Soils as a factor in Pinyon Pine mortality due to Ips Beetle infestation in Garden Park, Colorado: a case study.

By

Jeffrey R. Krecic

Submitted to the Department of Geography

and the Faculty of the Graduate School of the University of Kansas

In partial fulfillment of the requirements for the degree of

Master's of Arts

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Chairperson

Committee Members ______________________________

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Date Defended ______________________________

The Thesis Committee for Jeffrey R. Krecic certifies

That this is the approved Version of the following thesis:

Soils as a factor in Pinyon Pine mortality due to Ips Beetle infestation in Garden Park, Colorado: a case study.

Committee:

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Date approved:____________________

Abstract

Observations by European settlers indicate that the distribution of pinyon – juniper woodlands has been expanding in the southwestern United States over the last two centuries. Beginning in the late 1990s, drought conditions in the region, along with ips beetle infestations have led to destruction of entire viewsheds of pinyon pine trees. The reduced availability of moisture associated with drought stresses pinyon pines and reduces their ability to resist ips beetle infestation. They are unable to produce the sap necessary to pitch out the boring beetles and succumb to beetle larvae that hatch beneath the bark of affected trees. These woodlands exist on a marginal environment where slight variations in the moisture balance affect the survivability of such trees. Factors such as elevation, slope, aspect, tree density and soil properties affect the moisture availability of the trees. This study looks at the nature of soil as a possible factor in a tree's ability to resist ips beetle infestation. Trees situated on deeper, richer soils with greater water holding capacity and shallower slope were expected to show an increased resistance to ips beetle infestation. The results of this research, however, did not show any statistically significant difference between the soil conditions at infested and uninfected sites. This finding leads to speculation that after some as of yet unknown point in a drought cycle, even those trees on the best soils are susceptible to beetle infestation and cannot survive.

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Problem Statement

This thesis deals with the issue of widespread die-off of pinyon pine trees in south central Colorado. Specifically, since it is well understood that pinyon pine die as a result of ips beetle infestation, this research examines the potential role of soil moisture stress as a contributing variable to tree mortality.

Background

The United States is facing an epidemic of bark beetle infestations. There are several species of bark beetles, each associated with a different host tree. An analysis of each species of bark beetle is beyond the scope of this paper, rather this research focuses on the ips beetle and its host tree, the pinyon pine. Pinyon-Juniper (P-J) woodlands represent the third largest vegetation type in the United States. It is the most common vegetation type in the American Southwest, covering 10 states and part of northern Mexico (Shaw 2005). P-J covers 35.5% of the Colorado Plateau and approximately 30 million hectares in the Southwestern United States. It is widespread in the southern Rocky Mountain physiographic province in Colorado (Hraber 2007). Figure 1 shows the extent of P-J woodland in Colorado.

Opinions vary as to whether pinyon-junipers are an invasive pest to rangeland or are a valuable resource. Research of historical documents, tree rings and other proxy data indicate that PJ woodlands were once more “savanna like” than they are currently (West 1988). However, ranchers introduced livestock, which fed on the perennial grasses. Grasses act as a distribution mechanism for wildfires. The wildfires thin the trees and rejuvenate the grasslands (York *et al.* 1994). With the grasses thinned by overgrazing and soil erosion, the fires have difficulty spreading until the crowns of the trees are close enough to bridge the gap. When this change in vegetation occurs the nature of the fire has changed from a brush fire to a forest fire. It has a much greater fuel load, burns hotter and is more difficult to contain. Active fire fighting, as well as fire breaks such as roads, contributed to the transition of savanna to the dense P-J woodland we see almost universally today. Trees, unaffected by the grazing herbivores, increased canopy size and further reduced undergrowth (York *et al.* 1994). Soil erosion is accelerated without herbaceous vegetation to hold it in place. Once topsoil has eroded it is difficult for grasses to reestablish, even if the trees are removed. These factors have combined to create an environment of high-density PJ woodlands with little understory.

Figure 1. Extent of Pinyon-Juniper woodland in Colorado

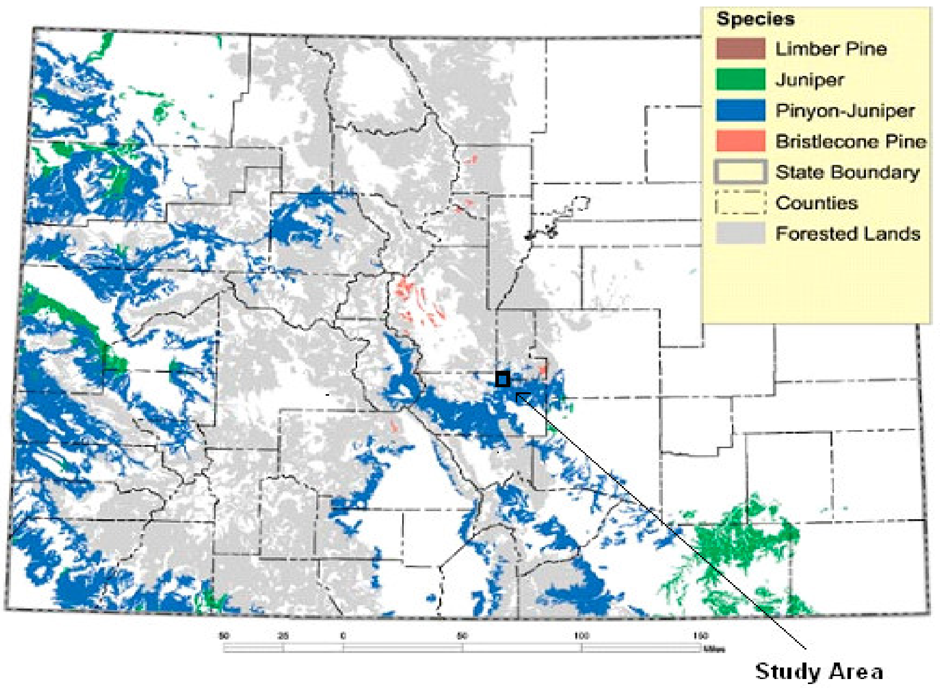


Image by: Colorado State Forest Service (CSU 2007)

In PJ woodlands two types of pines dominate: the pinyon pine, *pinus edulis* (Engelm) and the singleleaf pinyon, *pinus monophylla.* Both trees are very slow growing. In Colorado, *pinus edulis* is the pine component in the PJ woodland. Pinyons are coniferous, native evergreens that grow 10 to 50 feet tall. Ranchers consider the pinyon pine a pest species while Native Americans value the seeds (nuts) produced by the trees. The pine nut has been a stable of the Native American diet in the southwest United States for centuries. Pine nuts are very nutritious, with a single nut providing as much as 20 calories. They are 50% fat, 25% carbohydrates, and 25% protein (Bryce 2007). Despite an overabundance of pinyon pines there is little commercial pine nut harvesting in the United States. Most pine nuts found in grocery stores in the US come from China (Delco *et al.*1993).

Pinyon pines are easily killed by fire due to their relatively thin bark, flammable foliage and accumulation of dead lower branches (CSU 2007). Historically, frequent fires, often set by lightning, have been an important factor in reducing the density and distribution of P-J in the study region. With the advent of fire control, mechanical processes such as chaining - described later in this chapter - were used to thin P-J woodlands.

The Rocky Mountain Juniper, *juniperus scopulorum*, is the other major component of the PJ woodlands. It is also an evergreen but produces small blue-gray berries instead of nuts. These berries are not edible to humans. Junipers grow 20 to 50 feet tall, and have thin bark, and resinous wood that makes them very flammable (CSU 2007).

Distribution of pinyon pines and junipers vary within a P-J woodland. Pinyon pines tend to dominate at elevations above 7,000 feet with pure stands found at the upper elevation limits around 9,000 feet. Below 7,000, feet junipers dominate, with pure stands found at the lower elevations around 5,000 feet (Tausch *et al.* 1981). This pattern will vary with local climatic conditions and latitude.

Research by Colorado State University indicates reestablishment of the pinyon-juniper stands is by dispersal of seeds, usually by rodents and birds. This process is very slow with mature woodlands taking 60 to 100 years to reestablish (CSU 2007). Much of Garden Park is a dense pinyon-juniper forest of young to mature trees of stunted, shrub-like growth. Large, mature pinyon pines with tree-like growth were likely harvested for construction or firewood years ago.

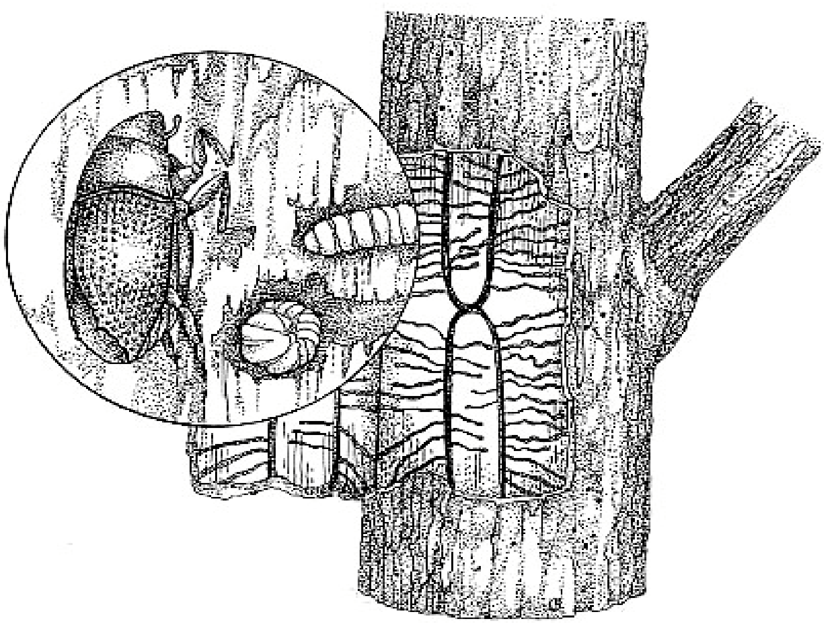
Ips beetles are a collection of bark beetles that infest pine and spruce trees. There are 11 species of ips beetles in Colorado, each associated with a different host tree species, always an evergreen (CSU 2007). This research focuses on *Ips confusus* which predominately attack pinyon pines. On occasion, they have been known to infest other pines.

Also know as "engraver beetles," ips beetles are not as destructive as other bark beetles (CSU 2007). Bark beetles such as mountain pine beetle, Douglas-fir beetle, and spruce beetle have been widely studied. The trees they infest are a valuable commodity to the timber industry. The bark beetles will attack healthy trees and have reached epidemic proportions throughout many western states and Canada. Ips beetles normally only attack trees that have been weakened. This weak condition may be due to wounding, root disease or other stresses. In areas where the beetle has established a significant foothold, the beetle may attack healthy trees. In some areas of the southwestern United States under severe drought conditions, ips beetles have reached epidemic proportions, destroying entire viewsheds. Neither group of beetles is a threat to deciduous trees. Both varieties are indigenous to North America (CSU 2007).

The ips beetle is about 1/8 to 3/8 inch long and is black to reddish-brown (CSU 2007). In the spring male beetles will bore through the bark of the pine tree. If the tree is healthy it will "pitch out" the beetle by creating enough sticky sap to engulf the beetle and push it out the bore hole. If the tree lacks the sap to pitch the male out, he will bore out a cavity in the phloem known as a nuptial chamber. The male will then produce pheromones to attract females, usually around three. The females excavate egg galleries radiating from the central chamber and lay their eggs. The radiating tunnels usually form "Y" or "H" patterns in the phloem (see Figure 2). The eggs hatch and the larvae begin tunneling smaller galleries in the sapwood. The larvae are ¼ inch long, white to gray legless grubs. When they mature they will fly off to infest new trees. Depending on the climate, two to four generations of beetles develop a year. Over the winter the beetles lie dormant under the bark or in litter at the base of trees. A harsh winter can lead to high ips beetle mortality. A mild winter means low mortality and possibly more breeding cycles per year (CSU 2007).

Infestation by ips beetles may not always kill the trees. Sometimes only parts of the trees are infested, but the tree survives (CSU 2007). A tree weakened by one infestation, however, may become infested again at a later date and die. More often the beetles do not kill the trees, but rather an associated fungus causes the tree to die. *Ophiostoma minus* is a blue stain fungus transported by the beetles. Fungal spores attach to the beetle's body and are distributed from tree to tree. As the beetles tunnel throughout the tree thousands of fungal spores are dispersed in the phloem. From there the fungus quickly penetrates the sapwood clogging the vascular system and killing the tree (Virginia 2007). Another fungus, black stain root disease, may be transported by ips beetles or by direct root-to-root contact. This fungus also chokes off the vascular system, killing the trees (Hessburg *et al.* 1995).

Figure 2. IPS BEETLE, *Image by Kathy Borne*



Insect Identification Laboratory, Va. Tech, Blacksburg, VA . Copyrighted Image

The tell-tale sign of ips beetle infestation is boring dust at the base of the pine tree. Small holes in the bark indicate the beetles have completed a life cycle and the adults have left that part of the tree (Colorado 2007). The presence of woodpeckers may also indicate the presence of beetles, as they are a favorite prey of the birds (CSU 2007). Other signs, which may indicate a combination of beetle and fugal attack, are discoloration of the needle leaves, tufted growth and needle loss.

Attacks can be divided into 4 stages based on the color of the trees. The green stage lasts for two to three months after initial infestation. In this stage, the cellular structure of the foliage changes as a result of water deficiency. This is due to interrupted translocation caused by beetles mining in the phloem and fungus colonizing in the sapwood. While the tree may appear normal to the human eye, remote-sensing equipment may be able to detect a shift in the spectral signature. Stage two, the yellow attack stage, usually becomes apparent in the spring of the second year when the normally green foliage turns yellow. This discoloration is from the tree becoming chlorotic. Chlorosis is a condition where a plant takes on an abnormal yellow color due to a lack of chlorophyll production, and is caused by a nutrient deficiency or in this case a pathogen. Stage three, the red stage, is the result of increased chlorophyll degradation. The tree is dead at this point. Stage four, the gray stage, is when the dead needles are shed, leaving the gray bark branches and trunk exposed. This stage is usually reached two to three years after the initial infestation (Franklin *et al.* 2003).

The pinyon-juniper woodlands of southern Colorado are much denser than historical records indicate they have been in the last 200 years. The close proximity of the trees makes it easier for the beetle to travel from host to host. It also means more trees are competing for less water. Climatic studies indicate that over the last 10,000 years the southwestern United States has undergone multiple periods of drought. This region is currently in one of these drought periods. What makes this drought different from previous droughts is a simultaneous rise in temperature. Temperatures are on average 3ºF higher than during the drought of the 1950's (Hamashige 2005). The rising temperatures mean increased evapotransporation exacerbating the drought conditions.

The increase in tree density in the study area (Garden Park, CO) is a result of multiple factors. When settlers first arrived in the valley, it was predominately a low-density pinyon-juniper woodland, with trees numbering 30 to 90 per acre. Fires were part of the natural process of restricting the number of trees in the area. Since cattle do not graze on the trees and the trees shade out the grasses, cattle ranchers actively thinned P-J woodlands. Ranchers and the Bureau of Land Management (BLM) cut down the trees and, later, bulldozers were used to keep the tree numbers down in a process known as "chaining". Two bulldozers with a large ship's anchor chain attached between them would drive parallel to each other leveling the trees in between. The short-term effect of chaining is severe soil disturbance and erosion. The erosion becomes more acute on steeper slopes. However, as grasses become established, the erosion is reduced to levels lower then the original P-J forest (Blair 2001). The BLM and ranchers used chaining throughout Garden Park between 1959 and 1984. It was believed that removing the P-Js would facilitate the growth of grasses, reduce soils acidity and lower competition for water. Pressure by environmental groups, who see the process as destructive and antiquated, has brought a ban on chaining in most western states with the exception of Nevada and Utah (Blair 2001).

Ranching in the valley today has become less profitable and the mountain pastures have become less productive, requiring more acres per cow. Therefore, there are fewer cattle grazing the land. Without chaining and grass seeding, the mountain pastures have become covered in P-J. Also, as techniques in forest fire fighting became more advanced the trees grew more plentiful. The net result is a dramatic increase in trees per acre. In some locations there are several hundred P-J per acre instead of the usual 30-90 per acre. In other words, more trees are competing for less water. This creates dense forests of unhealthy trees, highly susceptible to beetle and fungal attack. The beetles and fungus are killing the trees, leaving a huge fuel load ripe for the next forest fire.

Wildfires occur naturally throughout the western United States. They play an important role in maintaining the ecological balance of vegetation. Wildfires maintain healthy forests by reducing accumulated fuels, recycling nutrients and reducing tree density. With the arrival of settlers, the larger trees were removed for construction and firewood. This created an environment of smaller, densely packed trees with a lower resistance to fire. The smaller trees also act as a ladder for fires to move into the canopy of larger trees. When a fire moves into the canopy it becomes more destructive and difficult to control (Smeins *et al.* 2007).

In 2002 Colorado experienced its worst wildfire season in history. 3,072 fires burned over 600,000 acres. 380 houses and 624 outbuildings were destroyed. There were $79.3 million in insurance claims and over $200 million spent on firefighting and emergency re-habitation (CSU 2007). Between 1970 and 2003 there were over a dozen wildfires in and around Garden Park. They ranged from as small as 0.1 acres too as large as the 64.9 acre Cooper Mountain fire of 2000 (Smeins *et al.* 2007). None of the sites chosen for this study were in areas affected by these fires.

In an effort to reduce fuel loads and therefore the risk for catastrophic wildfires, the BLM has implemented a program of vegetative treatment. Methods used to remove excess fuel and thin woodlands include prescribed burns, and mechanical treatments. Prescribed burns usually treat an area of 60 to 200 acres while mechanical treatments cover areas from 67 to 420 acres (Smeins *et al.* 2007). For P-J woodlands, mechanical treatment is preferred. Mechanical treatments commonly used include roller choppers, hydro-axes, chainsaws, and brush hogs. A roller chopper is a large barrel with 12-inch long blades across its length that is pulled behind a tractor (See figure 3). The barrel is very heavy, weighing 20,000 – 35,000 pounds, and can be filled with water to add more weight. The tractor usually has a blade at the front to topple the brush and trees. The roller chopper then chops up the slash. A hydro-axe is an articulated tractor with a large mower-mulcher blade attached to the front (See figure 3). It can effectively knock down and chop up brush and trees up to 8 inches in diameter. The tractor has large rubber tires and the mulch created reduces disturbance and compaction of the soil. Both the roller chopper and the hydro-axe can treat large areas with a small crew relatively quickly. However, the hydro-axe has greater flexibility and can be used where it is desirable to leave some trees standing (Zachman 2003). Where conditions are unfavorable for proscribed burns and heavy equipment, trees are removed manually with chainsaws.

Figure 3. A roller chopper (left) and a hydro-axe (right). Photos courtesy of the Colorado State Forest Service and Cory Cobertt.

Previous Research

Investigators have been examining the ecology of pinyon-juniper woodlands for decades in order to sort out the factors that account for their unique and changing characteristics through time. Among these factors are the competition among species and the environmental conditions that provide the habitat that they occupy. Principal among these factors of habitat and competition among species are mortality agents, soil moisture and nutrient availability.

Mortality Agents

There are four primary mortality agents affecting pinyon pines; the ips beetle, fire, black stain root disease (BSRD) and the blue stain fungus. Ips beetles and the fungus have a symbiotic relationship. The Ips beetles often infest trees that have already been stressed by BSRD and blue stain fungus. Ips beetles also act as vectors for pathogens such as BSRD and blue stain fungus (Kearns and Jacobi 2005). Fire has been a part of the natural process of thinning the trees and shrubs and enriching the soil for grasses. Both pinyon pines and junipers have a very low resistance to fire (See Figure 4). Due to a lack of wildfires, tree density is high and ips beetle infestations can become epidemic. All these mortality agents interact to effect the environmental conditions in a P-J woodland.

Fire is a major factor in reducing tree density in the pinyon-juniper woodland. Trees differ in their resilience to fires and their ability to repopulate after a fire. Figure 4 shows that pinyon pines have almost no resistance to fire. Even at maturity the bark is too thin to protect the cambium which is critical to the tree's survival. Junipers are little better with only low/medium resistance at maturity. Table 4 shows the fire resistance rating of the dominate tree species in Colorado. Investigation of a mid-nineteenth-century forest fire revealed that thirty-eight percent of the junipers survived while only 0.6 percent of the pinyon pines survived (Tausch 1988). Other species native to Colorado have much higher resistances to forest fire.

Figure 4. Colorado tree species fire resistance rating

Species	Size when fire resistance is gained	Fire resistance at maturity	Bark thickness at base of mature tree	Branch density	Bud size	Needle length
Pinyon Pine	None	Low	Thin	Low	Large	Short
Ponderosa Pine	Sapling/Pole	High	Thick	Medium	Large	Long
Lodgepole Pine	Mature	Medium	Very thin	Low	Medium	Short
Limber Pine	Mature	Medium	Thin	Low	Large	Long
Bristlecone Pine	Mature	Medium	Medium	Low	Medium	Long
Douglas-Fir	Pole	High	Thick	High	Medium	Medium
Subalpine Fir	None	Very low	Very thin	High	Medium	Medium
White Fir	Mature	Medium	Medium	High	Medium	Medium
Juniper	Mature	Low/Medium	Thin/Medium	Low	Small	Short
Colorado Blue Spruce	None	Low	Thin	High	Medium	Medium
Engelmann Spruce	None	Low	Thin	High	Medium	Medium

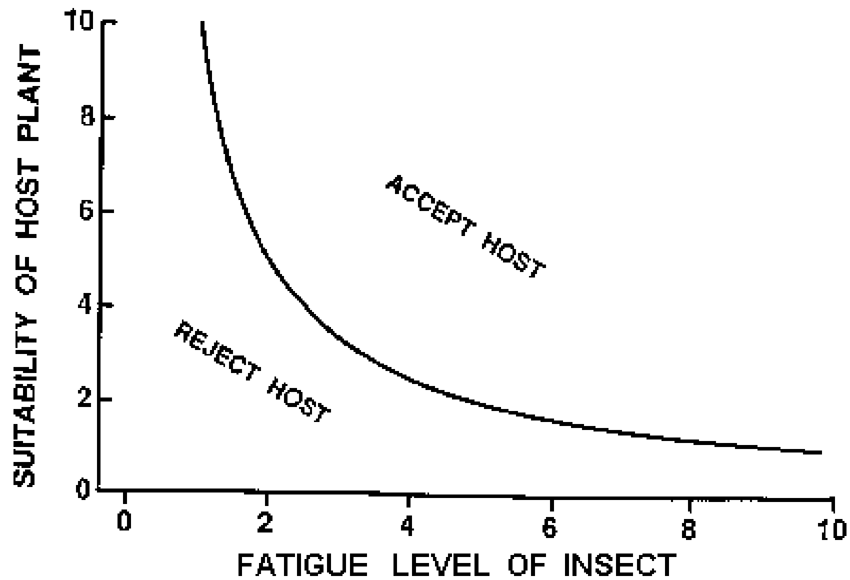
Sizes are defined as follows: saplings, 1-4 inches dbh; poles, 5-10 inches dbh; mature > 11 inches dbh. (dbh = diameter at breast hight) (Table adapted from Wildland Fire in Ecosystems: Effects of Fire on Flora, GTR RMRS-GTR-42-volume 2)

Black Stain Root Disease (BSRD) caused by the fungus, *Leptographium wageneri*, colonizes in water-conducting tissues of a tree's roots, collar and lower stem. BSRD blocks movement of water to the foliage. Infected trees will show characteristics of vascular wilt diseases. BSRD can kill saplings within a year and older trees within two to eight years. Work by Hessburg and others (1995) has looked at ips beetles as a vector for distribution of blue stain fungus and black stain root fungus. Research also reveals that soil type is not a factor in fungal development, although soil moisture is. The pathogen grows and distributes best during the spring and early summer months when there is the greatest amount of precipitation and snowmelt. Infection centers are areas of widespread BSRD impact. They typically have host trees in various stages of decline around the perimeter with dead trees in the interior. Infection centers are most distinct in dense stands where the host tree dominates. In areas of mixed species composition infection is less common. However, isolated trees or clumps can be infected and killed (Hessburg *et al.* 1995).

Ips beetles carry *Ophiostoma minus* or blue stain fungus. As the female tunnels through the phloem it introduces thousands of blue stain spores which establish throughout the phloem and then invade the sapwood. Blue Stain fungus feeds on the simple sugars and starches in the sapwood. It has no effect on the strength of the wood (Knaebe 2002).

The life cycle, range, habits, predators and effects of ips and bark beetles have been widely studied. Attention has focused more on mountain pine beetles due to their impact on the timber industry. John Byers (1995) has done detailed research on the beetle's life cycle, chemical response and fatigue level affecting infestation success. Indications are that some species of bark beetles require an initial flight period before they become attracted to the chemical stimuli indicating a suitable host tree. Stressed trees have a different chemical signature than healthy trees. The initial flight period and pine tree chemical signature suggest that proximity alone may not be a factor in host tree selection by ips beetles. Figure 5 shows the suitability curve of a beetle requiring an initial flight period. The curve would intersect the Y axis if the beetle does not require an initial flight period. Numbers 0 – 10 ten are hypothetical rankings. As the beetle flies around looking for a suitable host tree it becomes more fatigued. Byers study indicates that the beetle will pass up suitable host trees until it until it becomes tired. The more tired it become the less picky it is about a host.

Figure 5. Ips Beetle flight distance to host.



It is not certain if male beetles are attracted to chemicals produced by stressed or damaged trees or whether they randomly visit trees and check for suitability (Byers 1995). When they find a suitable host they release pheromones to attract female beetles. The distance a beetle can travel in search of a host is difficult to evaluate. Studies using marked beetles and sticky or pheromone traps show widely varying results. Some beetles have been recorded up to 46 km from their release points (Byers 1995). Factors such as species, habitat, winds and topography all effect resulting flight distances. Winds at the Garden Park valley shift several times a day with katabatic, anabatic and frontal winds. It would be difficult to evaluate the ability of any of these factors to distribute ips beetles.

While investigating the possibility that ips beetles are predisposed to pinyon pines that porcupines have damaged, Ilse and Hellgren (2007) found that chemical composition of trees was most important. They found that the beetles preferred trees with higher concentrations of fructose and glucose and lower amounts of limonene, sabenene, and terpnolene. While ips beetles colonized trees undamaged by porcupines, colonization was greater on damaged trees. They attributed the release of terpenes and the reallocation of carbon due to stress caused by porcupines feeding on the tree to the increased likelihood of colonization by ips beetles (Ilse 2007).

The availability of moisture directly affects the ability of pinyon pines to resist ips beetle infestations. Due to the tree canopy intercepting rainfall before it reaches the ground, inter-canopy spaces receive more moisture at ground level than under-canopy areas do. Work by David Breshears and others (1997) demonstrated that pinyon pines and junipers are able to extract water from shallow soils (less that 30cm) in inter-canopy locations. The root base of both species often extends well beyond the basal area. The research also showed that junipers were better able to extract the moisture from the inter-canopy soils than pinyon pines. In drought stress conditions, junipers exhibit higher levels of transpiration and photosynthesis than pinyon pines. They have higher water use efficiency and are therefore more drought resistant than pinyons. The ability of these two species to use shallow inter-canopy soil moisture influences the composition and spacing of P-J woodlands (Breshears *et al.*. 1997).

Junipers' greater efficiency in drought conditions may explain the greater proportion of juniper in a P-J woodland at lower elevations where precipitation is also lower.

Root systems of pinyon pines often spread well beyond the crown radius of the tree. Ips beetles prefer trees with a somewhat reduced root to crown ratio (Smeins 2007). This implies that trees with smaller root systems have less moisture available to them and are therefore more susceptible to ips beetles. Thus, tree density plays an important factor in ips beetle susceptibility. Species composition also plays a role. Those stands with a higher pinyon-to juniper composition are more susceptible to ips beetle infestation (Smeins 2007).

Neil Cobb and others (1994) looked at pinyon pines growing on different soils and examined genetic variation. They compared trees growing on severely water-and nutrient-poor cinder soil from Sunset Crater in Northern Arizona with trees growing on adjacent sandy-loam soil. By looking at the genotypic variations in glycerate dehydrogenase enzyme (GLY) locus among juvenile, intermediate and mature trees growing on the two soils they found that GLY slow homozygotes (SS) are selected for under highly stressful edaphic conditions. Biomass measurements suggest that GLY slow homozygotes (SS) were superior to other GLY genotypes in cinder soils. Older pinyon pines on the cinder soil have a higher frequency of SS homozygotes than juveniles on the same soil. However, there is no significant difference in SS homozygotes between juvenile and mature pinyon pines on sandy-loam soil. The difference in frequency of SS homozygotes on cinder soil indicates that genotypic variation has occurred in one generation. This difference indicates that pinyon pine are capable of adapting to varying soil water and nutrient levels. However, the lower frequency of SS homozygotes in juvenile pinyon pines growing on cinder soil suggests that other factors inhibit SS homozygotes from increasing in the population (Cobb 1994).

Using the same locations as Cobb, Catherine Gehring and Thomas Whitman (1995) examined the effects of animals feeding on pinyon pine (herbivory), to mycorrhizal fungi development on the roots. Mycorrhiza are fungal hyphae, which colonize the roots of a host tree. They exist in a symbiotic relationship. The mycorrhiza are provided a steady supply of food in the form of sugars translocated from the plant's photosynthesis. In exchange the mycorrhiza greatly increase the surface area of the tree's root system in the soil. The tree is able to absorb more nutrients and moisture as a result. Plants growing on sterile soils often do poorly without the introduction of mycorrhizal spores. The pinyons growing in cinder soils had higher levels of insect herbivory, lower levels of defensive resins, lower growth rates, higher levels of ectomycorrhizal colonization, and lower cone production than those on the sandy-loam soil. Pinyons growing in cinder soil treated with one pulse of simulated herbivory showed a 19 percent drop in ectomycorrhizal colonization. Pinyons growing in sandy-loam showed no significant change under the same treatment. The pinyons on cinder soil were quick to rebound with cone production but slow with mycorrhizal colonization. This indicates a higher resource allocation to cone production than mycorrhizal support after herbivory activity. These results suggest plants undergoing greater moisture stress are more likely to experience herbivory and reduced mycorrhiza. This finding is significant to plants in arid environments where small changes in temperature could affect a plant's ability to maintain sufficient water balance (Gearing 1995).

Work by Thomas Whitham and Susan Mopper (1985) indicates that pinyon pines exposed to chronic herbivory by stem-and cone-boring insects are altered architecturally. These trees develop stunted, shrub-like crowns. Those trees with relatively low herbivory grow upright, treelike crowns (Whitham 1985). The crowns of all the pinyon pine trees growing in the study area could best be described as having shrub-like crowns.

Soil Moisture and Nutrient Availability

The ability of rainwater or snowmelt to infiltrate the soil or generally a function of the vegetative cover. An inverse relationship exists between vegetative cover and runoff. The vegetation disrupts flow by intercepting rainfall with its canopy, creating surface roughness and increasing soil moisture absorption. Vegetation also changes the subsurface characteristics of the soil by creating macropores, which increase infiltration. Infiltration is higher under tree canopies than in intercanopy spaces.

Soils under junipers have particularly high absorption values (Bradford 2003). This absorption rate may be a function of the macrochannels created by roots close to the surface. Junipers are able to extract more shallow soil moisture than pinyon pines due to their root structure. This competitive advantage may result from a greater number of fine roots near the surface, characteristic of juniper (Breshears *et al.*. 1997). On a small-scale, bare patches become water sources for vegetated patches. Runoff, along with sediment, is transported downslope to enrich the vegetative patch that traps and stores it. Litter under the tree canopy protects the soil surface and contributes organic matter. This accumulation of organic matter in the soil increases infiltration and moisture holding capacity (Reed *et al.* 1999).

While organic matter in soil increases the water holding capacity, P-J tend to produce residues which inhibit moisture infiltration and render the soil hydrophobic. Hydrophobic soils are widespread throughout the intermountain west and are characteristic throughout the study area (Brady and Weil 2002). The apparent contradiction between soil organic matter enhancing infiltration and water holding capacity and soil inhibiting infiltration and enhancing runoff is a further impetus to examine moisture availability as a controlling variable to tree mortality in dry soils.

Plants growing in a semi-arid environment are particularly sensitive to climate change. Lower precipitation can cause a widespread mortality in plants already at the lower limit of drought tolerance. A study by Rebecca Mueller and others (2005) found that pinyon mortality following a drought was six-and-a-half times higher than juniper mortality. The same study also showed that mature, reproductively active pinyon pines had a higher mortality rate than smaller pinyon pines. Also, juniper negatively impacts pinyon survivability by reducing pinyon root biomass and ectomycorrhizal colonization.

A study by Breshears and others (2005) compared the recent drought in the southwestern United States with one that occurred in the same region in the 1950's. They compared the 4 driest years of the drought, 2000 to 2003 and 1953 to 1956 respectably. The amount of total precipitation was greater for the recent drought than the 1950's drought. However, warmer temperatures accompanied the recent drought causing increased moisture stress on the pinyon pines. At an intensely studied area of P-J woodland near Los Alamos, New Mexico, soil water content was measured before, during and after the drought. The measurements indicate that from October 1999 to August 2000 and again from August 2001 to October 2002, the site experienced dry soil water conditions (<15% volumetric water content). During 2002 and 2003 ips beetle infestation was observed along with pinyon pine mortality greater that 90%. The Los Alamos site along with three other sites in Colorado, Utah and Arizona were studied using aerial surveys and satellites. Normalized Difference Vegetation Index (NDVI), used to quantify local vegetation response in the form of mortality, photosynthetic activity and greenness, showed a greater than 20% decrease in value during the same period. Junipers, which are more drought tolerant, also experienced mortality rates ranged from 2 to 26% in the same study area. Global climate change is projected to result in increased temperatures and more droughts in the southwest United States (Breshears *et al.*. 2005).

Due to the vastness of the southwest United States, remote sensing is often an effect way monitor the health of woodlands. Kevin Price used Landsat TM to monitor soil erosion in the pinyon-juniper woodlands of central Utah. Results suggest erosion rates were high in the past, but much of the soil had already eroded, leaving a surface armored by rock debris. Kevin Price also developed a new method for evaluating soil loss. Refered to as the SEDIMENT (Soil Erosion Direct measureMENT) technique it involves running a line from the base of two adjacent tree trunks. The line is attached to the trunks at the height of mineral soil level, on the down-slope side of each tree. Presumably this is the soil level when the tree was first established. The distance from the line to the soil is then measured at 20cm intervals. From these measurements estimates of total soil loss since the trees were established can be calculated. This technique was compared to TM spectral data and Universal Soil Loss Equation (USLE) and found to be more effective predictor of soil loss than the latter (Price 1993). Franklin and others (2003) used Landsat TM to track the red-attack stage of mountain pine beetles in Canada. Wulder and others (2006) looked at various uses of remote sensing for monitoring mountain pine beetles. Most of this research was focused on identifying infested locations to indicate where logging should take place to salvage as much timber and possible and contain the spread of the beetle.

The Bureau of Land Management and Forest Service has done -- and are continuing to do -- research on the pinyon-juniper woodlands, ips beetles, fire suppression, and climate change. The Healthy Forests Initiative is a program taking a holistic approach to managing P-J woodlands. Programs of thinning undergrowth to lower the fuel load are paying off with healthier forest and less intense fires. Removal of the dead trees reduces the host options for the ips beetle, thus reducing their impact. In a novel program, the removed fuel is being used to produce energy for local schools (Colorado Forest Products 2007).

Considerable research has focused on the effect of mechanical treatment on P-J woodland. R. S. Aro (1971) looked at the effect of chaining, double chaining, windrowing and fire on conversion of P-J to grasslands. He found that fire was most effective and single chaining was least effective at removing the trees. Younger trees often survive chaining and grow two to three times faster than normal, due to reduced competition for limited resources, namely moisture.

Research into runoff in P-J woodland indicates there are two times of the year when it is most pronounced. During the summer, heavy rain from thunderstorms creates the greatest runoff due to the intensity and raindrop impact. The lack of raindrop impact makes the spring thaw less severe. Surface runoff is an important part of the total water budget in P-J woodlands. It is also important in the transport of sediments and nutrients (Wilcox 1994).

Studies looking at soil permeability, infiltration rates and sediment yields following mechanical treatment revealed varying results. In a study by Gerald Gifford and others (1976), looking at 14 sites in southern Utah cleared of P-J and seeded with grass, there was no consistent decrease in sediment yields or infiltration rates (Gifford *et al.* 1970).

Research by Tausch and Tueller (1977) looking at long term plant succession following chaining showed that chaining is not as severe a disturbance to vegetation as fire and allows for much higher survival rates. Analysis of the impact of chaining on soil erosion found that the sites that had been chained 40 to 50 years earlier had thicker, better developed soils than unchained areas. Gabriella Blair (2001) compared chained to adjacent unchained sites in the northern part of Garden Park. The chained sites showed established grassy and herbaceous ground cover and lower amounts of erosion than unchained areas. There was little understory beneath the unchained P-J woodland and the soil was thin, consisting mostly of organic litter over bedrock. The results indicate that chaining in these areas reduced soil erosion and increased herbaceous ground cover.

The needle layer (duff) under pinyon pine crowns is a significant factor in controlling undergrowth. In mature P-J stands the needle layer may cover half the ground surface. If not removed, the duff continues to repress undergrowth development for years following removal of the tree. As P-J woodlands mature, grasses become depleted in the inter-space between trees. However, the grasses increase in vigor at the duff boundary. Under the crown in the deep duff there is an almost complete exclusion of understory (Everett *et al.* 1983). Reasons for such exclusion include decline in soil pH and difficulty in seed germination on the low bulk density and organic rich duff.

Research by Lee MacDonald and Edward Huffman (2004) at sites of recent wild and proscribed fires in Colorado showed that soil water repellency was strongest in areas where woodland fire severity was moderate to high. The water repellency decreased with soil depth and time. After 12 months there is no statistical difference in soil water repellency between burned and unburned areas. Analysis by S. K. Woche and others (2005) indicate that the quality of soil organic matter is more important for the setting properties of soil than the quantity of soil organic carbon. They also found that sandy soils were more hydrophobic than silty soils (Woche at al 2005).

Study Area

Garden Park was chosen as the site for the study for several reasons. First, there is a considerable amount of historical information about the area. The changes to the environment have been well documented including old photographs of the landscape. Second, Garden Park is typical of pinyon-juniper woodlands in Colorado with the exception that the infestation level of ips beetles has not reached epidemic proportions there. Third, the BLM and Forest Service control much of the land, making access easier, and their knowledge has proven invaluable. Fourth, The University of Kansas has a field camp in the valley that was used as a base of operations (pictured in the center of figure 7). Fifth, the University of Kansas, Department of Geography has a good working relationship with many of the old ranching families in the valley. Their cooperation was greatly appreciated in collecting samples on private land.

Garden Park valley is in central Colorado (see Figures 6 through 9). The valley is five miles north of Cañon City, Colorado in northeastern Fremont County. The Garden Park valley is about 28 square kilometers with elevations ranging from 5800 to 6200 feet. It is a graben bound by reverse faults (Johnson *et al.* 1981). The floor of the valley is relatively flat with higher elevations to the north. Fourmile Creek, also known an Oil Creek, runs from North to South through the valley. It is a perennial stream with several ephemeral tributaries in the valley. The valley lies between the southern terminus of the Pikes Peak section of the Front Range and the upper Great Plains in the Florence-Cañon City embayment (Wheeler 1995). Thrusting and faulting of sedimentary strata along the foothills created cuestas and hogbacks (these can be seen in the background on figure 7). Prominent geomorphic features include pediments, alluvial fans and fan terraces, floodplains and floodplain terraces formed on sediments deposited from the canyons onto the valley floor. One of the more distinct formations in the valley is a band of red sandstone known as the Fountain Formation. This is the same formation that created the Garden of the Gods in Colorado Springs and the Flatirons of Boulder, Colorado. It is an alluvial formation from the Pennsylvanian age and gets its red to pinkish color from an abundance of pink feldspar (Gibson 2007). An outcropping of the Fountain Formation can be seen on the left side of Figure 6.

The soils in the study area vary depending on the local geomorphology. There tends to be an inverse correlation between the slope and soil development. Pediment surfaces and fluvial terraces have thicker soils, with the latter being poorly developed. Soils are deeper up-slope where dissection of the pediment surface is less distinct. The pH of the soils tends to be neutral to alkaline at the surface with the exception of areas under pinyon and juniper. The buildup of needle leaf litter from P-J will acidify the soil. At depth the soil is almost uniformly alkaline with heavy concentrations of calcium carbonates (Johnson *et al.* 1981). The Cerrillos soils of Garden Park are alluvial deposits from the Fountain Formation. The Sedillo soil is formed in pedisediment on pediments on the Fountain Formation. Fort Collins and Kim soils are found on the plains, fan and terraces of the valley floor. Neville is found on the foot slopes, fans and terraces. Wesix is found on limestone outcrops associated with cuestas and mountainsides. Ustic Torriorthents is found on the steep mountain slopes (Wheeler *et al.* 1995). Refer to appendix C for a detailed description of each soil type.

The climate varies considerably due to continentality and mountainous topography. Temperatures range from lows around –18c in the winter to 38c in the summer. Precipitation also varies considerably from year to year. Climate data for Cañon City from 1888 to 1978 show an annual average precipitation of 12.5 inches. However, it ranges from as low as 5 inches to 24 inches per year (Johnson). Climate data recorded from 1971 to 2000 indicates an average of 13.35 inches of precipitation with a minimum around 8.15 and maximum of 15.06 inches (NRCS 2007). Sixty-five percent of all precipitation falls between April and September (Wheeler *et al.* 1995).

The small valley of Garden Park has a rich and varied history. Cañon City was founded in 1859, six miles to the south, near the mouth of the Royal Gorge. Settlers began farming and ranching operations in Garden Park soon thereafter. Fourmile Creek, which drains the Garden Park valley, is often referred to as Oil Creek because of the discovery of a seep near the south end of Garden Park. On that site in 1862 the first commercial oil well was completed west of the Mississippi (Wikipedia 2007). In

1877 dinosaur bones were found in the valley. Several significant finds have been uncovered and excavation continues to this day. However, it wasn't black gold or dinosaur bones that would trigger the boom that would transform the region. Gold was discovered in Cripple Creek in 1891 and set off a gold rush. In 1892 the Shelf road connecting Cañon City to Cripple Creek was built. The toll road ran through Garden Park and followed Fourmile Creek and then Cripple Creek, a tributary of Fourmile Creek, on up to the mines. The Shelf road was and still is dangerous with steep cliffs and sections just wide enough for one vehicle. When first built it took six hours to travel but it was a key link from the gold mines to the rest of the world. The cliffs at the north end of Garden Park offer world-class climbing opportunities and are growing in popularity (these cliffs can be seen in the center and right of Figure 6).

Garden Park got its name during the gold rush when the residents started growing vegetables to feed the miners and townsfolk. As the mines played out the settlers of Garden Park took up ranching. Seven families owned most of the private land in the valley for the next 100 years, passing the land, cattle and invaluable water rights down from generation to generation. During the winter the ranchers grazed the cattle on irrigated pastures in the valley. In the spring they herded the cattle up the foot slopes. Most of this land was leased from the BLM. As the summer progressed the herds were moved further up the mountains, always moving on to greener pastures. The high pastures had sparse vegetation and a low carrying capacity (around 100 acres per cow), due to the semi-arid conditions. This limited herd sizes and required them to be constantly on the move. As winter approached, the herds were brought back down to the irrigated fields. While the cattle were on the mountain slopes, the ranchers were able to harvest two to three crops of hay from the irrigated pastures to feed the cattle over winter (Johnson *et al.* 1981).

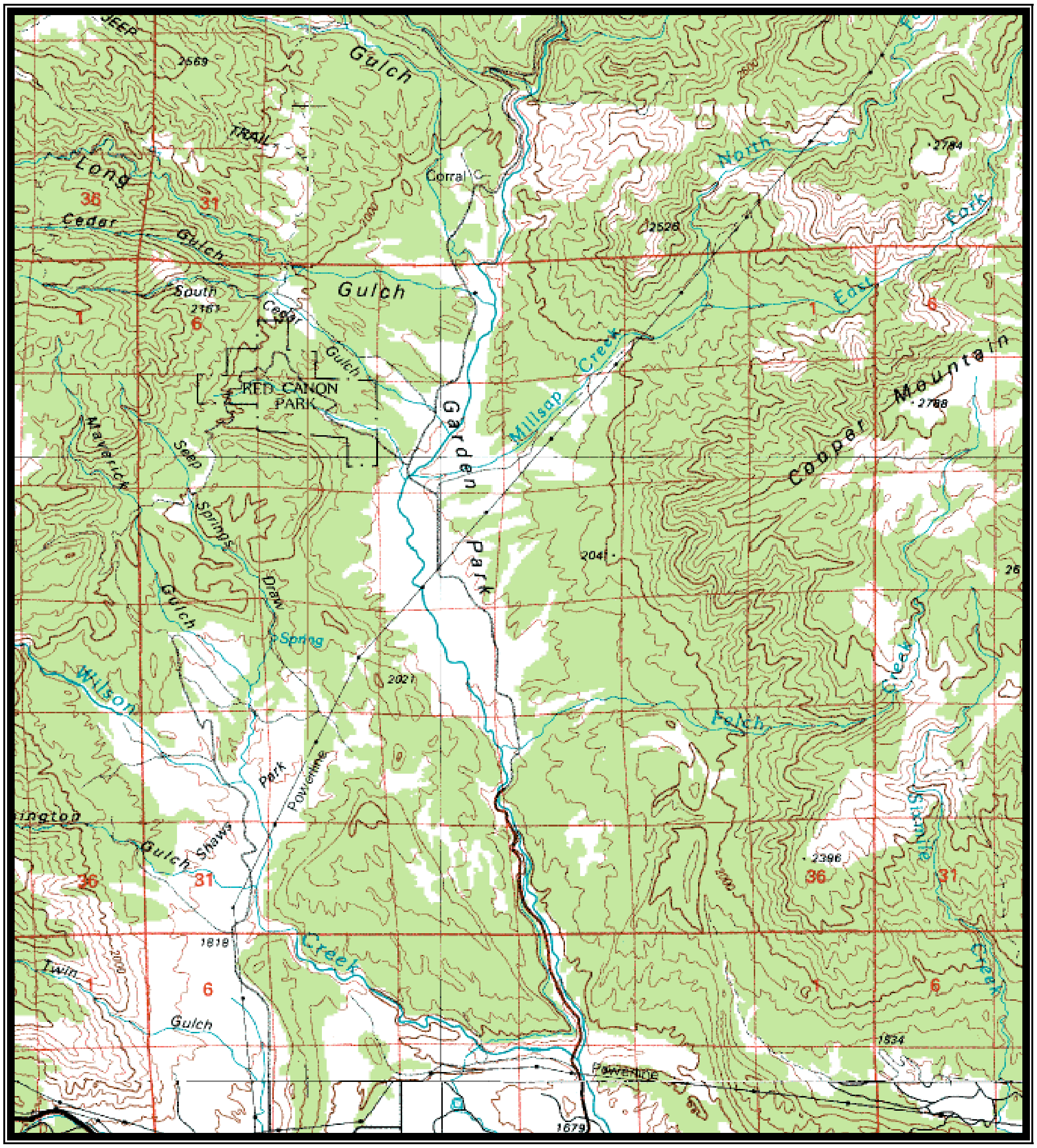
Ranching in Garden Park has never been a very profitable proposition. However, changes over the last 20 years have placed increased pressures on this way of life. Prior to 1967, the BLM used chaining to remove the pinyon and juniper and seeded the land with grass to increase productivity. This practice ceased in Colorado after 1967 due to environmental concerns (Blair 2001). Without chaining or other methods to remove the P-J, the trees took over the pastures within 20 years. As tree density increased, forgeable grasses decrease making marginal pastures even less productive. Ranchers also faced economic pressure from large feed lot operations on the High Plains. Many of the younger generations of these families are leaving the valley for more lucrative opportunities elsewhere (Johnson *et al.* 1981). Several of the ranchers have sold off some or all of their land to developers. The developers are dividing the land into 35-acre ranchettes. These plots are being bought up by people with different views of the environment in Garden Park. They are not trying to work the land and they like the woodlands, so they have little interest in thinning the P-J. If conditions continue along the current path there will be no ranching in Garden Park in the near future (Schnell *et al.* 2004).

Figure 6: View northwest across the northern third of Garden Park, Colorado. Taken from the western slope of Cooper mountain. Note the Fountain Formation to the left. Photograph by Jeff Krecic 2005

Figure 7: View west across the central third of Garden Park, Colorado. Taken from the western slope of Cooper mountain. Photograph by Jeff Krecic 2005

Figure 8: View southwest across the southern third of Garden Park, Colorado. Taken from the western slope of Cooper mountain. Photograph by Jeff Krecic 2005

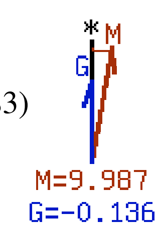
Figure 9.



Garden Park, Colorado

Map center is UTM 13 481017E 4268506N (WGS84/NAD83)

Cooper Mountain quadrangle, Projection is UTM Zone 13



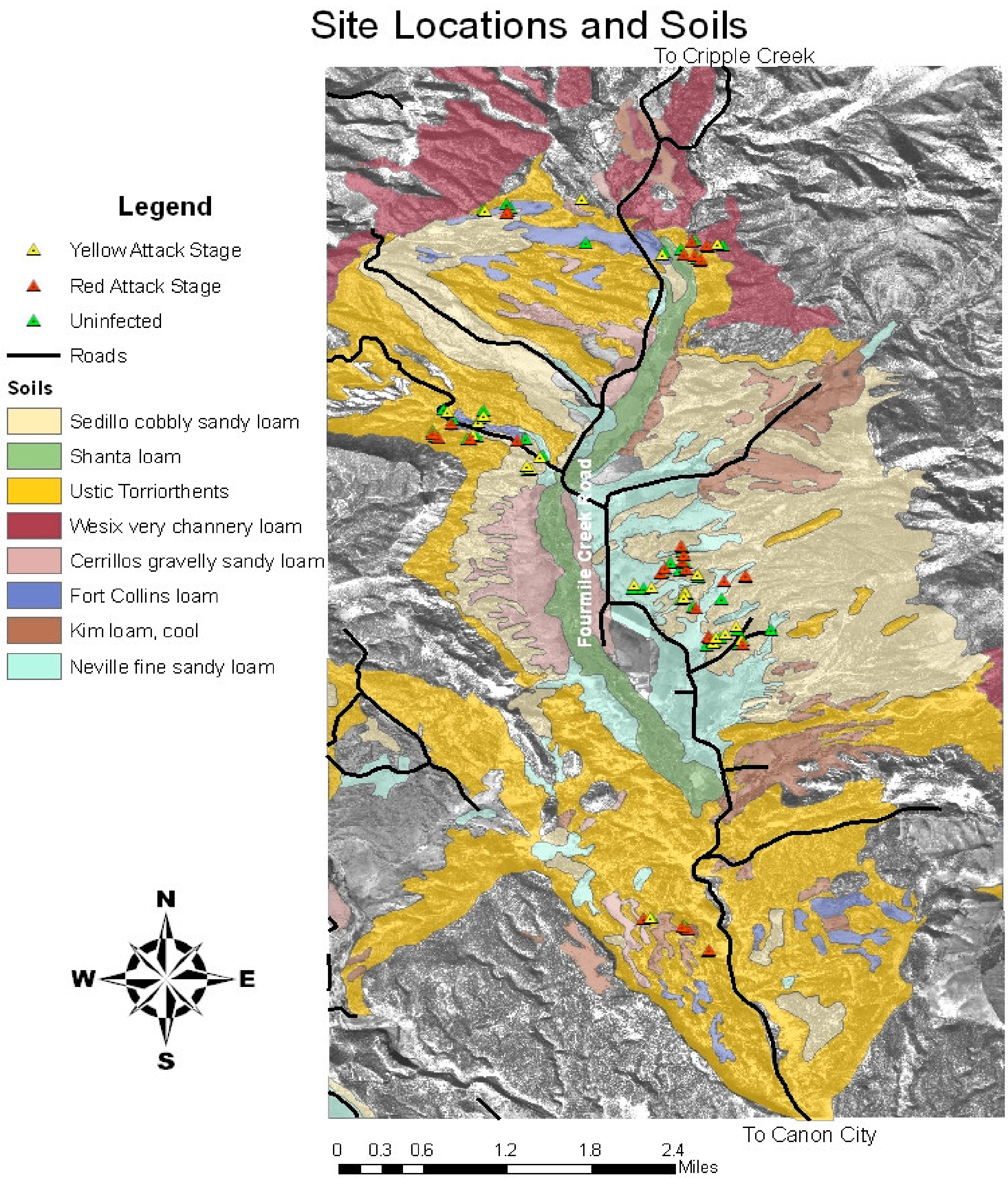
NAD83 Datum

The site map of the study area was produced using ArcGIS at the University of Kansas, Department of Geography computer laboratory (see Figure 10). The following data were downloaded from the USGS Seamless Data Distribution web site:

- A black and white aerial photo of the study site with 1 foot spatial resolution and 255 value spectral resolution.
- A National Elevation Data raster map with 10 meter spatial resolution and 255 spectral resolution.
- A roads layer for physical referencing and access to study sites.
- A Digital Ortho Quadrangle (DOQ) map of the area to identify landmarks and government/private property boundaries.

The soils dataset came from the www.ncgc.usda.gov/products/datasets/ssurgo website, Soil Datamart product. The coordinates were recorded from each site on a Garmin e-Trex Global Positioning System (GPS) in decimal degrees using the NAD 27 Datum. The the locations of all the study sites were then plotted on ArcMap to create Figure 10.

Figure 10.


Site Locations and Soils
To Cripple Creek
Legend
Yellow Attack Stage
Red Attack Stage
Uninfected
Roads
Soils
Sedillo cobbly sandy loam
Shanta loam
Ustic Torriorthents
Wesix very channery loam
Cerrillos gravelly sandy loam
Fort Collins loam
Kim loam, cool
Neville fine sandy loam
Fourmile Creek Road
N
W
E
S
To Canon City
0
0.3
0.6
1.2
1.8
2.4
Miles

Research Methods

In August of 2006 the study area was visually assessed and it was determined that infected trees were scattered in small clusters throughout the valley. Fifty infested trees were selected from various locations throughout the valley in an effort to assess soil conditions at differing topographic positions in the landscape and at a variety of geomorphic features. The position of a site on the landscape and its geomorphic history result in a series of sites with a wide range of site characteristics such as soil type, depth, slope, elevation and aspect. Each site consists of a subject tree and a ten-meter radius plot surrounding it. Only trees with a minimum diameter of 5.5 inches were picked. This condition was necessary to ensure that the tree was mature enough to be a suitable host for the ips beetle. The beetle requires a mature tree with thick bark to protect it from predators and the elements. The trees were either in yellow or red attack stage and showed definite signs of ips beetle infestation. Visual inspections of the sample trees were made. Only those with clear signs of infestation were selected. See Figure 11 for an example of a tree showing clear boring tubes and galleries. Those that showed injury from other sources such as, human activity, rock fall or trees that were shaded out for example were excluded. Data from a nearby, at least 20 meters away, healthy tree of the same size was collected as a comparison. The mean diameter for infested trees was 9.97 inches; for healthy trees it was 9.65 inches. Diameter is an indicator of tree age. Trees of similar diameter were selected to eliminate age as a possible determinant. Most of the trees in this study are estimated to be between 60 and 100 years old. The healthy trees may have had pitch tubes but never signs of infestation, such as clear tubes, fraise, or loose bark. Data from the healthy trees taken outside the ten-meter site radius are of comparable size to the infected ones and are considered representative of the pinyon population.

Figure 11. Note the clear bore holes on the left photo. After the bark is pealed away the galleries and boring dust are clearly visible. Photos by Jeff Krecic.

The latitude and longitude of all sample trees were taken with a Garmin GPS and used to plot their location on the site map (refer to Appendix 1 for GPS coordinates for site locations). Tree health was visually assessed and categorized as either yellow or red attack stage. Trees of gray attack stage were not used as it is difficult to verify that the tree was infested while still alive. Slope aspect was determined using a compass. South-facing slopes receive more direct sunlight than north-facing slopes.

The temperatures during the day are highest on south-facing slopes, causing greater evaporation. The vegetation on these slopes experiences greater evapotransporation and tends to be sparser than that on north-facing slopes, so moisture conditions should vary with slope aspect.

The slope angle was calculated using an Abney level. This measurement was not designed to evaluate slope as a defining characteristic in ips beetle infestation. To do so would require evaluation over a large area and would be best accomplished with remote sensing supported by field observations. Slope steepness varied widely over the study area sites, and it too was expected to impact soil moisture conditions. The minimum slope was one degree for infected sites and 2 degrees for uninfected sites. The maximum slope was 62 degrees for uninfected sites and 68 degrees for infected sites. The mean slope for infected sites was 18.76 degrees while the mean slope for uninfected sites was 17.10.

The distance from the trunk of the subject tree to the nearest mature pinyon pine or juniper was measured to determine if direct competition affected infestation probability. This measurement varied from as little as four inches to greater than 300 inches, well beyond the root diameter of these trees. Uninfected sites had a mean distance of 102 inches, infected sites had a mean distance of 82 inches.

To determine tree density all trees within a ten-meter radius were counted. They were categorized as either pinyon pines, which were classified as healthy, unhealthy, saplings or junipers, which were subdivided into healthy, unhealthy or saplings. Trees were considered saplings if their diameter at breast height was 4 inches or less. No other woody tree species were present in any of the sample sites. Mature trees were given a score of 1 and saplings ½ for a value of tree density. Those numbers were added together to get a plot density value. Uninfected sites had a mean plot density of 10.13. Infected sites had a mean plot density of 13.12.

Soil samples were taken using a bucket auger (see Figure 12). Samples were stored in sealable plastic storage bags for later analysis at the Kansas University Department of Geography soil laboratory. Soil depth to refusal was recorded. Uninfected sites had a minimum depth of three inches and a maximum beyond the 60 inches the bucket auger could reach. The mean depth was 14.38 with a standard deviation of 12.414 inches. The infected sites had a minimum depth of three inches and maximum depth >60 inches. The mean was 14.74 and standard deviation was 10.571 inches.

Figure 12. Soil sampling method and materials. Photo by Jeff Krecic.

Soil series was evaluated using the Fremont County Soil Survey. Soil samples were taken at the base of each tree. An "A" sample was taken from the top layer of soil. A "B" sample was also taken if the soil depth was greater than eight inches. A distinction must be made at this point. The samples were labeled "A" and "B" but they do not necessarily represent A and B horizons in the soil. Most of these soils are aridisols. Many are on steep slopes, are very shallow and poorly developed. Some soil profiles do not have a B horizon. For these reasons, taking samples which were pure A or B horizons was impractical. A total of 160 samples were collected. They were dried in an oven at 60 degrees Celsius for twenty-four hours. Organic matter larger than 2mm were removed and the samples were ground and sifted with a 2mm sieve. They were then analyzed for color, pH, particle size and organic matter.

Laboratory work was performed in the Geography Department soils lab at Kansas University. Soil color was determined using a Munsell Color Chart. A small amount of the soil sample was moistened and compared to the color chips in the chart. The Munsell system measures color based on hue, chroma and value. The hue is the amount of yellow or redness of the soil. The chroma is the intensity or brightness and the value is the lightness or darkness. Soil color does not affect the behavior of the soil, rather it gives us clues about the soil properties. Darker soils tend to have more organic matter. Changes in soil color at depth are indicative of different soil horizons. These horizons tell us much about the soil series and development. Color can also tell us much about the parent material from which the soil formed. In the study site, Garden Park, the soil color varied considerably. It ranged from a 10R 3/6 to a 2.5 3/4. Soil color was instrumental in determining the soil series. Soils that are dark red are derived from red sandstone formations found throughout the valley. Soils that are brown are derived from limestone, gneiss, and granite parent materials.

The Soil Survey of Fremont County Area, Colorado was used to identify the soil series of each site (refer to Figure 7 for the soil distribution of the sites.) The dominant soil series for both infected and uninfected sites was Sedillo and Ustic Torriorthent. The Soil Survey of Fremont County describes the vegetation on both these soils as sparse pinyon and juniper with an understory of grasses and cactus.

Other soils identified on the study sites are included for completeness and are summarized in appendix C.

Soil pH affects the cation exchange capacity of the soil and therefore the plant's ability to take up nutrients. Soil pH also impacts the activity of soil microbes. Plants have different tolerances of pH ranges. In the study area the soils usually have a relatively high pH due to the arid environment. However, the needle leaf debris of pinyon pines acidifies the soil as it decomposes. Soils tend to aggregate more at lower pH and disperse at higher pH. The result is that under P-J the surface soil pH is often very acidic, ranging from 4 to 6, while the subsoil may be very alkaline, with a pH as high as 8.5 or 9.

The pH was measured by mixing 20 grams of soil in a 50 ml beaker with 20 ml of reverse osmosis water. The mixture was stirred for at least 15 minutes. A calibrated pH meter was then submersed in the mixture and a reading taken. The results showed pH ranged from 4.3 to 9.1. This is not surprising as the soil in the study area tends to be alkaline and the fallen needle leaves acidify the soil directly under the tree. The mean pH and standard deviation were not statistically different from infected to uninfected trees.

Soil organic matter is an important factor in soil productivity. Organic matter binds mineral particles to form soil structures. It also affects water infiltration ability. Soils higher in organic matter are darker in color and hold more moisture. Humus is the colloidal fraction of the soil organic matter. Humus, like clay particles, has a surface charge. This surface charge holds nutrient ions and water molecules and exchanges them with plant roots. Humus has a much greater capacity to hold water and nutrients than clay. A small amount of humus can have a big impact on soil productivity.

To determine the organic content of the samples, a loss-on-ignition test was performed. Samples were passed through #14 and #18 sieves. Crucibles were weighed, approximately 20 grams of soil added and weighed again. The samples were oxidized in a muffle furnace at 550-degree Celsius for 2 hours to burn off any organic matter. After the samples cooled down they were weighed again. The difference in weight was the lost organic matter (Ben-Dor 1989).

Soil particle size was performed using the hydrometer method (Gee 1979). Due to time constraints it was impractical to test all the soil samples. 30 samples for infected and 30 samples from uninfected sites were selected using a stratified random sampling method. Three samples were chosen at random from every ten site. That is three from sites 1-10, three from 11-20, etc… Fifty grams of prepared soil samples were mixed with 100ml of a 5% sodium hexametaphosphate solution and allowed to sit for 12 hours. The sodium hexametaphosphate effectively dispersed the soil separates. The samples were then mixed and added to 1000ml of reverse osmosis water. A hydrometer reading was taken after 40 seconds and again at two hours.

They were adjusted for temperature and the readings calibrated based on blank readings (Gee 1979).

Statistical Analysis

To test the hypothesis, multiple statistical methods were employed. A chi-square test was used to see if the distribution of sites on various soil types were normal. If soil water holding capacity were a determining factor in ips beetle infestation we would expect to see an uneven distribution. Infected site would be more prevalent on soils with low water holding capacity. Because I was comparing paired samples, one of infected sites and one of uninfected site, I used pair difference of means tests. With a two-tailed *T*-test if the probability-value is less than .005 then there is a statistical difference in the two sample means. The tests were preformed on the data for soil depth, pH, organic matter, particle sized, site slope, proximity to nearest tree and plot density [1].

Hypothesis:

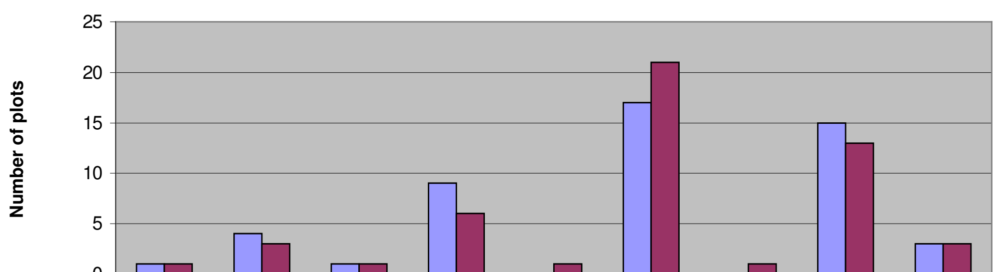
H_o: There is no significant correlation between soil type and pinyon pine ability to resist ips beetle infestation.

H_a: There is a significance correlation between soil type and pinyon pine ability to resist ips beetle infestation.

1. For a more sophisticated analysis of the data Paired Hotelling's *T*-squire test could be used. Due to my inexperience with multivariate statistical analysis and a desire to test each factor individually I chose separate paired *T*-tests.

A chi square test was performed on the soil types to determine if there was a statistical correlation among infected and uninfected sites and the soil at those sites. The various soil types were categorized based on their available water capacity as described in the “Soil Survey of Fremont County Area, Colorado” (See Figure 14). The null hypothesis was that there is no correlation between soil type and pinyon pine ability to resist ips beetle infestation, which proved to be true in this case study. Figure 13 illustrates there is little difference in the distribution of sites on various soil series. Figures 15 and 16 show there was very little variation between the actual and expected count for each category. Sedillo was the most common soil type for both infected and uninfected sites. Ustic Torriorthent and Neville were the second and third most common soil types for both infected and uninfected sites.

Figure 13. Site locations and Soil Series



	Cerrillos	Fort Collins	Kim	Neville	Rizozo-Rock	Sedillo	Shanta	Ustic Torriorthent	Wesix
Infected Sites	1	4	1	9	0	17	0	15	3
Uninfected Sites	1	3	1	6	1	21	1	13	3

Figure 14. Category of soil series based on available water capacity

C atagory	Available Water Capacity	Soil Series
1	Very Low	Ustic Torriorthents, Wesix
2	Low	Rizozo, Sedillo
3	Moderate	Cerrillos
4	High	Fort Collins, Kim, Neville, Shanta loam

Figure 15. Soil Type Table

		Soil Type Category				
		1	2	3	4	**Total**
Uninfected	Count	18	17	1	14	50
	Expected Count	17	19.5	1	12.5	50
Infected	Count	16	22	1	11	50
	Expected Count	17	19.5	1	12.5	50
Total	Count	34	39	2	25	100
	Expected Count	34	39	2	25	100

Figure 16. Soil distribution chi-square test

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	1.119(a)	3	.773
Likelihood Ratio	1.121	3	.772
Number of Valid Cases	100		

a 2 cells (25.0%) have expected count less than 5. The minimum expected count is 1.00.

Soil depth was measured as samples were taken. It was expected that pinyon pines on deeper soil would have greater access to water and nutrients. However, a difference of means test indicated that there was no difference in depth between the soil on infected sites versus uninfected sites. The uninfected mean was 14.38 inches and the infected mean was 14.74. Results of the paired sample *T*-test ($T = -0.17$; $P = 0.87$), clearly indicating no significant difference in mean soil depth. The distribution on a histogram shows a positive skew for both infected and uninfected sites. They have similar patterns with a peak at very shallow soil depths and a small peak at the maximum measurable soil depths. However, infected sites had a small peak at around 20 inches and uninfected sites had a larger peak at 40+ inches. Some of the healthiest trees sampled were growing on rocky outcroppings with little to no soil while a nearby infected tree was growing in deep soil. This observation indicates that soil characteristics may play little part in how much moisture a pinyon pine receives, especially during prolonged dry periods.

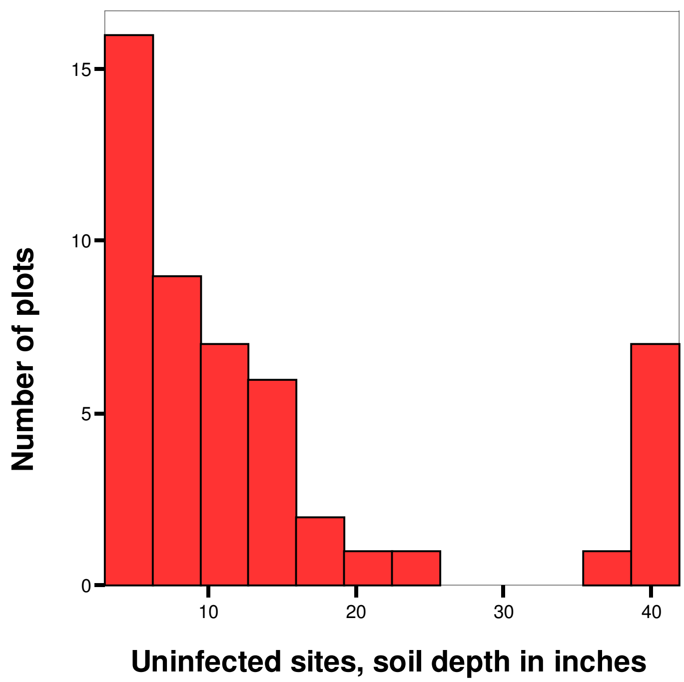
Figure 17. Mean Soil Depths

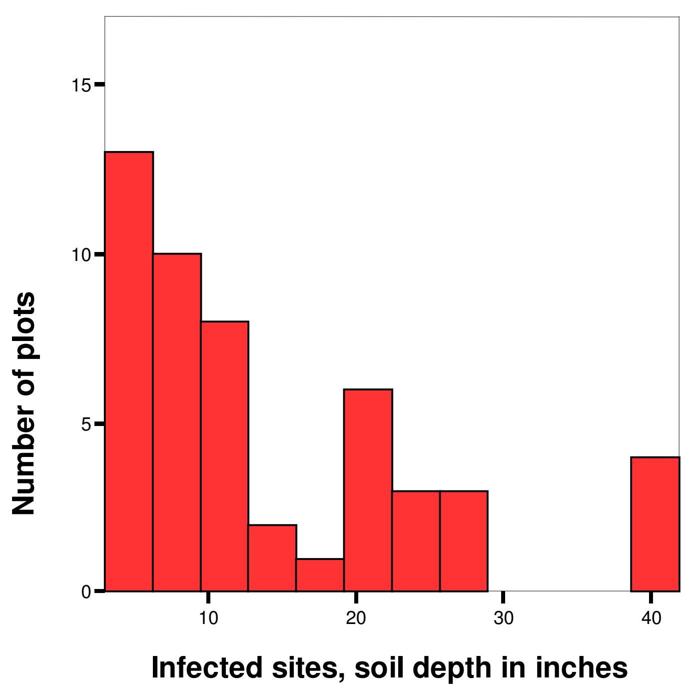
Site	Number	Mean	Standard Deviation	Standard Error Mean
Uninfected	50	14.38	12.4	1.8
Infected	50	14.74	10.6	1.5

Figure 18. Soil Depth *T*-test.

Paired Sample Test								
	Paired Differences							
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Soil Depth, Uninfected - Infected	-0.36	15.12	2.14	-4.66	3.94	-0.17	49	**0.87**

Figure 19. Histogram of Soil Depth Distribution





Soil pH is an excellent indicator of overall soil condition. As pH decreases the cation exchange capacity of the soil also decreases. At very low pH's the availability of macronutrients such as calcium, magnesium, potassium and nitrogen, which are critical to plant health, are severely limited due to leaching. However, the micronutrients zinc, copper, iron and manganese are readily available at low pH levels. The opposite is true at high pH level and may reach toxic levels. In alkaline soils macronutrients are readily available and micronutrient availability is curtailed (Brady 1998).

Most soils in an arid or semi arid environment like Southern Colorado are alkaline. However, the fallen needle leaves of the pinyon pine acidify the soil. In general organic matter introduced to the soil will lower the pH but decomposing pine needles are particularly acidic. Even healthy pinyon pines drop needles throughout their lives, slowly adding organic matter and acidifying the soil under their canopy. When ips beetles infest a pinyon pine it becomes chloridic and enters yellow and red attack stage. By the time it has reached the gray attack stage it is dead. In yellow attack stage the needles start dropping in greater numbers until the gray stage when they have all dropped. Pine needles do not decompose rapidly and a pinyon pine can take two years or more to die from an infestation.

I measured the pH levels in all samples taken to see if there was a significant difference in pH at infected verse uninfected sites. The pH might have been a factor in ips beetle infestation. However, it is more likely a symptom of infestation. The mean pH for the “A” samples (the top eight inches of soil) at infected sites was slightly lower than uninfected sites, as expected mean pH 7.19 and pH 7.39 respectably; it was not statistically significant though ($T = 1.90$; $P = 0.064$). The pH’s for the “B” samples were almost identical with means of 8.11 for infected and 8.09 for uninfected ($T = -0.14$; $P = 0.893$), indicating the acids from fallen pine needles are not working their way down beyond the first 8 inches of soil. The histograms for the “A” and “B” samples for infected and uninfected sites all show a slight negative skew. Peak pH is around 8.0 for all four histograms.

Figure 20. Mean Soil pH

The pH of "A" Soil Samples

Site	Number	Mean	Standard Deviation	Standard Error Mean
Uninfected	50	7.39	0.76	0.11
Infected	50	7.19	0.74	0.10

The pH of "B" Soil Samples

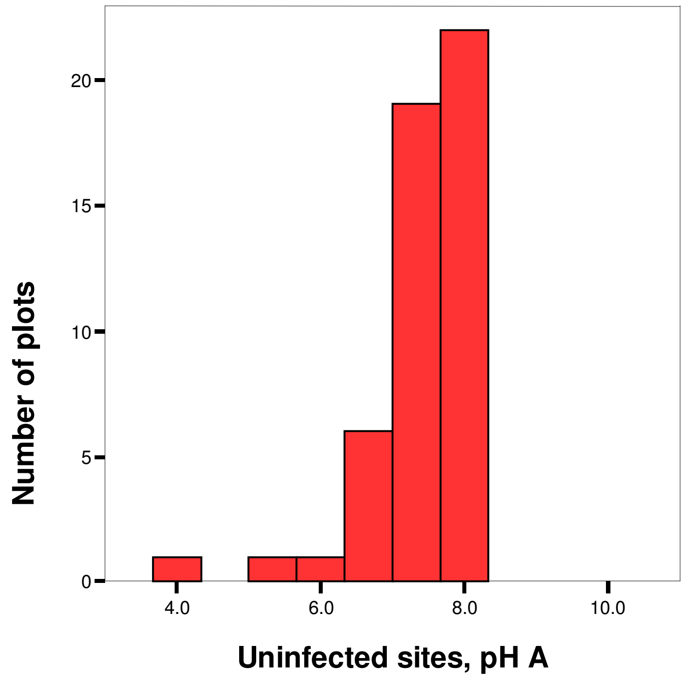
Site	Number	Mean	Standard Deviation	Standard Error Mean
Uninfected	21	8.09	0.30	0.07
Infected	21	8.11	0.55	0.12

Figure 21. Soil pH *T*-test

Paired Sample Test

	Paired Differences							
				95% Confidence Interval of the Difference				
Soil pH Sample A, Uninfected - Infected	Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
	0.20	0.74	0.10	-0.01	0.41	1.90	49	**0.064**
Soil pH Sample B, Uninfected - Infected	Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
	-0.01	0.48	0.11	-0.23	0.23	-0.14	20	**0.893**

Figure 22. Histogram of Soil pH, Sample "A" Distribution



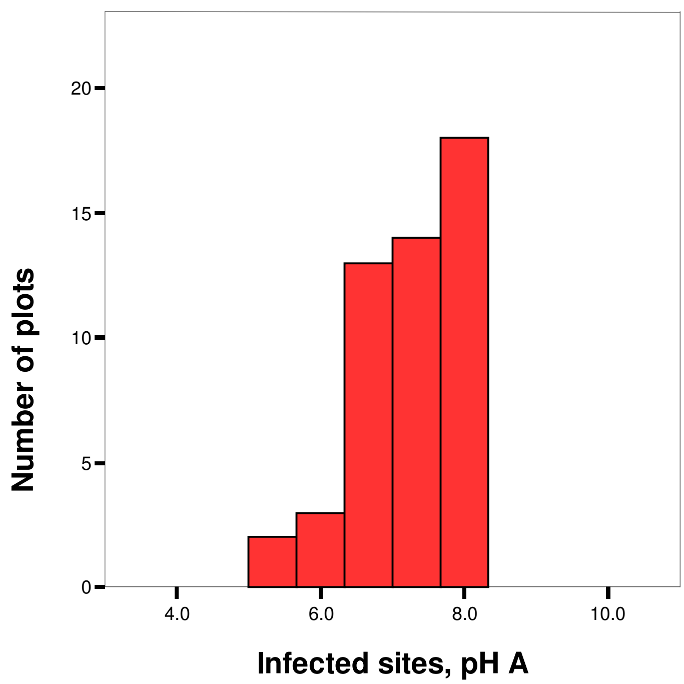
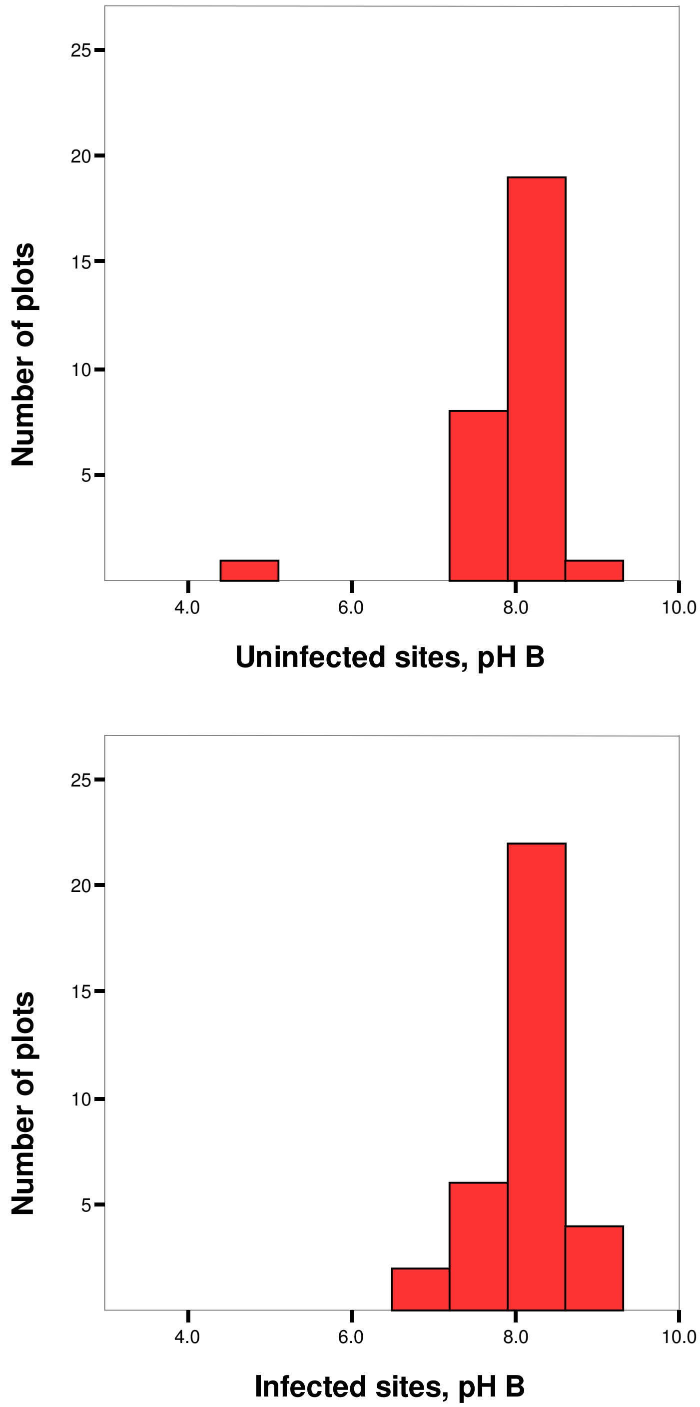


Figure 23. Histogram of Soil Sample "B" Distribution



Soils with higher organic matter should have higher water holding capacity. The samples were tested for percentage of organic matter using the loss on ignition method. There were some samples that had extremely high resulting percentages. They were likely due to errors in collection or lab testing. Using Tukey's method, with a hinge of 3, outliers were identified and removed. This involved eliminating those sites with an organic matter content greater than 3 times the interquartile range plus the upper quartile, (UQ + (3 * (UQ –LQ)) (Hoaglin 1983). The remaining organic matter samples were then analyzed using a paired sample t-test. The test was run with the outliers and without the outliers. Neither test showed a significant difference between the two groups. See figures 24-26 for a breakdown of the analysis for the data with outliers removed. The histogram of "A" soil samples shows a positive skew with a peak around 5% soil organic matter. The histograms for the "B" samples were more interesting. The uninfected site histogram has a very slight positive skew while the infected site histogram has a strong positive skew with organic matter levels as high as 10%.

If the alternate hypothesis were correct then the soils on uninfected sites would have more organic mater. The opposite was true. The infected sites had a higher organic matter content. This was likely due to the infected trees dropping their needle leaves as the infection killed off more of the tree. The dropped needles along with the boring dust from the beetles increased the organic matter content of the soil.

However, The results of the paired *T*-test showed no statistical significance ($T = 0.17$; $P = 0.866$) for the "A" samples (the top eight inches of soil) and ($T = 1.47$; $P = 0.157$) for the "B" samples (the subsoil).

Figure 24. Mean Soil Organic Matter Percentage

The Percentage of Organic Matter of "A" Soil Samples

Site	Number	Mean	Standard Deviation	Standard Error Mean
Uninfected	44	7.13	3.57	0.54
Infected	44	7.26	3.52	0.53

The Percentage of Organic Matter of "B" Soil Samples

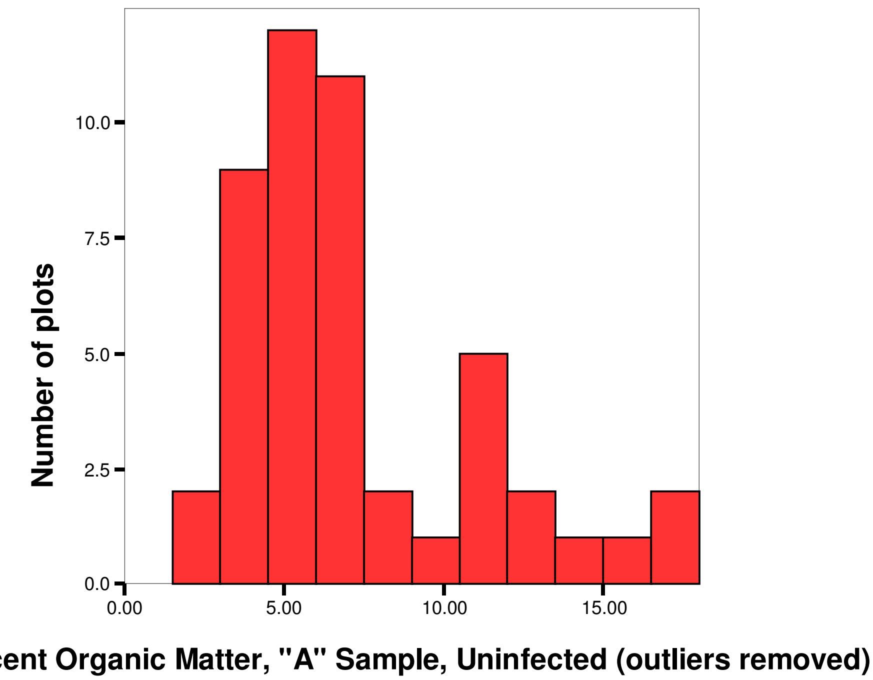
Site	Number	Mean	Standard Deviation	Standard Error Mean
Uninfected	23	4.13	1.35	0.28
Infected	23	4.78	2.23	0.47

Figure 25. Soil Organic Matter *T*-test

Paired Sample Test

	Paired Differences							
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Soil OM Sample A, Uninfected - Infected	0.12	4.82	0.73	-1.34	1.59	0.17	43	**0.866**
Soil OM Sample B, Uninfected - Infected	0.65	2.12	0.44	-0.27	1.56	1.47	22	**0.157**

Figure 26. Histogram of Percent Organic Matter, "A" Samples



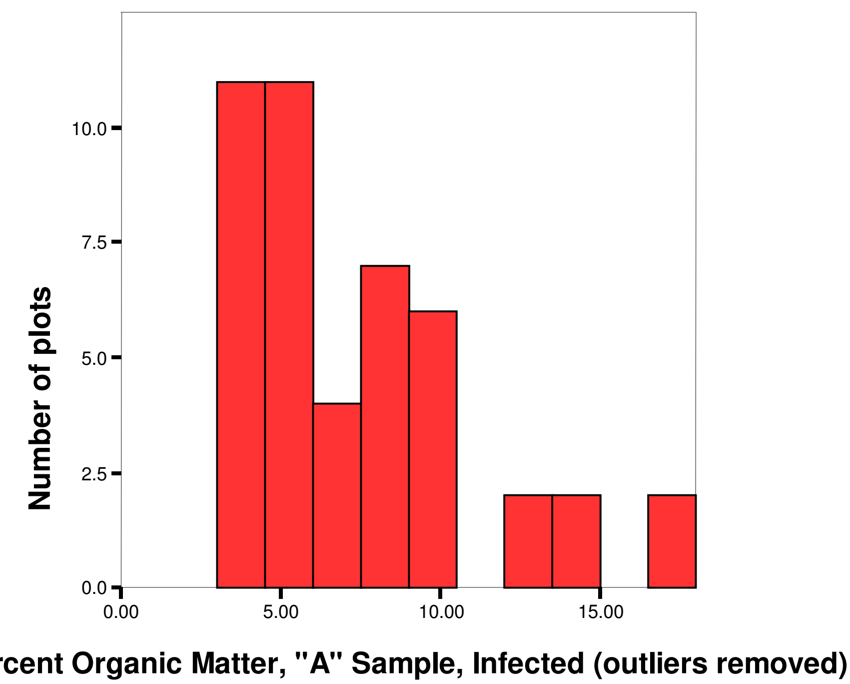
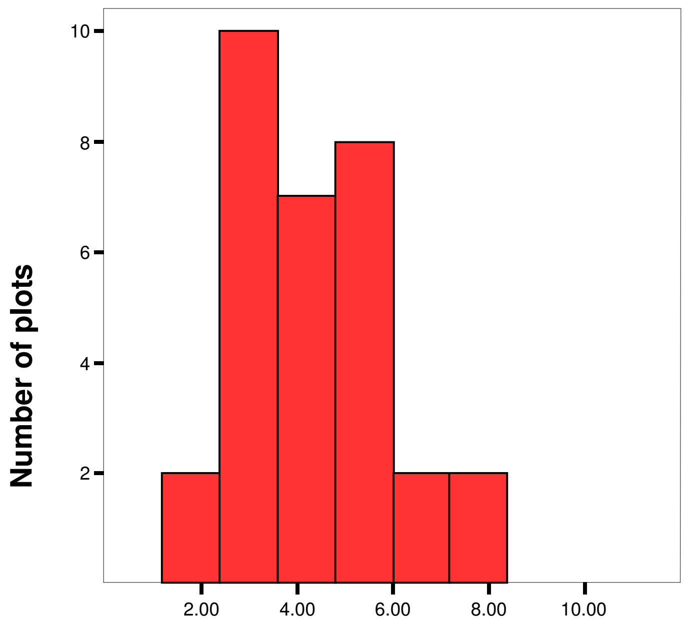
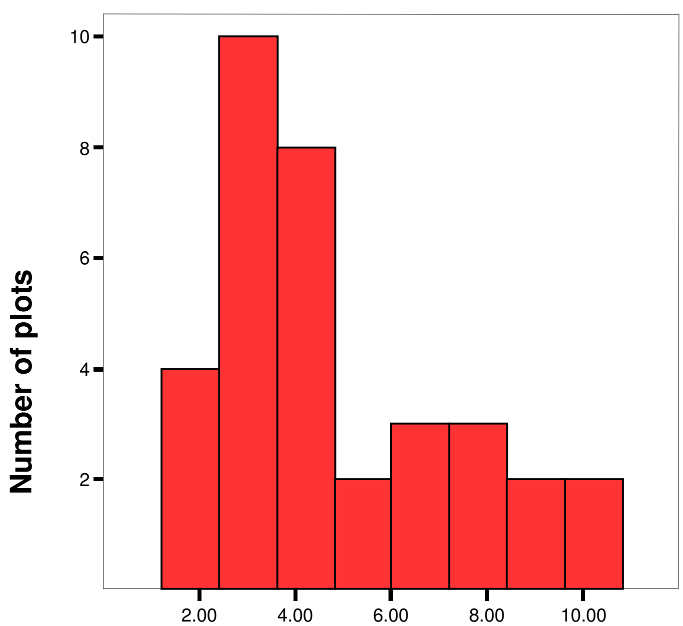


Figure 27. Histogram of Percent Organic Matter, "B" Samples



Percent Organic Matter, "B" Sample, Uninfected (outliers removed)



Percent Organic Matter, "B" Sample, Infected (outliers removed)

Particle size analysis was conducted using the hydrometer method. The composition of soil particles affects how swiftly water moves through the soil and how much water the soil can hold. The greater the clay content the more water holding capacity. Also the greater the cation exchange capacity. If soil particle size has an impact on a pinyon pines ability to resist ips beetle infestation we would expect higher clay content at uninfected sites. While the infected sites did have a slightly higher mean percentage of clay, the results of the paired *T*-test show there is not statistical difference between the mean percentage of clay in the two groups (T = -1.22; P = 0.233).

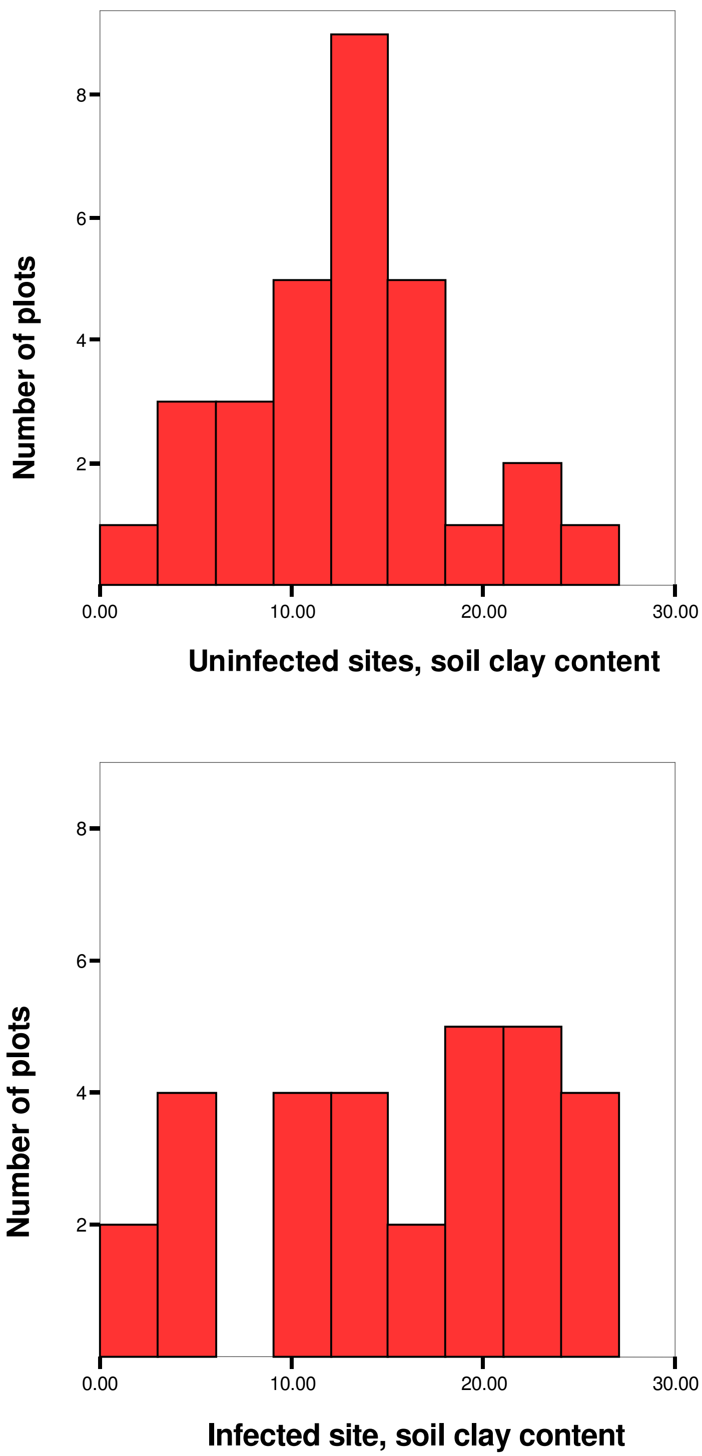
Figure 28. Mean Percentage of Clay in "A" Samples

The Percentage of Clay of "A" Soil Samples				
Site	Number	Mean	Standard Deviation	Standard Error Mean
Uninfected	30	12.97	5.6	1.02
Infected	30	14.93	7.5	1.37

Figure 29. Clay content *T*-test

Paired Sample Test								
	Paired Differences							
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Clay content Sample A, Uninfected - Infected	-1.97	8.85	1.62	-5.27	1.34	-1.22	29	**0.233**

Figure 30. Histogram of Clay content in "A" Soil Samples



The slope on which a tree is growing will affect the amount of water available to it. Soils on steeper slopes are shallower and run-off is greater. This experiment was not designed to test slope as a factor in infestation. Because these are paired samples the slopes should be similar. The infected sites had a mean slope of 18.76 degrees, which was slightly higher than the 17.10 for the uninfected sites. The result of the pair T-test showed the sample means to be statistically similar ($T = -0.87$; $P = 0.389$). This similarity of mean slope angle supports the pair sample method.

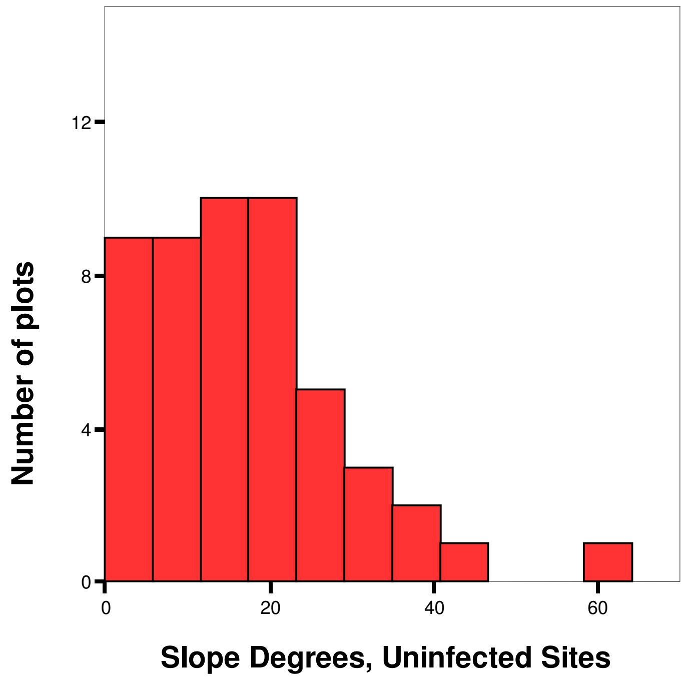
Figure 31. Mean of Slope in Degrees

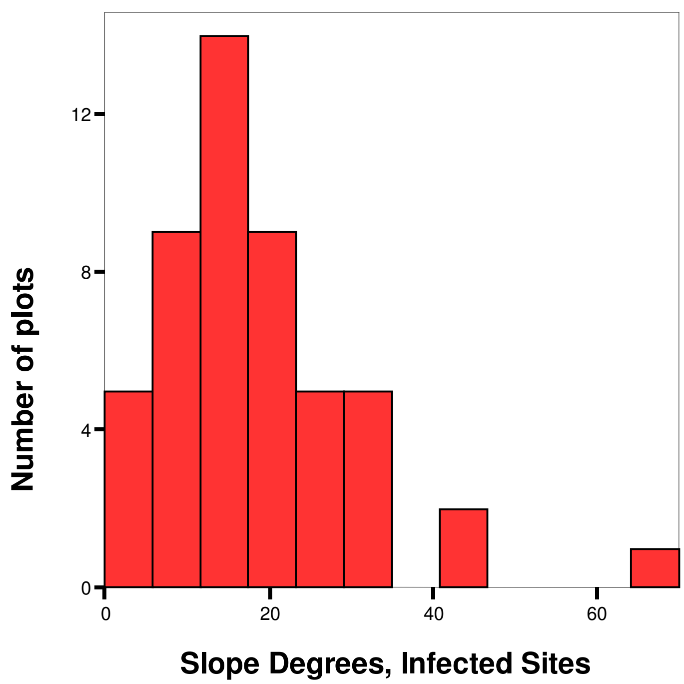
The Slope, in Degrees				
Site	Number	Mean	Standard Deviation	Standard Error Mean
Uninfected	50	17.1	12.19	1.73
Infected	50	18.76	12.19	1.72

Figure 32. Slope *T*-test

Paired Sample Test								
	Paired Differences							
				95% Confidence Interval of the Difference				
Slope in Degrees, Uninfected - Infected	Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
	-1.66	13.5	1.91	-5.5	2.18	-0.87	49	**0.389**

Figure 33. Histogram of Slopes





The proximity to the nearest tree was measured to see if direct competition for available water affected the chance of infestation. The mean distance from uninfected trees to the next closest tree was 101 inches. For infected sites it was 81 inches. This difference would appear to be significant but the paired t-test score ($T = 1.40$; $P = 0.169$) showed it to not be the case. Both histograms show a positive skew but the peak for uninfected sites was between 25 and 50 inches while the infected sites peaked at 0 to 25 inches. This finding may indicate that very close proximity may be a factor and dwindles in significance with distance. It is reasonable to suggest that trees growing very close together would stress both trees making them more susceptible to infestation.

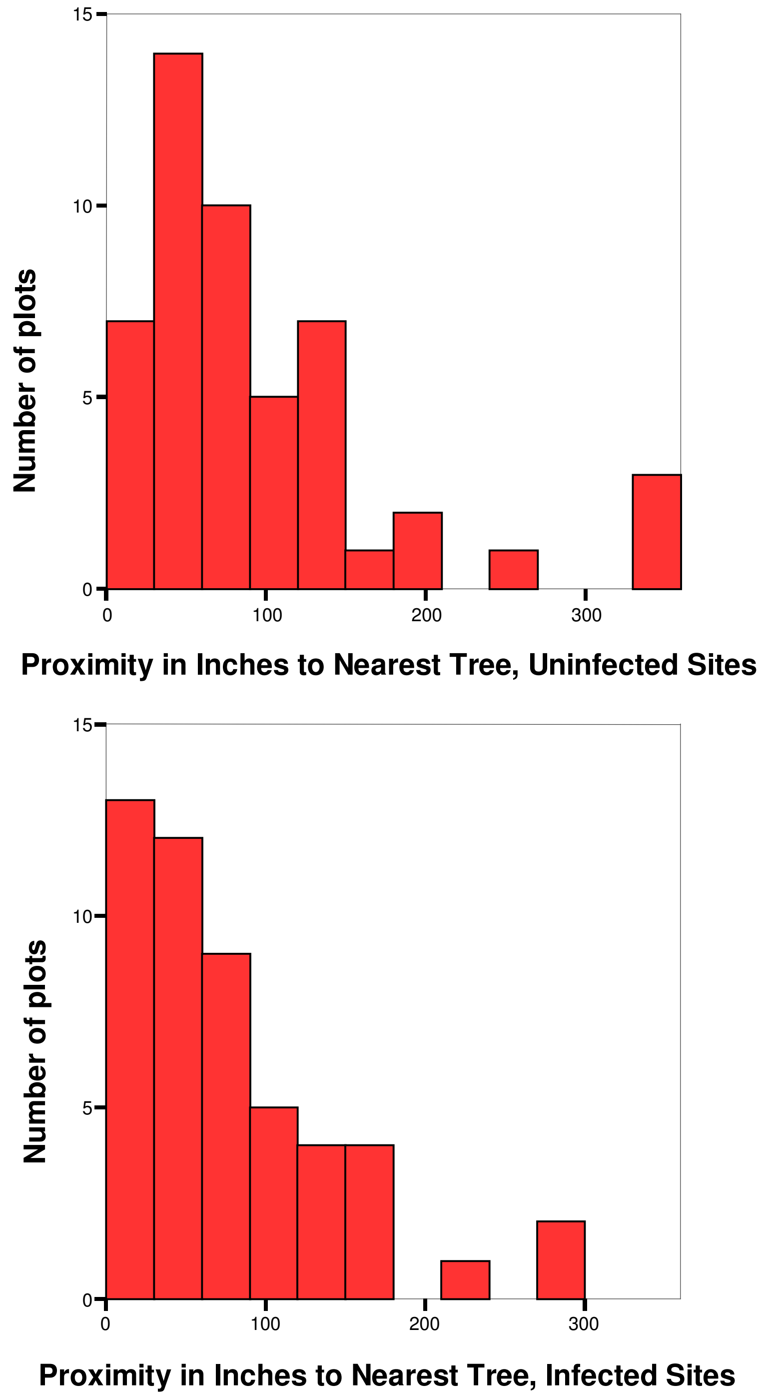
Figure 34. Mean Proximity to Nearest Tree

Proximity to Nearest Tree				
Site	Number	Mean	Standard Deviation	Standard Error Mean
Uninfected	50	101.5	85.33	12.07
Infected	50	81.78	67.19	9.50

Figure 35. Proximity *T*-test

Paired Sample Test								
	Paired Differences							
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Proximity in Inches, Uninfected - Infected	19.76	100.09	14.15	-8.68	48.2	1.40	49	**0.169**

Figure 36. Histogram of Proximity



High tree density and drought have been sited as reasons for ips beetle infestations reaching epidemic proportions. This study was designed to test whether soil had an impact on infestation, not tree density. However, I thought it important to collect density information to see if there was a variation. The plot density values proved to be the only statistically significant factor in this study. The mean plot density for uninfected sites was 10.13 and for infected sites it was 13.12. The result of the the pair *T*-test was significant ($T = -3.39$; $P = 0.001$). This supports previous research that high tree density plays a role in ips beetle infestation.

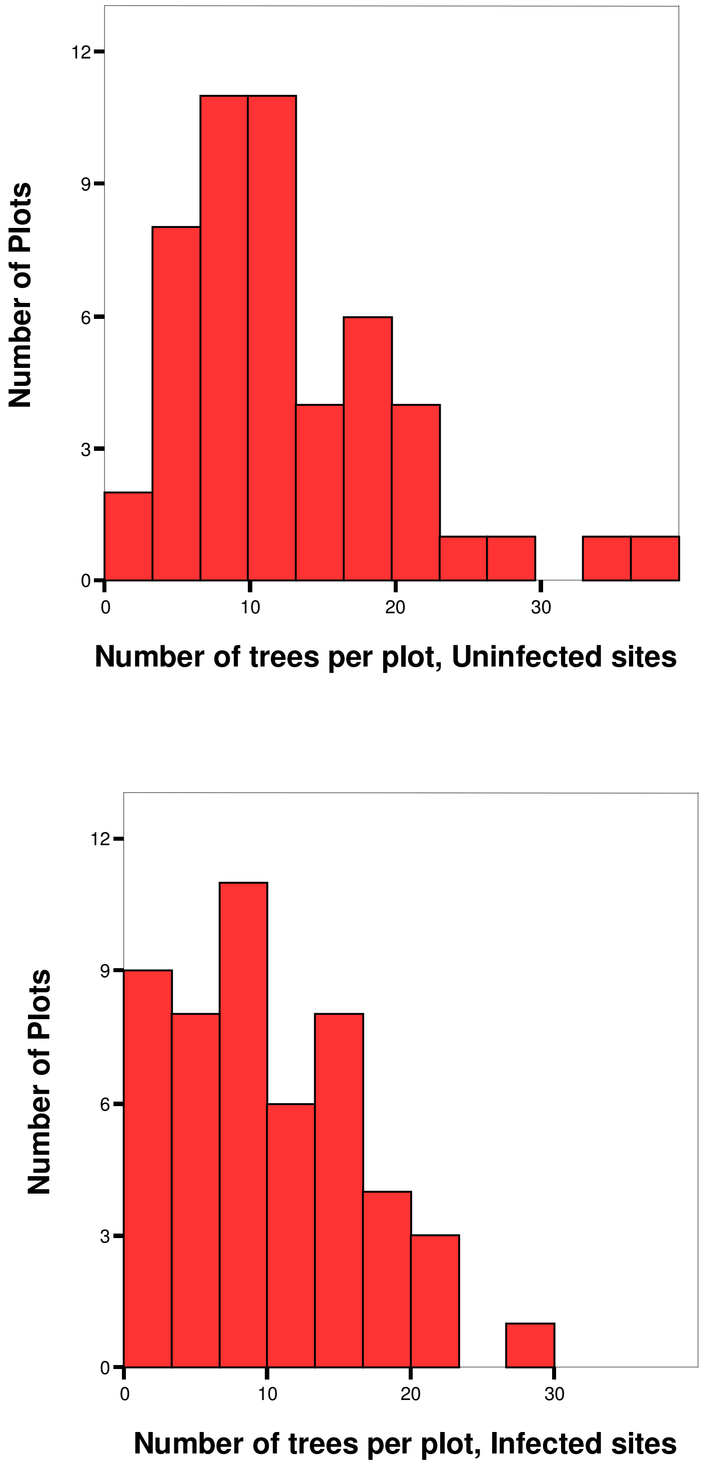
Figure 37. Mean Plot Density Value

Plot Densty Value				
Site	Number	Mean	Standard Deviation	Standard Error Mean
Uninfected	50	10.13	6.71	0.95
Infected	50	13.12	7.75	1.10

Figure 38. Plot Density Paired *T*-test

Paired Sample Test								
	Paired Differences							
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Plot Density Value, Uninfected - Infected	-2.99	6.24	0.88	-4.76	-1.22	-3.39	49	**0.001**

Figure 39. Histogram of Plot Density Values



Conclusion

The null hypothesis was not rejected. There is no statistically significant correlation between general soil factors at the plots tested, each of which should affect moisture availability to trees, and pinyon pine ability to resist ips beetle infestation. Neither the soil series, depth, organic matter, pH nor slope affected the likelihood of infection. This lack of correlation may be a function of how pinyon pine trees get their moisture. Pinyon pines have a shallow root system without a taproot. They acquire water though the surface soil so soil depth may not be significant. This can be seen on the landscape as there are many healthy pinyon pines on rock outcropping with little to no soil. The lack of a taproot is why chaining can topple pinyon pines and junipers.

Pinyon pines reduce the soil quality around them. They acidify the soil with their needles, make the soil hydrophobic and increase erosion. The accumulated duff under the boughs also decreases seed germination among grasses and shrubs. If deep, well-developed soils were critical to their survival it would seem they are their own worse enemy, but this is not the case. Perhaps the pinyon pines survival method is to reduce competition for moisture from underbrush by making the soil underneath and around them unlivable for grasses and shrubs.

A difference of means test on tree density and proximity indicate that this is a most important factor. This association may be due to competition for rainfall and snowmelt. Previous research has shown that dense vegetation and particularly competition with juniper reduces root biomass in pinyon pines. These trees receive much of their water from intercanopy spaces. In dense woodlands there is little to no intercanopy space. It may also be due to the protection a dense stand of tree provides to the ips beetle. A lone tree provides less protection from the elements and predators than a dense stand. Figure 40 illustrates this point. Here is a small cluster of pinyon pines. The trees on the ends are green; the tree in the middle is in red attack stage. These trees are growing on fairly level open ground with a fairly well developed soil. It is likely that the tree in the middle was least capable to fend off ips infestation because of competition for moisture from neighboring trees. A reduced root mass and less intercanopy space to draw precipitation from may also be factors.

Figure 40. Pinyon pines in green, yellow, and red attack stages.

A prolonged drought and increased temperatures may ultimately be the driving force behind high pinyon pine mortality. The ips beetle may just be a beneficiary of a changing climate. Mild winters may be resulting in reduced ips beetle mortality over the winter. Longer warmer summers allow for more breeding cycles per year. Dense woodlands of drought-stressed trees create an ideal environment for ips beetle outbreak. With current fire suppression regimes the ips beetle acts as the natural thinning agent in the P-J woodland.

Pinyon pines in a mixed P-J environment are living in marginal conditions for the species. In more arid conditions you will find stands of pure juniper. If the mixed P-J environment is becoming dryer then it stands to reason that it will begin to look like a pure juniper environment. Were the climate to change and the area get wetter we would expect to see a greater ratio of pinyons to junipers. However, the current trend in the southwest United States is for hotter, dryer weather. Historical evidence indicates that the southwest United States has gone through significant drought cycles in the past. Whether this current drought is part of the natural cycle or part of some greater global warming trend remains to be seen.

Though the soils at these plots did not prove to be significant variables, it was important to study them to eliminate them as a factor for ips beetle infestation. It may also be that during drought or near drought conditions that soil moisture storage is depleted by trees growing in that soil, and even the best soils are unable to supply needed moisture to the trees and beetle infected trees die. Climatic change and tree density appears to be the most important factors. More moisture or fewer trees competing for that moisture, regardless of soil type, should ensure that fewer trees succumb to ips beetle infestation. This conclusion supports the current practice of thinning P-J woodlands as a method for sustaining a healthier ecosystem.

Fire and ips beetles operate as natural agents to thin P-J. Where fires are lacking ips beetles excel. When the ips beetle infestation reaches epidemic proportions the fuel load is high, making the area susceptible to catastrophic wildfire. When ips beetle infestation reach epidemic proportions and wipe out entire viewsheds then all that is left are saplings. The saplings are too small to support ips beetles, which move on or die off. The area has a large fuel load and is primed for a wildfire. The wildfire burns the remaining trees and clears the ground for grass and shrub seed germination. The grasses take over until the pinyon pine and juniper encroach again and the process starts over.

Future research may want to take a holistic approach to evaluating the relationships among the factors affecting pinyon pine mortality. Climate changes affect the sustainability and composition of the P-J woodland. Human modifications to the environment also affect the natural balance. Forces such as fire and insect infestation trigger ecosystem shifts from P-J woodland to rangeland. These factors are all interrelated to alter or sustain the environment and must be considered together if a complete picture of the forces shaping P-J woodlands are to be understood.

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Appendix A

Site Coordinates, Infected Sites

Site #	Latitude	Longitude	Site #	Latitude	Longitude
1	38.58069	105.23736	2	38.58079	105.23699
3	38.58246	105.23967	4	38.58255	105.23891
5	38.60385	105.22153	6	38.60404	105.22135
	38.60247	105.22239	8	38.60313	105.22268
9	38.60368	105.21899	10	38.60347	105.21837
11	38.60353	105.21999	12	38.60342	105.21988
13	38.60237	105.22124	14	38.60209	105.22107
15	38.60197	105.22063	16	38.30176	105.22078
17	38.57948	105.23827	18	38.57926	105.23847
19	38.57963	105.23867	20	38.57932	105.23862
21	38.52746	105.21982	22	38.52731	105.21986
23	38.60852	105.23299	24	38.60375	105.23265
25	38.60724	105.24060	26	38.60747	105.24033
27	38.60697	105.24076	28	38.60797	105.24075
29	38.60728	105.24307	30	38.60735	105.24321
31	38.60248	105.22461	32	38.60286	105.22456
33	38.56130	105.21989	34	38.56034	105.22000
35	38.56118	105.21974	36	38.56097	105.21956
37	38.56066	105.21934	38	38.56069	105.21917
39	38.56119	105.21903	40	38.56120	105.21869
41	38.56163	105.21813	42	38.56201	105.21331
43	38.56239	105.21692	44	38.56195	105.21679
45	38.56095	105.21643	46	38.56093	105.21630
47	38.56054	105.21635	48	38.56054	105.21674
49	38.56733	105.21831	50	38.56538	105.21854

Appendix B

Site Coordinates, Uninfected Sites

Site #	Latitude	Longitude	Site #	Latitude	Longitude
51	38.56779	105.21596	52	38.56769	105.21596
53	38.52973	105.22205	54	38.52990	105.22217
55	38.53002	105.22256	56	38.53014	105.22246
57	38.53075	105.22655	58	38.53075	105.22655
59	38.53101	105.22593	60	38.53101	105.22577
61	38.56691	105.22764	62	38.56649	105.22768
63	38.56663	105.22581	64	38.56645	105.22654
65	38.56807	105.22478	66	38.56825	105.22469
67	38.56863	105.22441	68	38.56927	105.22382
69	38.56440	105.22123	70	38.56455	105.22142
71	38.56607	105.22229	72	38.56594	105.22220
73	38.56551	105.22245	74	38.56537	105.22266
75	38.56797	105.22097	76	38.56769	105.22095
77	38.56854	105.22219	78	38.56837	105.22277
79	38.56933	105.22250	80	38.56927	105.22231
81	38.57013	105.22245	82	38.57048	105.22259
83	38.57104	105.22267	84	38.57098	105.22254
85	38.58310	105.24427	86	38.58284	105.24390
87	38.58261	105.24462	88	38.58259	105.24485
89	38.58282	105.24785	90	38.58295	105.24813
91	38.58319	105.24848	92	38.58339	105.24846
93	38.58422	105.24657	94	38.58475	105.24644
95	38.58550	105.24694	96	38.58587	105.24739
97	38.58444	105.24370	98	38.58485	105.24363
99	38.58516	105.24322	100	38.58572	105.24320

Appendix C

Soil series, derived from the Soil Survey of Fremont County Area, Colorado

Cerrillos is a gravelly sandy loam with a slope of three to eight percent. It is a deep, well-drained soil formed on alluvial fans and fan terraces. It is derived mainly from red sandstone. The typical Cerrillos has a A horizon of 0 to 10 inches. It is reddish brown, has a weak fine granular structure; soft, very friable, non-sticky and non-plastic. The Bt extends from 10 to 19 inches and is reddish brown. It is moderate medium prismatic to subangular in structure; slighty hard, very friable, slightly sticky and slightly plastic. The Bk is from 19 to 31 inches and is light reddish brown. It has a weak medium subangular blocky structure; slightly hard, very friable, slightly sticky and slightly plastic. The C1 is reddish brown and extends from 31 to 39 inches. It is massive; soft, very friable, slightly sticky and slightly plastic. The C2 is reddish brown and extends from 39 to 72 inches. It is massive; slightly hard, very friable, sticky and plastic.

Cerrillos soils are mildly alkaline and the A and Bt horizons and moderately alkaline and violently effervescent at the Bk and C horizons. Available water capacity is moderate and erosion is slight to moderate. The average annual precipitation is 13 to 15 inches and the average annual air temperature is 48 to 52 degrees F. These areas are usually rangeland dominated by blue gramma, needlandthread, wheatgrass, prairie junegrass and little bluestem.

Fort Collins is a loam formed on plains, fans and fan terraces with slopes ranging from one to eight percent. It is formed in alluvium and is deep and well dreained. The typical Fort Collins soil has an A horizon of 0 to 4 inches. It is a dark brown to medium brown loam. It has a weak fine granular structure; soft, very friable, slightly sticky and slightly plastic. The Bt is 4 to 16 inches of yellowish brown clay loam. The structure is moderate medium prismatic; hard, friable, sticky and plastic. The Bk1 is light yellowish brown extending from 16 to 21 inches. The structure is moderate medium subangular and blocky. It is hard, friable, sticky and plastic. The Bk2 extends from 21 to 32 inches and is pale brown. It has a weak coarse subangular blocky structure; slightly hard, friable, sticky and plastic. The C extends from 32 to 60 inches and is yellowish brown. It is massive; slightly hard very friable, slightly sticky and slightly plastic.

Fort Collins soil ranges from neutral and the A horizon to moderately alkaline and the C horizon. The Bk1 horizon is strongly effervescent while the Bk2 and C are moderately and slightly effervescent respectably. Fort Collins soil has a high water capacity and slight hazard of erosion. The average annual precipitation is 12 to 14 inches and the average annual air temperature is 51 to 53 degrees F. Fort Collins soil used primarily as rangeland with blue gramm, western weatgrass and sideoats grama and the dominant vegetation.

Kim soil is similar to Fort Collins in that it is a loam with slopes ranging from zero to eight percent. It is formed in alluvium and eolian material. Kim is a deep, well drained soil that forms on fans, fan terraces, plains, side slopes, stream terraces and terrace breaks. A typical Kim soil has an A horizon of 0 to 4 inches which is pale brown. The structure is moderate fine granular; soft, very friable, non-sticky and non-plastic. There is no B horizon with an Kim soil. The AC horizon extends from 4 to 10 inches and is pale brown. It has a weak coarse prismatic structure; slightly hard, very friable, slightly sticky and slightly plastic. The C1 horizon extends from 10 to 44 inches and is light yellowish brown. The structure is weak coarse prismatic parting to weak medium subangular blocky; hard, very friable, slightly sticky and slightly plastic. The C2 horizon is pale brown and runs from 44 to 60 inches. It has a weak coarse prismatic structure; soft, very friable, slightly sticky and slightly plastic.

Kim soil has a high water capacity and slight hazard of erosion. The average annual precipitation is 11 to 15 inches and the average annual temperature is 48 to 53 degrees F. The entire profile of a Kim soil is moderately alkaline and strongly effervescent. Like Fort Collins the vegetation is primarily grasses; blue grama, western wheatgrass, and sideoat grama. However, Kim soil areas are a less productive rangeland than Fort Collins soils, as they tend to be shallower soils than the Fort Collins series.

Neville is a fine sandy loam with slopes of three to eight percent. It is deep and well drained and forms on foot slopes, fans and fan terraces. Neville is formed in alluvium derived from red sandstone and siltstone. The typical profile for Neville soil is A/AC/C. The A horizon is from 0 to 3 inches and is yellowish red. It has a weak fine granular structure; soft very friable, slightly sticky and slightly plastic. The AC horizon extends from 3 to 15 inches and is yellowish red. The structure is weak medium subangular blocky structure; slightly hard very friable, slightly sticky and slightly plastic. The C horizon is 15 to 60 inches and is also yellowish red. The structure is massive; slightly hard, very friable, slightly sticky and slightly plastic.

The water capacity of Neville is high but runoff is medium to high with corresponding hazards of erosion. The average annual precipitation is 12 to 15 inches and the average temperature is 47 to 52 degrees F. The entire profile is strongly effervescent and moderately alkaline. The native vegetation is mainly grasses, such as blue grama, western wheatgrass, needleandthread, and prarie junegrass. Like Fort Collins and Kim this soil is used mainly for rangeland.

Sedillo is a cobbly sandy loam to a very gravelly loam forming on slopes from two to twenty five percent. It forms on pediments, alluvial fans and fan terraces in calcareous, gravelly and sandy alluvium or alluvium derived from metamorphic and igneous rock. It may also form in landslide deposits. A typical Sedillo soil has a dark brown A horizon of 0 to 4 inches which has a weak thin platy structure: slightly hard, very friable, non-sticky and non-plastic. The Bt horizon extends from 4 to 10 inches, yellowish brown, weak mediom subangular blocky stucture: hard, friable, slightly sticky and slightly plastic. Moderately thick clay films on the faces of the peds are common. The Bk1 horizon is from 10 to 16 inches and very pale brown. It has a weak fine subanglar blocky structure; hard, friable, slightly sticky and non-plastic texture. The Bk2 is from 16 to 35 inches and pale brown. It is massive; slightly hard, very friable, slightly sticky and non-plastic. The 2Bk3 is extends from 35 to 42 inches and pale brown to white. It is massive slightly hard, friable, sticky and slightly plastic. The 2C extends from 42 to 60 inches and is very pale brown. It is massive; slightly hard, friable, sticky and slightly plastic.

Sedillo soil is neutral to mildly alkaline to a depth of six to nine inches. The Bk horizons are moderately alkaline and violently effervescent. Permeability is moderate and available water capacity is low. Runoff is slow or medium on shallow slopes but increases to rapid with high erosion on slopes up to twenty five percent. The average annual rainfall is 13 to 15 inches and an average annual air temperature of 48 to 50 degrees F. The typical plant community consists of P-J woodland with an understory of blue gramma, Scribner needlegrass, needleandthread, sideoats grama, red threeawn, and pricklypear.

Shanta is a loam formed in alluvium on floodplains and stream terraces. It has little slope, usually zero to 3 percent yet is well drained. The profile for Shanta is a deep, multi-layer, A horizon transitioning into an AB then a C that is a stratified sandy loam. The A1 horizon is from 0 to 2 inches and a grayish brown to brown. It has a weak fine granular structure; soft, very friable, slightly sticky and slightly plastic. The A2 horizon is 2 to 10 inches and is grayish brown. The structure is moderate fine subangular blocky structure; slightly hard, very friable, slightly sticky and slightly plastic. The A3 horizon is a vary dark grayish brown and extends from 10 to 22 inches. The structure is moderate medium subangular blocky structure; slightly hard, very friable, slightly sticky and slightly plastic. The AB horizon is runs from 22 to 49 and is also a very dark grayish brown. The structure is weak coarse subangular blocky structure; soft, very friable, slightly sticky and slightly plastic. The C horizon extends from 49 to 60 inches and is brown to dark brown. The structure is massive; soft very friable, non-sticky and non-plastic.

Shanta has a high water holding capacity and slight erosion hazard. The average annual precipitation is 12 to 15 inches. The average annual air temperature is 48 to 53 degrees F. The A1 horizon is slightly effervescent and mildly alkaline while the A2 horizon on down are all strongly effervescent and moderately alkaline. Like the other deep soils on relatively level surfaces the native vegetation is mainly grasses, such as blue grama, western wheatgrass, needleandthread, and prarie junegrass. Most

Shanta soils are used for irrigated or non-irrigated pasture with a few used as rangeland.

Ustic Torriorthent soil forms on mountain slopes of fifteen to ninety percent. It is a very gravelly sandy loam forming around boulders and rock outcrops. It can range from shallow to deep and is well drained to excessively drained. They are composed of residuum and colluvium derived from gneiss and granitic rock. The typical Ustic toriorthent soil has an A horizon of 0 to 2 inches which is dark grayish brown. The structure is weak fine granular; soft very friable, slightly sticky and ono-plastic. The AC is extends 2 to 10 inches and is light brownish gray. It is a weak medium and coarse subangular blocky structure; loose, firm, very sticky and plastic. The C1 extends from 10 to 27 inches and is light brownish gray. The structure is massive; very hard, firm, very sticky and very plastic. The 2C2 is 27 to 42 inches of brownish yellow gravelly loam. It is massive; slightly hard, friable, slightly sticky and non-plastic. Beyond is a 2Cr of fractured calcareous sandstone.

Ustic Torriorthent is neutral at the A horizon and progressively more alkaline with depth. Permeability is moderately rapid and water capacity is very low. Runoff is rapid and erosion is very high. The average annual precipitation is about 11 to 15 inches with an average annual temperature of 43 to 52 degrees F. The plant community consists of sparse pinyon and juniper with an understory of Scribner needlegrass, blue grama and Indian ricegrass. As soil conditions deteriorate pricklypear, cholla, and yucca increase.

Wesix is a very channery loam. It is shallow and well drained. Wesix soil forms on mountainsides, pediments, canyonsides and cuestas on five to forty degree slopes. Wesix is formed from limestone residuum. The typical Wesix soil has an A/AC/C/R profile. The A horizon is 0 to 3 inches and brown. The structure is weak fine granular; soft very friable, slightly sticky and non-plastic. The AC extends from 3 to 8 inches and is pinkish gray. It has a weak fine subangular blocky structure; soft, very friable, slightly sticky and non-plastic. The C horizon is pale brown and runs from 8 to 13 inches. It's structure is weak fine subangular blocky; slightly hard, very friable, slightly sticky and non-plastic. The R horizon from 13 inches down is fractured limestone bedrock.

On Wesix soils available water capacity is very low and erosion hazard can range from slight to very high. The average annual precipitation is 12 to 14 inches and the annual air temperature is 47 to 52 degrees. The soil is moderately alkaline and strongly effervescent throughout the profile. Vegetation is mainly pinyon and juniper with an understory of sparse grasses and cacti.