of only 84-210 galls per hectare, with 1680 trees per hectare. In this context there is no reason to encourage the use of one treatment over another in the management of western gall rust, as it appears to be related to the installation more than any other factor.

Environmental variables are the most evident driving forces in the amount of gall rust infection. This has been reported by Bella and Navratil (1988) and Hoff (1990) who found elevation to be important, Peterson (1971) described summer rains as important, and Chang et al. (1989) described a relationship between sunlight, wind, and vapor pressure deficit. In the present study, elevation, mean annual temperature and site index all had positively correlated relationships with the amount of infection.

Gall rust resistance has been described as a maturation-related phenomena, as the result of a difference in the microclimate as the crown rises (van der Kamp 1988). Others suggest that there is a chemical change in exudates and chemicals that are released by the trees as they mature. Other studies (Hoff 1990, Egan and Merrill 1997) have observed genetic differences between populations suggesting that there is a genetic component to rust resistance. In personal observations during this study, it was observed that there were some heavily infected trees that had branches mixed together with trees that had no galls at all. This suggests that there may be a significant level of resistance in some individuals, and resistance breeding might be effective.

Petterson (1971) described a year, or a couple of years, of high infection as a wave year. In this analysis of the age of galls, the year with the most galls was 1997 (Figure 4.4). For this study it is a wave year because it had a statistically significant greater number of galls established than most other years in the study (12 out of 17 years $p<0.05$). Compared to data for El Niño Southern Ocean Events (Figure 4.4), 1997 is a very strong El Niño. Looking back at previous studies, additional wave years were seen in 1957 (Petterson 1971), 1971 (Bella and Narvatil 1988), 1975-76 (van der Kamp 1988), and 1990 (van der Kamp 1994, van der Kamp et al. 1995). Comparing the wave year events to the El Niño data, 1957 was an important year ending the 1950's drought and signaling a shift in the long pattern of decadal oscillations in climate cycles to annual variation. And 1997 leading into 1998 saw another strong shift to a drier time period (personal communication with Ron Nielson). While these events are pronounced and coincide very well with wave years, the others are less clear: 1971 is regarded as a La Niña event, 1976 is a weak El Niño event, and 1990 is seen as normal year with no southern ocean event.

Precipitation values from northern California for the same time period are weakly negatively correlated to the Oceanic Niño Index (Figure 4.5). This suggests that an aspect of El Niño events may alter the environment in ways other than the amount of precipitation.

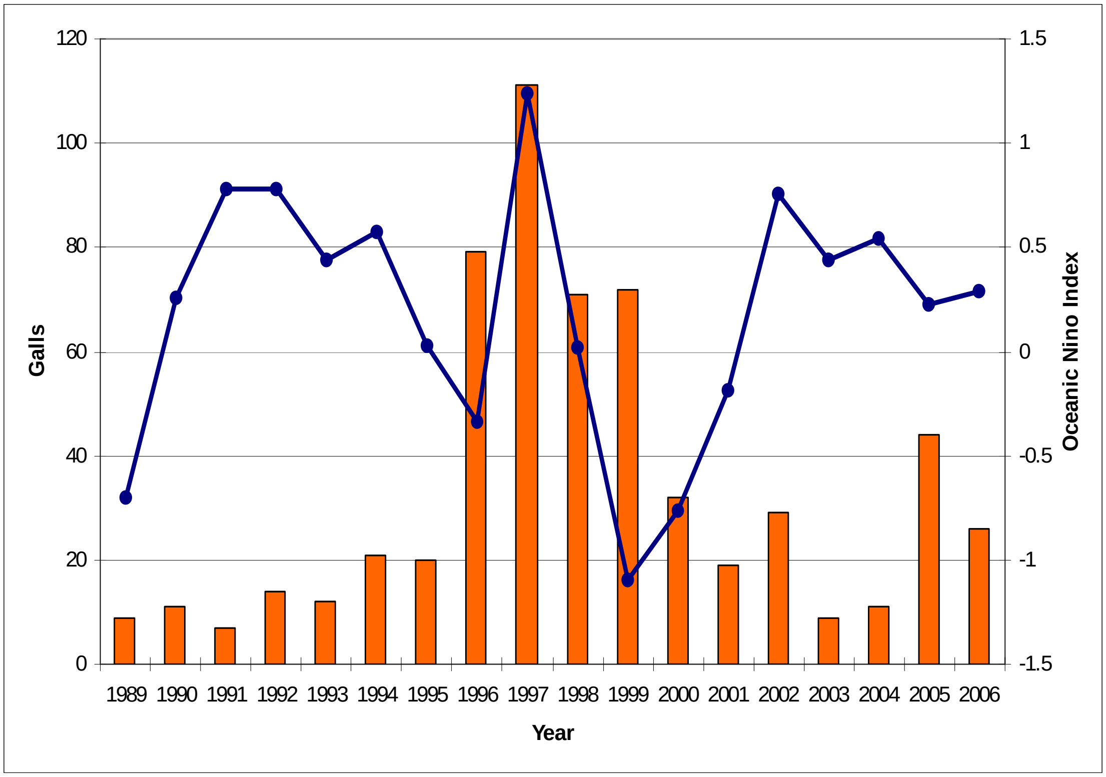

Figure 4.4: Gall count (bars, left axis) by year with Oceanic Niño Index (line, sea surface temperature anomalies between 5°N-5°S and 120°W and 170°W) on the right axis. ONI above 0.5 indicate an El Niño trend and values below -0.5 indicate a La Niña trend.

These may include timing of precipitation or direction of storm tracks. However, increases in gall rust incidence appear to follow periods of increased precipitation at the study installations (Figure 4.6). This leads to the assumption that these periods of higher precipitation alter the environment in a manner that allows for greater spore production, release, or movement or that the increase in available moisture allowed the hosts to increase the susceptible surface area.

It is possible to make a connection between wave years of western gall rust and El Niño patterns, but more research should be conducted to clarify any connections. This would include an analysis of the different weather patterns that arise due to southern ocean events in the different study locations, which could be located around western North America. Additionally, a further review of the literature to identify any other proposed wave years would be helpful and lead to a greater confidence in the findings.

The management of western gall rust has generally been to ignore it or to prune, thin or harvest infected parts of trees and stands (Old 1981). While there does not appear to be any advantage or disadvantage to fertilizing, thinning, or vegetation control,

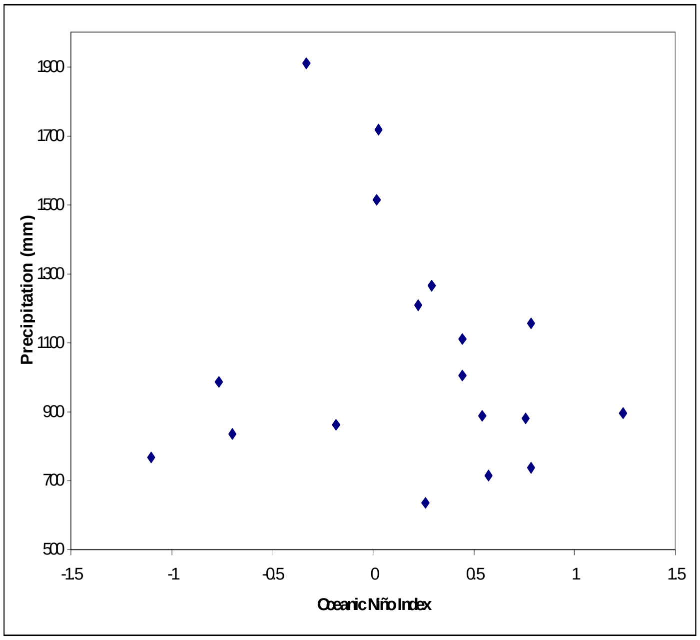

Figure 4.5: Precipitation amount (mm) compared to ONI values for the period 1989 to 1996.

it would be wise for forest managers to consider this potentially important disease in the selection of species and the location of the planting. Blenis and Duncan (1997) proposed that delayed thinning in lodgepole pine to remove trees with infections would be an appropriate management tool. With a predominance of monoculture plantations, this pine to pine rust has the potential to impact a great number of hectares given the proper environment (Hansen and Lewis 1997). Much like the foliar pathogens that are capable of responding very quickly to a change in atmospheric conditions, western gall rust should be capable of rapidly spreading through a large area (Old 1981). Most resistance research has shown that, as soon as trees are more than 20 years of age, they are relatively resistant to gall rust infection (Zagory and Libby 1985). However, personal observation leads me to believe that this is not entirely true for trees that are planted off site and in exotic environments.

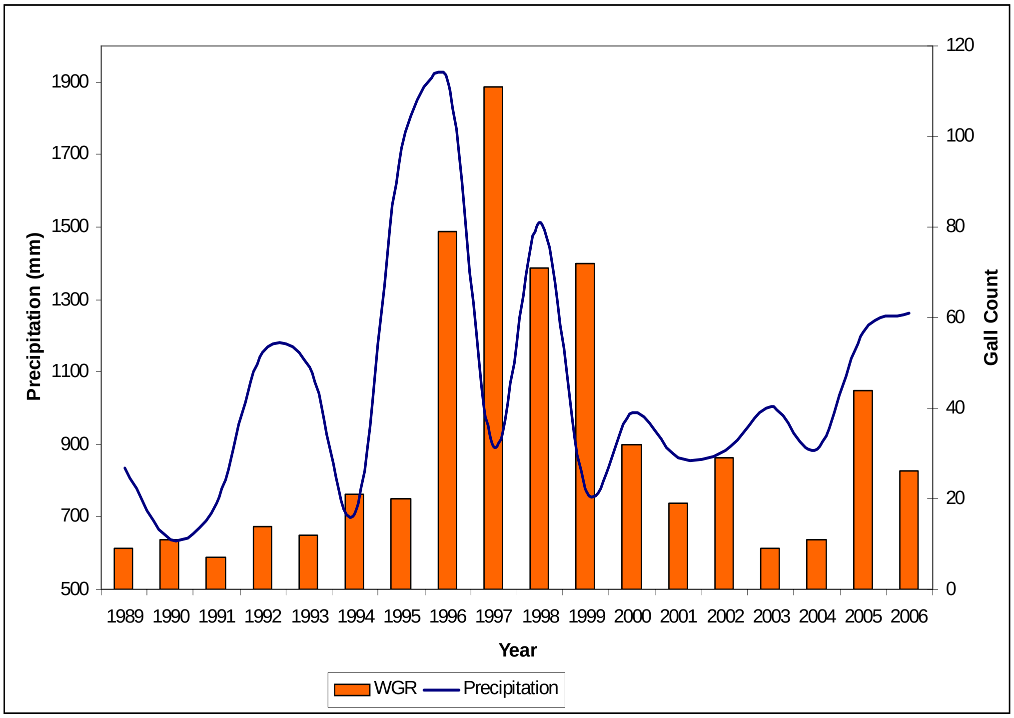

Figure 4.6: Mean precipitation of the six study sites (line) and gall rust incidence for all six sites (columns) by year between 1989 and 2006.

Chapter 5: Conclusion

Forest health is an important part of all forest ecosystems. This is true in mixed natural forests and monoculture plantations. However, the management of the latter becomes more difficult relative to dealing with harmful agents because of the large proportion of susceptible host species. This study has shown that the location of different ponderosa plantations plays a very large role in determining what pests and pathogens are present (Figure 5.1). The site productivity and the ecological characteristics that make up site index are very important. It has also shown that there is little evidence that vegetation control, fertilization, and insecticides contribute any meaningful impact on the presence or absence of either insects or pathogens (Figure 5.1). While these may be important treatments in a silvicultural system and prescription, managers can be less concerned about how they will affect forest health. Commercial thinnings are a little more of a concern as previous studies have shown an association between the amount of forest health issues in thinnings due to residual stand damage, wounds, and soil compaction. However, this was not observed in this study due to the pre-commercial size of the trees when thinning occurred and the care that was taken in the operation.

Treatments seem to create a better environment for western gall rust; either for the trees, creating larger targets, or by creating a microclimate optimal for the fungus. Wave years are a well-documented occurrence throughout the range of western gall rust. Several studies have pointed out that there were years that had abnormally high levels of infection. There has been little research into the cause of wave years. This study presented evidence

Response	Site	Treatment	Site X Treatment	Site index	Elevation	Precipitation	Mean Temperature
Needle Retention	Yes	None	None	None	+	-	None
Total Foliar Herbivory	Yes	None	None	-	-	None	-
Gouty Pitch Midge	Yes	None	None	None	+	-	+
Sequoia Pitch Moth	Yes	Yes	Yes	-	-	None	-
Total Foliar Pathogens	Yes	None	None	None	-	None	None
Western Gall Rust	Yes	Yes	None	None	+	None	+

Figure 5.1: A comparison of the important variables in each of the responses that were measured. Site is important in all cases. Treatment is important to the sequoia pitch moth and western gall rust. No one environmental variable stands out and only elevation is important to all of the responses.

that wave years may be related to global climate patterns, especially El Niño, and asserts that there are weather cycles that influence the incidence of gall rust. However, there is only associative evidence for the occurrence of wave years correlated with southern ocean oscillations.

Foliar pathogens are a concern throughout the world. This remains the case in northern California and the rest of western North America. Their importance should not be underestimated due to the low levels that were observed in this study. While no treatment effect was observed in the present study, treatments may have an effect on sites that are experiencing epidemics of disease. Due to the strong relationship between fungal pathogens and climatic conditions, it is not surprising that there were installation differences observed.

With the general consensus in the scientific community that the global climate is changing, and generally warming, there could be an increase in pathogens and insects throughout western North America. We may already be seeing this in British Columbia, the Rocky Mountains and the southwestern United States as there are epidemics of dothistroma (Woods et al 2005), bark beetles and massive piñon die back (Anonymous USFS 2005), respectively. The general model currently shows that there could be a warming in the winter months with increased moisture during winter and spring. This could very well promote the growth of fungal pathogens and drier summers would put an added stress on trees allowing some insect populations to increase with detrimental effects to forests.

Scientifically, this study has advanced the knowledge of how plantation forest practices impact a variety of different insects and pathogens. Generally, there do not appear to be significant treatment effects within any of the study installations. Biologically there is a very small proportion of the trees that were affected by pests or pathogens. In most cases there was only a single digit percent of the foliage, trees, or branches that were affected. This should have a small if not negligible impact on the growth of the trees. However, it is important to realize that these organisms are present and the potential for their spread may increase in the future. Therefore, there should continue to be an interest in the scientific and forestry communities to address these issues as dynamic systems change.

Management strategies that could help to deal with the organisms seen in this study are relatively simple. There should be an attempt to limit the amount of susceptible species and hosts in an area that is experiencing high levels of forest health issues. In the case of the gouty pitch midge, periodic application of insecticide, appropriately timed to do the insects the most damage, may be able to reduce the population substantially. Additionally, using stock that is more resistant to the midge would be advisable. As was reported there are some families that appear to be somewhat resistant to the midges due to an increased level of branch exudates. Sequoia pitch moth infestations can cause very large levels of pitch to be exuded from the bole of susceptible trees. In the case of fuel breaks there should be an attempt to minimize the number of pitch moth attacks. This is also important due to the attraction of bark beetles to similar situations. Foliar herbivory appears to be more of an issue on less productive sites at environmental extremes. This could cause plantation degradation in areas that experience a significant level of competition, drought, or other stress on the trees due to the additional defoliation and decrease in competitiveness.

This study showed that ponderosa pine plantations in northern California have a certain amount of pests and pathogens present at all installations. This was not a high level and is probably not affecting the growth and yield of the plantations. It does demonstrate that the possibility exists for an increase in the infection and infestation rate and amount if conditions change such as the suspected link between general warming and the outbreak of dothistroma needle blight in Canada. This should be anticipated and planned for as these are dynamic systems that are ever changing and the current climate situation means extra care should be taken in this consideration.

After consideration of the initial hypotheses (Table 5.1), needle retention did decrease with increasing site productivity. Total foliar herbivory did not increase with site productivity and increased as temperatures rose and elevation fell. Sequoia pitch moth was lower with site productivity, although treatments that increased growth tended to increase pitch moth attacks. The gouty pitch midge was the highest at the low productivity installations and the highest elevation installations. Foliar pathogens were higher at high productivity installations, although there was no treatment effect. There was only an associative relationship between the observed wave year and an El Niño event.

Table 5.1: Comparison of initial hypotheses to final conclusions.

Needle Retention	Decrease with site productivity, no treatment effect. Reject null hypothesis
Total Foliar Herbivory	Lowest at highest site, increased with higher temperature and lower elevation. Cannot reject null hypothesis
Sequoia Pitch Moth	Lower with higher site productivity, treatments that increased growth tended to increase pitch moth attacks. Reject null hypothesis
Gouty Pitch Midge	Highest at low productivity sites and highest elevation sites. Cannot reject null hypothesis
Total Foliar Pathogens	Higher at high productivity sites, no treatment effect. Higher elevations decreased infection. Weakly reject null hypothesis
Western Gall Rust	Highest at most productive sites. Only associative relationship between observed wave year and an El Niño event. Reject null hypothesis

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