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For nearly two decades, foresters in the Oregon Coast Range have been witnessing a substantial decease in Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* [Mirb.] Franco.) vigor and growth, caused by Swiss needle cast (*Phaeocryptopus gaeumannii*). Currently, no solutions are in sight but aerially-applied sulfur may alleviate Swiss needle cast and its growth impacts. In this trial, three treatments were imposed on Douglas-fir trees infected with Swiss needle cast; 1) sulfur, 2) sulfur + nutrients, and 3) no treatment. Volume growth, taper, and other responses to treatments were tested by intensive sampling of 120 trees. Tree attributes such as crown ratio, crown width, and sapwood area at crown base showed no significant differences between treatments. Means of both foliage mass and years of needle retention on a five-year-old sample branch were also not different between sulfur and control treatments. However, both of these attributes were different between the sulfur + nutrient and control treatments ($p = 0.0599, 0.0205$). Using a variable exponent taper model, it was determined that trees within the sulfur treatment did not have a significantly different taper from the control, whereas the sulfur + nutrient treatment did show decreased taper when compared to the control ($p = <0.0246$). This change in taper in the sulfur + nutrient trees however, has not translated into a significant increase in cubic foot volume. Likewise, numerical

integration of the taper equation did not reveal any volume differences between the control and sulfur + nutrient treatments ($p = 0.6087$). The dollar value of trees removed in the first thinning also did not differ among treatments, implying that sulfur and sulfur + nutrient treatments are not able to increase volume enough in four years to produce additional profits in the first commercial thinning.

Taper, Crown, and Volume Responses of a Coastal Oregon Douglas-fir Stand to Sulfur Treatments for Control of Swiss Needle Cast

by

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

Nicole L. Younger

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1 Introduction

The growth impact of Swiss needle cast (SNC) on Oregon Coast Range Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* [Mirb.] Franco.) has been considerable. One of the earliest estimates of volume loss was approximated at 23%, and as high as 50% in severely infected stands (Maguire *et al.* 1998). The disease clogs stomates of current year needles and eventually leads to the premature loss of foliage, which affects both crown structure and dynamics (Weiskittel 2003). Weiskittel and Maguire (2004) also found that foliage retention (which commonly used as a measure of SNC severity) had a significant effect on stem taper. These authors reported that for a given tree diameter at breast height (dbh) and relative height, a reduction in foliage retention significantly reduced diameter inside bark throughout the stem, except below breast height, thereby increasing the amount of taper in a tree with poor needle retention or a high level of SNC infection.

In an attempt to lessen the impact of SNC, several recent studies have found that sulfur, which acts as not only a nutrient but also a fungicide, can decrease the severity of the disease and improve foliage color and retention (Stone *et al*. 2004, Chastagner 2002). This parallels recent discoveries by Williams and Cooper (2003), which have revealed that many plants, including tomato, cotton, tobacco, and French bean, actually hold sulfur in their xylem for an induced defense response against certain types of fungi. The nutritional value of sulfur in trees has been underestimated in the past as well. The Oregon Coast Range is an area naturally rich in available nitrogen (e.g. Perakis *et al.* 2006), which may have aggravated a sulfur deficiency in many areas of this region. It is common for Douglas-fir to exhibit a growth response to N + S treatment, but not to an N treatment alone, as in Northeast Oregon and central Washington (Garrison *et al.* 2000). Analogous responses have also been observed in other conifers from North Carolina to British Columbia (Yang 1998, Brockley 2000).

Sulfur has also been proven safe for aerial application in forests. The 2005 Material Safety Data Sheets reported sulfur to be “considered essentially non-toxic by ingestion”, and “not expected to be toxic to aquatic life” (Baker 2004). This suggests that aerial application of elemental sulfur may be a viable approach for lessening the impact of SNC and simultaneously addressing the sulfur deficiency in Oregon Coast Range Douglas-fir plantations. Only a limited number of studies, however, have actually examined the influence of sulfur on Costal Douglas-fir tree and stand attributes beyond just diameter, height, and SNC infection rates.

The objective of this research project was to determine if tree crown and stem allometrics of Douglas-fir have responded to four years of sulfur and sulfur + nutrient treatments. Specific objectives are to: 1) test the influence of sulfur and sulfur + nutrient treatments on tree-level characteristics such as sapwood area, crown ratio, crown width, foliage biomass, and foliage retention; 2) test for changes in stem taper attributed to the treatments; 3) test for differences among treatments in cubic foot volume and value of logs removed in the first commercial thinning; and 4) describe patterns and shifts in growth allocation along the bole before and after treatment. I hypothesized that aerial application of sulfur for consecutive years may decrease taper, thereby increasing the diameter at the small end of logs, and thereby increasing volume taken out during the first thinning in the Oregon Coast Range.

2 Literature Review

2.1 Sulfur

Sulfur is essential to life. Approximately 0.25% of the human body's mass is sulfur (Harper *et al.* 1977), making it the fourth most plentiful mineral in the human body. Sulfur is found in the muscle, skin, bones, blood and in keratin, the key protein of hair and nails (Mindell 1997). The ancients referred to it as brimstone and included it in the first book of the Bible; even then it had multiple uses. The Greek poet Homer mentioned a "pest-averting sulphur with its properties of divine and purifying fumigation" nearly 2,800 years ago. Today, we use sulfur in black gunpowder, for vulcanization of natural rubber, for production of sulfuric acid, in making of sulfite paper and other papers, as a fumigant, for bleaching of dried fruits, an insulator, a bleaching agent, a disinfectant, and a refrigerant. Despite these many uses, including those in agriculture, until recently it has been overlooked as a fertilizer or fungicide for use in forests.

2.1.1 Sulfur as fertilizer

A fertilizer is a substance applied to soil to enhance its ability to produce plentiful, healthy plants (Jasinski *et al.* 1999). Nitrogen, phosphorous and potassium are the three most commonly added nutrients for crop growth, however, in the past 20 years, sulfur has been increasingly recognized as an essential ingredient for plant nutrition because it is an essential component of amino acids, proteins, fats, and other compounds found in plants. In the soil, sulfur (SO_4) also plays a pivotal role in the movement of acidic cations such as H^+, and Al^{3+}, as well as nutrient cations such as Ca^{2+} and Mg^{2+} (Johnson and Mitchell 1998). The increased use of fertilizers that contain little or no sulfur and the decrease in atmospheric sulfur deposition from reduced industrial emissions have resulted in an increasing soil sulfur deficiency worldwide (Jasinski *et al.* 1999). Recently, attention has begun to shift from monitoring effects of increasing atmospheric deposition of S to understanding the effects of decreasing inputs and S deficiencies in the Northeastern US forested watersheds (Zhang *et al.* 1999). A paired watershed study in Maine was recently completed that showed a significantly higher basal area increment growth of sugar maple in the watershed treated with $(NH_4)_2SO_4$ than the control. The ammonium sulfate treatment was meant to simulate local pollution that has declined in the past few decades (Elvir *et. al* 2003). Even our harvest methods (whole tree vs. limbed) can have an adverse effect on sulfur cycling in forests. Zhang et al. (1999) found that eight years after whole-tree harvesting the S soil constituents differed from the pre-harvest conditions. A large study of foliar nutrition in the Pacific Northwest from 103 different sites found that Douglas-fir had less than the critical foliar sulfur concentration (11%) on ninety-five percent of the sites. The only nutrient more limiting than sulfur was nitrogen, which was found to be less than the critical value on ninety-seven percent of the plots across the Northwestern United States (Moore *et al.* 2004). This conclusion is logical considering none of the test sites were located in the Oregon Coast Range, but scattered throughout Eastern Oregon and Washington, Western Montana, and Idaho, where nitrogen deficiencies are commonplace. The symptoms of S deficiency are similar to those of N deficiency; a fairly uniform chlorosis of foliage and a stunting of growth (Leaf 1968). It's this stunting of growth which could make an investment in sulfur fertilization worthwhile.

Aside from being a fertilizer, sulfur plays a pivotal role in proper utilization of nitrogen fertilizer. Fertilizer additions of specific nutrients can create imbalances of other nutrients and, in turn, lead to reductions in growth and/or negative effects on tree health (Lambert 1986). Turner and others (1979) found that when N deficient Douglas-fir trees were fertilized with urea, the plots that showed a growth response all had adequate levels of SO_4-S in the foliage while two of the four plots that did not show a growth response to the nitrogen fertilization had a SO_4-S deficiency in the foliage. This is due to a known biochemical relationship between S and N. It has been found that there is a constant ratio of 0.030, on a gram atom basis, between organic S and total N in the foliage of healthy conifers (Turner *et al.* 1979, Kelly and Lambert 1972). The results of these studies leave land managers with a potentially important tool for predicting the N/S status of a tree by assessing the SO_4-S in foliage before applying wasteful amounts of nitrogen. This N/S relationship may explain why many nitrogen deficient stands treated with N fertilizers alone show no growth response, and may perhaps aggravate or induce a sulfur deficiency. Brockley (2000) came to similar conclusions about the predictive ability of SO_4-S in *Pinus contorta* (lodgepole pine) foliage. His results showed that in stands which had a pre-fertilization foliar SO_4-S status of less than 60 mg/kg and N/S ratio was less than 13, there was no significant response to N fertilization alone, but always a growth response to N and S fertilization. In a similar fertilization trial with N, N + S and N + K treatments, an N/S ratio of 14.7 was tested. The critical S level was determined from foliar nutrient tests which attempted to satisfy the 14.7 N/S ratio (Garrison *et al.* 2000). After four years, they reported an increase in Douglas-fir volume growth to both the N and N + S treatments, where the N + S plots tended to show greater volume response than the N alone. Similarly, Yang (1998) showed better growth of N and S fertilized stands over N fertilization alone in a 30-year-old *Pinus contorta* stand in Alberta. And once again, in a study of *Pinus radiata* in Southeast Australia, the same conclusions were drawn. Kelley and Lambert (1972) explained this N/S dependency by concluding that nitrogen is only taken up at the rate which sulfur is available. Protein formation is limited by the availability of nitrogen, and nitrogen is limited by sulfur, therefore, sulfur often limits growth. One contradicting study, conducted on Vancouver Island Douglas-fir, found no additional response to S added in conjunction with N (Weetman *et al.* 1997). This was most-likely due to the fact that high sulfur levels were present in the foliage before treatments began. In fact, there was so much sulfur available that not even the added nitrogen induced a sulfur deficiency. Despite the lack of N+S treatment effect, this result lends credibility to the fact that the response can be predictable based on pre-treatment foliage sulfur levels.

Aside from SO_4-S concentrations, an increase in foliar mass the first year after fertilization has also been proven to be a good predictor of tree growth response (Brockley 2000, Brockley and Sheran 1994, Valentine and Allen 1990). This “screening” method is used on smaller candidate stands to determine nutrient deficiencies before applying the treatment at a larger scale.

To further test the contribution of S during N fertilization, trials were conducted in Douglas-fir stands in the Pacific Northwest (Blake *et al.* 1990). This study included surface soil cores and subsoil samples to assess presence of nutrients before treatments as well as foliar sampling and growth response analysis. The conclusions in this study were different. They found that supplemental additions of SO_4-S as $(NH_4)2SO_4$ did not consistently improve average N responses in stands characterized by the soil SO_4-S criteria used. Sulfur did improve growth, but not at predictable rates. They partially attributed this result to stand clumpiness in N+S treatment plots.

A greenhouse study conducted on two different hybrid aspens tested the diameter, leaf area and biomass growth when treated with different combinations of sulfur and phosphorous (Liang and Chang 2004). They concluded that to achieve the best growth response, applying S with P is recommended, as the effect of S application is dependent on the level of P supply in the soil for most of the measured growth parameters.

There are multiple forms of sulfur available for fertilization. When looking for an immediate response, ammonium sulfate (AS) is superior over elemental sulfur (S^0) due to the slow oxidization of the elemental prills (Brockley and Sheran 1994). However, it has been determined that despite its delayed oxidation, S^0 was as effective as the more readily available AS in stimulating radial growth after six years in lodgepole pine and both forms are equally effective in alleviating S deficiencies (Brockley 2004). In Wales, a fertilization study used gypsum as the sulfur source and saw a positive growth response (Lambert 1986).

Application rates of sulfur for forest fertilization have been examined in many studies. Two rates, 50 and 100 kg/ha, of sulfur hand application in a British Columbia lodgeple pine forest were tested by Brockley (2004). He reported only a modest improvement in foliar S concentration from 50 to 100 kg/ha for both sulfur sources, AS and S^0.

2.1.2 Sulfur as a fungicide

Elemental sulfur is man's oldest fungicide (Williams and Cooper 2004). Literature on the use of sulfur as a fungicide dates back hundreds of years and is often inaccessible and overly qualitative. With recent discoveries of plants producing sulfur as a natural fungal defense, interest has risen considerably. An additional reason for using sulfur as a fungicide is its negligible toxicity to animals and low toxicity to plants, including a low toxicity to beneficial insects (Williams and Cooper 2004). Sulfur is even considered an "organic" fungicide to many modern horticulturists (Wolford 2005). The material data safety sheets (MSDS) for sulfur claim that it is, "Considered essentially non-toxic by ingestion", skin and eye contact may cause irritation, while the inhalation danger is only as a nuisance dust (Baker 2004). The MSDS also directly states that, "this material is not expected to be toxic to aquatic life".

In 1996, elemental sulfur was first found in xylem of resistant and not in susceptible genotypes of *Theobroma cacao* in response to *Verticillium dahliae*, a fungus, making it the only known, inorganic phytoalexin (Williams and Cooper 2003). In a 2003 study by Williams and Cooper they tested several other species of plants and fungi to find that sulfur formation may be widespread in higher plants as an induced defense response. These species included tomato, cotton, tobacco, and French bean.

The mode of action of elemental sulfur fungicide is still highly debated but the current accepted hypothesis is that fungal cells are permeable to S^0, so it is taken up into the cytoplasm where it affects the mitochondrial respiratory chain (Williams and Cooper 2004).

2.1.3 Current fungicidal uses of sulfur in agriculture

As previously discussed, sulfur is undoubtedly the oldest fungicide. Its biological properties make it practically inescapable in modern pesticide formulations. Approximately one-third of all registered pesticides contain at least one sulfur atom (Lamberth 2004).

Crops such as peaches, nectarines, plums, prunes, almonds, and cherries have long been treated with sulfur for control of rusts and scabs. Prior to 1998, sulfur compounds were the only fungicides registered for use on Prunus spp. against rusts in the United States (Soto-Estrada *et al.* 2003). It was found that rust lesions on these fruit trees were significantly reduced by six different fungicides, their common names being; benomyl, azoxystrobin, chlorothalonil, tebuconazole, myclobutanil, and wettable sulfur. None of the success rates between these fungicides were significantly different, although it was noted that when ideal environmental conditions for the disease existed and stem lesions were already present, single applications of azoxystrobin or tebuconazole were more effective than sulfur (Soto-Estrada *et al.* 2003). However, it also seems the efficacy of sulfur treatments may vary based on what kind of sulfur is used. Ritchie and Pollard (2003) found that micronized wettable sulfur, which consists of much finer sulfur particles, may provide more effective control than wettable sulfur against peach scab.

Sulfur has also long been used in combating the effects of powdery mildews on crops such as soybean, chicory and others. Although alternate products have been identified for powdery mildew control, sulfur continues to be recommended for control of powdery mildew due to its efficacy, low costs, and low mammalian toxicity (Yorinori *et al.* 2004). In comparing sulfur to two other environmentally friendly and natural fungicides, soya lecithin and salicylic acid, for control of powdery mildew on chicory, sulfur proved to be superior by significantly firming heads and increasing yields (Trdan *et al.* 2004).

Reductions of flax yields caused by pasmo throughout the Canadian provinces of Manitoba and Saskatchewan and now in North Dakota, have prompted research into identifying controlling products. Not surprisingly, sulfur, as well as azoxystrobin, significantly reduced pasmo infection when compared to a control. However, when it came to significantly improving the yields of pasmo infected flax, azoxystrobin and prothioconazole outperformed sulfur (Halley *et al.* 2004).

Perhaps the most impressive aspect of sulfur's effectiveness in crop protection is the fact that it is also considered organic. The National Organic Program Standards (NOPS) conceived by the USDA, allows the use of products such as lime sulfur and elemental sulfur. Ironically though, many modern pesticide management plans call for other fungicidal products because they require fewer applications. These other products are not necessarily more effective than sulfur when it comes to scab in fruits but Schnabel and Layne (2004) found that reduced-fungicide programs consisting of chlorothalonil, captan, or azoxystrobin were more effective than sulfur against other peach diseases such as brown rot and anthracnose. Despite much successful research in sulfur-alternatives, peach growers in the Southeastern United States continue to favor frequently applied sulfur as opposed to more expensive, but more effective, fungicides which are only applied four to five times per year (Schnabel and Layne 2004). Even in Tanzania where farmers use sulfur to protect their cashew plants from powdery mildew, overuse is an issue. This is a concern due to the cost of additional unnecessary sulfur, and deleterious soil acidification (Nathaniels *et al.* 2003). In Iran, where sulfur is a byproduct of the local petroleum industry, the use of sulfur in agriculture is encouraged. The high use of sulfur there has prompted studies concerning the breakdown of agricultural sulfur to H_2SO_4. Sameni and Kasraian (2004) while studying this, pointed out that there can be substantial benefits to sulfur oxidization in alkaline soils such as a supply of SO_4 to plants, and a reduction of pH making micronutrients such as P and Mn more available to plants. However, they concluded, after testing the oxidization of the petroleum byproduct (a 90% Sulfur, 10% bentonite powder) for pH, SO_4 content and EC, that there was not a significant difference between the control and the treated soils.

Timing of sulfur spraying on peach crops for protection against fungi has been shown to be critical. Ideal timing seems to vary based on weather events (Soto-Estrada *et al.* 2003), and the biology of the target fungus (Scherm and Savelle 2001). Soto-Estrada found that application of wettable sulfur was effective at decreasing stone fruit rust infections when applied prior to forecasted rains, and after lesion detection. They also suggested that efficacy may depend on temperatures being above 15°C. Logically so, the biology of the target fungus is also intimately related to the timing of fungicide application. This was particularly obvious to a group of researchers in Georgia who were attempting to reduce midseason fungicide sprays of wettable sulfur on peach. These conclusions are most likely also true of sulfur application on SNC infected Douglas-fir.

2.2 Swiss Needle Cast

2.2.1 Impacts on Douglas-fir

Swiss needle cast (SNC) is a leaf pathogen caused by the fungus *Phaecryptopus gaeumannii*. Although native to the Pacific Northwest it was first recognized in Switzerland in the mid-1920's in young Douglas-fir plantations established with seedlings from America (Stone 2006). It was first reported in the United States in 1938, and by 1940 it was wide spread in New England. It was initially assumed that SNC flourished when Douglas-firs were planted in sub-optimal conditions, however, severity of SNC impacts began to increase rapidly in the Pacific Northwest in the 1980's, forcing scientists to look upon this disease as much more than just a consequence of poor site selection (Hansen *et al.* 2000).

P. gaeumannii destroys needles on Douglas-fir by disrupting gas exchange in the needle by clogging stomata with pseudothecia (Manter 2000). These fruiting bodies can be seen on infected needles as rows of black 0.1 mm dots on the needles' underside (Worrall 2005). Tree symptoms typically appear a few years after infection when the oldest needles become chlorotic, then brown and drop. The number of pseudothecia generally increases with age of the needle, though defoliation has been found to be directly related to the number of stomata clogged by the pseudothecia of the fungus. Needles are generally shed when approximately 50% of stomata are occupied, regardless of needle age (Hansen *et al.* 2000). After the death of older needles that would have previously been present, the trees crown appears thin. It was originally thought that only tightly spaced plantations were susceptible but the recently vigorous

SNC in the PNW has not followed this rule, attacking even large open grown trees (Worrall 2005).

The primary indicator of SNC is the premature loss of needles. In the Oregon Coast Range, healthy Douglas-fir typically retains three to four years of needles or more (Filip *et al.* 2000). When SNC is severe, only one cohort may be present. In a 1997 - 2004 survey of SNC severity across the Oregon Coast Range it was determined that mean foliage retention has changed very little, remaining between 2.17 years and 2.47 years of needles retained (Kanaskie and Maguire 2004). In general, it has been found that conifers generally hold their needles between two and ten years (Kikuzawa and Ackerly 1999). This can vary considerably within a species based on things such as crown position (Niinemets 1997), branch growth rate (Balster and Marshall 2000), tree age (Maillette 1982), total tree height (Xiao 2003), and genetics (McCrady and Jokela 1996). Needle longevity is also affected by several site factors such as nutrition (Balster and Marshall 2000), density (Piene and Fleming 1996), altitude and latitude (Reich *et al.* 1996, Xiao 2003), and of course diseases such as SNC. Besides longevity, needle color is also an indicator of SNC. In late winter to early spring SNC trees are easily spotted by the yellow to yellow brown color that occurs fairly uniformly across the stand.

Permanent plots in the Oregon Coast Range have shown that mean foliage retention is lowest in the upper third of the tree crown and greatest in the bottom third of the tree crown (Kanaskie and Maguire 2004). This finding was supported by Weiskittel et al. (2006), who found that SNC infected crowns have a greater portion of their current and 1-year-old needles located higher in the crown while the 2-, 3-, and 4-year-old needles are shifted towards the bottom of the crown relative to healthy crowns. Weiskittel (2003) also revealed that the number of secondary lateral branches declined in response to SNC, and branches in the lower portion of the crown actually elongated faster. Crown recession is also altered by the severe needle loss caused by SNC. Defoliation may negatively impact tree height growth, as well as alter the within crown light environment, causing the crown base to rise faster, resulting in lower crown ratios in diseased trees.

The growth impacts SNC has had on Oregon Coast Range forests have been considerable. One of the earliest estimates of volume loss was estimated at 23% on average and as high as 50% in the severely infected stands. Spread over the infected region, 187,000 acres, means that approximately 40 million board feet were lost to this disease in 1996 alone (Maguire *et al.* 1998). Because SNC has existed in the Coast Range to some degree for decades, it is now thought that perhaps growth expectations have actually been lowered due to its constant presence. Further analysis is currently underway to determine to what degree SNC has actually lowered growth expectations; thereby underestimating growth losses (Maguire *et al.* 2004). Even more concerning is that the 2006 SNC aerial surveys indicated a marked increase in the area of forest with symptoms, compared to the previous three years (Kanaskie *et al.* 1996). In the 1996 survey, infected area was conservatively estimated at 325,000 acres.

Stem properties such as taper and sapwood area are strongly controlled by the crown of a tree. Previous work has shown that SNC can affect stem properties by narrowing sapwood, narrowing growth rings, lowering sapwood moisture content, and increasing wood density while decreasing the overall weight (Johnson *et al.* 2003). Weiskittel and Maguire (2004) found that SNC, as measured by foliage retention, had a significant effect on stem taper. They found that for a given DBH and relative height, a reduction of foliage retention significantly reduced diameter inside bark throughout the stem, except below breast height, thereby making the stem more conical.

2.2.2 Current management options for Swiss needle cast

Fertilization of a healthy tree is expected to considerably improve needle and crown attributes. It was previously thought that by increasing crown size, or leaf area, with fertilization, a tree will be less severely affected by SNC. Brix (1981) found that Douglas-fir needle size, number of needles per shoot and number of shoots increased significantly after fertilization, increasing the overall stand dry matter production. Along these same lines, Zeide and Gresham (1991) found that crowns were denser on better quality sites, and Brockley and Simpson (2004) studying fertilization of spruce and lodgepole pine in British Columbia also found a significant increase in leaf area after application of nitrogen with other nutrients. There are a wealth of studies which show improved needle characteristics after fertilization. Curiously, Pensa and Sellin (2002) have seen needle longevity decrease as site fertility increases. Along these same lines, Balaster and Marshall (2000) found a decrease in foliar retention after fertilization of a healthy stand. Despite these discrepancies, the question here is whether fertilization is beneficial to trees infected by SNC.

Some have theorized that abundant nitrogen in the Oregon Coast Range actually predisposed it to the SNC outbreak in the first place (Waring *et al.* 2000). The excess of available nitrogen in the Coast Range caused ratios between N and other nutrients to be unusually high, forcing the tree to store the N in its needles as soluble amino acids, a form which favors fungal growth. Supporting this theory, strong negative correlations have been found between percent dry weight of N in the needles and needle retention (Crane *et al.* 2000). More recently, a study of fertilization of Douglas-fir with combinations of N, P, K and micronutrients suggested that highly infected trees should not be fertilized. The greatest volume responses to these fertilizers occurred when foliar %N was low, and foliage retention was high (Mainwaring *et al.* 2005). As previously noted, SNC infected trees often have a relatively high %N and lower foliage retention, making them poor candidates for fertilization with nitrogen.

Application of a variety of fungicides has been tested in combating SNC disease. Chorothalonil (Stone *et al.* 2004) was aerially sprayed as Bravo WeatherStik 720 at a rate of 5.5 pt/30gal./acre for five consecutive years in a young Oregon Douglas-fir plantation. They found significantly reduced infection levels and increased needle retention a year after the last treatment; however the follow-up data collection revealed that the residual effect of this fungicidal treatment on inoculum reduction lasted only two years. The lack of a residual effect was noted in many other studies as well (Stone *et al.* 2005). Thiolux micronized elemental sulfur was aerially applied to Douglas-fir plantations at a rate of 60 lbs/acre. For the two years following the application, infection of one year old foliage was reduced significantly in all treated plots (Stone *et al.* 2004). In a Washington study, a one time application of Thiolux, several copper fungicides, a biologically-based material, and Daconil WeatherStick were tested for reduction in needle pseudothecia counts. The only significantly successful fungicides were Kocide and Daconil Weatherstik (Stone *et al.* 2004). Daconil was also proven to be successful in significantly lowering the levels of SNC, improving needle coloration, and generally decreasing needle loss when sprayed for three consecutive years (Chastagner 2002). Stone *et al.* (2005) suggested, after observing lower incidences of SNC after spraying elemental sulfur, that additional research is needed to determine the effects of sulfur fungicide sprays on tree growth.

As many second growth Douglas-fir plantations in the Oregon Coast Range near time for thinning, managers are forced to consider the effects that thinning either commercially or precommercially may have on the severity of SNC. In healthy trees, Albaugh *et al.* (2006) determined that in stands where nutrients and water were adequate but light and space limitations developed, individual tree foliage mass development could be increased with thinning. Growth of SNC infected trees after a thinning depends primarily upon two factors. The first being the net effect of basal area removal and secondly, the lower stand basal area. Research in Oregon has determined that the change in severity of SNC is independent of growth response after thinning (Mainwaring *et al.* 2005). In New Zealand, experiments were done to test if infected stands thinned to 90 and 300 stems per acre improved or worsened SNC severity. They found both treatments were not statistically different from unthinned control stands, and also noted that neither of the treatments improved needle density or retention (Hood and Sandberg 1979). After following the needle retention response on thinned Douglas-fir for two years, Mainwaring et al. (2005) found that in the more heavily SNC infected stands the first year after thinning retention decreased about 0.2 years, and the second year saw an increase of 0.3 years. They also saw a positive basal area response to thinning, although less so as SNC severity increased.

It is currently believed that thinning SNC infected stands will most likely be beneficial due to the increased amount of resources available to residual trees. In addition, it has been recommended that the traditional 'thinning from below' method be used, as this technique removes trees that are more susceptible to the fungus, leaving the trees with the better traits (Mainwaring *et. al.* 2005).

2.3 Tree Crown and Needle Attributes

2.3.1 Sparseness

Crown sparseness is a measure of leaf area density and is very useful for assessment of foliage loss or retention. Much like crown ratio and volume, sparseness can help to predict tree growth. Unlike these measures however, sparseness is a better indicator of disease impacts, and estimation of susceptibility (Waring and Pitman 1985) because it takes into account density of leaves by including sapwood area. When defoliating agents are involved, gross crown dimensions alone often overestimate total foliage area. To obtain this index of crown sparseness, a stem disk from crown base is removed to measure sapwood area (cm^2), and crown length is obtained by measuring the distance from the lowest live branch to the tip of the terminal leader. Dividing crown length (CL) by sapwood area (SA) provides the sparseness index for an individual tree. There is strong evidence that CL:SA can help predict foliage mass of two year old needles in SNC infected Douglas-fir (Maguire and Kanaskie 2002). The second year needles are a common measure of SNC severity and this relationship may be utilized. The same study also showed that plot basal area declined significantly as the sparseness increased. Weiskittel and Maguire (2004) studied the sparseness response to silvicultural treatments of fertilization, vegetation management and thinning and found that only the pre-commercially thinned plots revealed a change in CL:SA. They also found a CL:SA difference through time in SNC infected plots. It should be noted that the significant decrease in CL:SA after thinning supports the emerging trend of improved needle retention in thinned plots.

2.3.2 Crown profile and volume

Crown volume, a useful surrogate for photosynthetic active foliage, is typically quantified via measures of crown width and length (Avery and Burkhart 2002). In order to make an accurate measure of volume however, defining a profile is useful. Hann (1999) created a direct, deterministic profile equation specifically for Coast Range Douglas-fir. This equation fits well with the fact that the widest branch on a crown (LCW) does not always occur at the bottom of the crown. The top of the crown and the bottom of the crown (the cylindrical shaped section below the LCW) are modeled differently to account for this. Once crown width is defined, the crown width at any height within the crown can be predicted. Weiskittel (2003) created a crown profile model by modifying Kozak's 1988 stem taper equation. It described the trend in crown radius over height within the crown, assuming that crown radius is a nonlinear function of predicted maximum crown width, branch position, and tree descriptors. Marshall et al. (2003) created crown profile equations for stand grown western hemlock in Northwestern Oregon. This model uses Hann's 1999 methods, including a constant "k" which can be changed to model for a variety of geometric solids. Roeh and Maguire (1997) created a profile equation for coastal Douglas-fir which uses a more indirect method of measuring branch characteristics along the bole and then predicting crown width from those relationships. Baldwin et al. (1997) created a polynomial function which modeled the outer crown radius from crown height and crown length variables. This model is unique in that it simultaneously models a roughly conical area of defoliation within the live crown as a function of relative crown height. Dubrasich, Hann and Tappeiner (1997) created a weighted nonlinear regression equation which estimated crown width at crown base for unmeasured trees with the variables maximum crown width, crown ratio, crown length, DBH, and total height, as well as additional terms for taper. Volumes were then determined with the objective of comparing wildlife habitats in Oregon.

2.3.3 Crown ratio

Crown ratio (CR) is generally defined as the ratio of the length of the live crown (CL) to total tree height (H). A larger crown ratio is generally expected to produce higher growth rates for trees of a given species and age, and due to its ease of measurement in the field, it is frequently utilized in growth and yield models. Shaw et al. (2003) determined CR to be a significant variable when predicting taper in longleaf pine. However, crown ratio is also valuable as an indicator of general tree health and vigor, can be an important feature of wildlife habitat, and can even be used to answer other ecosystem questions (Schomaker 2003). Monleon et al. (2004) examined the differences between compacted and uncompacted crown ratios and the effect these differences have on torching indices used to predict crown fire risk. This study highlights the importance of relating how CR is measured in the field to the questions being asked. Temesgen et al. (2005) used a logistic model that predicts CR from size, competition and site variables in complex forest stands in Southeastern British Columbia. The size variables which predicted CR well included diameter outside bark at DBH, tree height, and slenderness. Site attributes were quantified with elevation, slope and aspect. Competition from surrounding trees was also included as it significantly affects CR of subject trees. These variables included crown competition factor as well as basal area per hectare for larger trees. Ritchie and Hann (1987) developed and fit logistic equations for predicting height to crown base for several tree species in Oregon using nonlinear regression. Their model variables included height, crown competition factor, stand basal area, site index and diameter divided by height. The accuracy of the bole-ratio predictions when compared to the true bole ratios were best for Douglas-fir and ponderosa pine of the fourteen species examined. Maguire and Hann (1990) took crown ratio prediction one step further by creating a multiplicative model with lognormal errors for predicting five year crown recession in Southwestern Oregon Douglas-fir. They used current crown ratio and height, breast height age, height growth, and crown competition factor as explanatory variables. This model could allow a user to predict recession rates and therefore crown volumes into the future.

2.3.4 Prediction of leaf area

Direct measurements of leaf area can be very costly and time consuming, knowing this, an allometric model, which predicts leaf area from sapwood area, was created (Shinozaki *et. al.*1964). The original idea was that a set of cylindrical pipes, being the sapwood, connects the foliage with the roots, and a certain amount of transpirating foliage requires a proportional amount of conducting pipe. This is commonly known as the "pipe model theory". Since then many attempts have been made to try to improve this theory by adding additional explanatory variables. Ninety-four to 99% of variation in leaf area was explained by sapwood area at breast height, crown ratio and length, and crown competition factor in conifers of northern Idaho (Monserud and Marshall 1999). Like the study above, many have attempted to simplify the process of obtaining sapwood area at crown base by taking into account the taper of the sapwood down to breast height where the measurement is easier to obtain. However, Stancioiu et al. (2005) concluded that the measurement of sapwood at the base of the live crown considerably improved leaf area predictions over the breast height sapwood measurement. This suggests that when obtaining a crown base disk is possible, it is the preferred method for predicting leaf area. Many models which fit sapwood taper to existing tree bole taper models exist with varying degrees of success (e.g., Waring *et al.* 1982, Maguire and Hann 1987, Stancioiu and O'Hara 2005, etc.). The pipe model theory has even been the basis for entire growth models by estimating growth rates of tree basal area and height (Valentine 1985).

Models were also developed to predict sapwood area at crown base from DBH, total height and height to crown base for Douglas-fir (Maguire and Hann 1987). In 1989 Maguire and Hann further improved these models by including covariates such as crown length, radius, and crown base stem diameter on Oregon Douglas-fir to try to predict the CB sapwood area. They found that no single variable was a good predictor of CB sapwood area, but combinations representing conic surface area preformed well. They went on to conclude that this surface area should accurately reflect total leaf area given the strong relationship found between sapwood area and leaf area in Douglas-fir. Maguire and Batista (1996) did a thorough study of sapwood taper for coastal Douglas-fir across Oregon, Washington and British Columbia. They fit ten different known bole taper equations to sapwood taper and found that a variable exponent model with six parameters and three basic tree-level predictors, diameter, height, and height to CB, preformed best.

The pipe model ratio, the ratio between foliage biomass and sapwood area, has been found to vary depending on site quality (Berninger *et al.* 2005), stand density (Shelburne *et al.* 1993), local climate (Whitehead *et al.* 1984) and perhaps even maximum height (Yoder *et al.* 1994).

Although sapwood area measurements have been proven to make leaf area estimates more accurate, other studies show that it doesn't always improve the model. Snell and Brown (1978) found sapwood area to be significant for three western conifers, one of which was Douglas-fir, but in the other four conifer species sapwood area was no better than DBH as a foliage biomass predictor. Others have found that leaf area within a crown is not distributed uniformly. Breaking the crown into three strata, lower, middle and upper Valentine et al. (1994) found that there was less foliar dry matter per unit of cross-sectional area in the lower stratum than in the other two strata.

In conclusion, it seems that both structural (DBH, crown dimensions, stand characteristics, etc.) and physiological (pipe model) variables can be used to compliment one another to find the very best leaf area predictions possible.

2.4 Tree Form and Volume

2.4.1 Diameter growth distribution along the stem

Because certain silvicultural treatments may influence the form of a tree, it is inappropriate to measure diameter growth at one point along the bole and assume that the same growth response is occurring along the entire length of the bole. There is a strong, yet complex connection between the bole and the crown which it supports.

Thus, any treatment or disease which influences foliage distribution in the crown influences the bole form as well. Studies on this subject have related diameter growth along the bole to crown characteristics, stand density, stand nutrition/fertilization, as well as environmental factors.

Most pertinent to this study, and most controversial of these factors which determine diameter growth along the bole, is fertilization. How different types of fertilizer affect tree taper have been examined many times, yet conflicting results still exist. Karlsson (2000), in a study of taper after thinning and nitrogen application in Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) saw a more pronounced taper in trees thinned and fertilized as opposed to trees that were only thinned. He attributes the increase in taper to the additional leaf area, and hence growth, which is being allocated to the lower portion of the stem while height growth remains constant. Mead and Tamm (1988) concentrated on taper as part of an 'optimum fertility experiment' in Norway spruce and found an increase in average tree taper associated with nitrogen, and the 'complete fertilizer' application. Other similar studies have also found an increase in taper after fertilization (Sterba 1978, Gordon and Graham 1986). Contradicting those findings, Valinger (1992) claimed an increase in biomass in the upper stem, decreasing taper. Not surprisingly, other authors also received mixed results. Miller and Cooper (1973) fertilized Corsican pine on a poor site with varying amounts of ammonium sulfate and elemental nitrogen. They determined that form factor remained unaltered while taper changed only slightly. Groot et al. (1984) factorially applied treatments of thinning and urea fertilization on jack pine to find an overall slight decrease in form factor but indicated that fertilization had a positive effect on form factor.

2.4.2 Taper

It is common knowledge that the diameter of a tree deceases from the ground to the tip of the tree. The exact way in which stem diameter decreases, or tapers, along the bole in different tree species and under different conditions is still an area of active research. For a given basal area, a stem with less taper will yield a greater volume than a stem that tapers strongly. With ever diversifying wood products, being able to estimate the amount of each product available in any given stand can only be done with the assistance of a good taper equation. Volume equations only yield a stem volume. Taper equations however, can make those volume estimates considerably better as well as make it possible to estimate inside bark diameter at any point on the bole, merchantable volume or height between any given top and stump diameter, as well as provide individual log volumes at any length of log.

In earlier attempts to model tree taper, a single model was used to represent the entire bole length. These equations were empirical in nature as opposed to being based on geometry. Behre (1923) published one of the earliest single taper equations in America. He noted that for the western second growth species the previous equations from Europe and even the East coast were not working due to a “falling off in the tops”, as well as a very difficult to deal with root swell which increases gradually with size (Behre 1923). He proposed an equation with a hyperbolic form which fit western species better than the traditional equation of the time created by A. G. Höjer of Stockholm in 1903.

In 1949 another simple single function taper equation was published (Matte 1949). Matte realized that a tree is a cylindrical solid whose volume could be determined by the revolution about an axis, as in an integral. The only problem was determining the function which represented taper. He addressed the two major problems with taper equations of the time, 1) determining the function which described taper without the “falling off in the tops” or the underestimation of taper in the butt of the tree, and 2) the effect of tree-size upon stem form.

In 1969, Kozak et al. published a single function equation which was parabolic as well (Kozak *et al.* 1969). There were initial difficulties with negative diameters in the top third of spruce and cedar as well as cases of overestimated top third diameters in other species. The negative diameters were corrected by forcing the regression constants to yield only one root of X. In the end, only 17 of the 19 species groups tested had standard errors of the estimates that were less than 2, and only 9 species had standard errors of less than 1. The two species with the highest standard errors were Douglas-fir and sitka spruce.

Butt flare in larger trees frequently resulted in large standard errors near the bottom of the trees when using single function taper equations (Kozak 1969). Others reported on this same complication with this type of equation (Ormerod 1973) this was dealt with through the use of awkward assumptions. The simplicity that was the downfall of these equations was, at the time, also a necessity. But without the help of computers, which would advance taper functions decades later, these equations were the best available.

2.4.2.1 Segmented Polynomial Taper Models

Max and Burkhart (1976) were the first to use a segmented polynomial regression model to predict taper. In this equation the three different geometric solids which make up the shape of a tree, neiloid frustum, paraboloid frustum, and cone each represent one of the three segments of the segmented polynomial. The domain is partitioned and each sub model is defined on each section. These sub models are then grafted together at join points by imposing restrictions on the model in such a way that the entire function is continuous. These join points must then be estimated by using a modified Gauss-Newton nonlinear least squares procedure. Four versions of the segmented polynomial equation were tested; (i) two quadratic functions grafted at one join point, (ii) two quadratic functions, one join point with the added restriction that diameter is zero at the tip of the tree ($\hat{y} = 0$ when $x = 1$), (iii) one quadratic to represent the butt, a first degree polynomial for the middle section, and a quadratic with the same restriction, and two join points (iv) same as previous only the center function is quadratic as opposed to linear. Max and Burkhart concluded that model (iii) fit well for plantation trees of smaller heights while model (iv) was a better all around model due to the longer center section of the bole between the two join points which was quadratic. Model (iv) is displayed below as equation 1.

$$Y = \beta_1(x-1) + \beta_2(x^2-1) + \beta_3(\alpha_1 - x)^2 I_+(\alpha_1 - x) + \beta_4(\alpha_2 - x)^2 I_+(\alpha_2 - x) + \varepsilon \quad [1]$$

Where: $Y = d^2/D^2$

α_1 = upper join point

α_2 = lower join point

$I_+(\alpha_1 - x)$ = 1 when $(\alpha_1\text{-x}) \geq 0$, 0 otherwise

$I_+(\alpha_2 - x)$ = 1 when $(\alpha_2\text{-x}) \geq 0$, 0 otherwise

x = h/H (h = height above ground, H = total height)

β_1 through β_4 are parameters to be estimated

This method of defining taper was used by several other authors in the 1970's and early 1980's including Ormerod (1973), Demaerschalk and Kozak (1977), Cao et al. (1980), and Clark et al. (1991).

Ormerod, believing firmly in the value of a geometric based taper model as opposed to empirical models, created a model in 1973 that used just two sections with the inflection point estimated to be at .3 of total height. He compared his equation with Kozak's 1969 model and found the standard errors to be better. However, Ormerod's assumption that DBH outside bark is equal to DIB at one foot had to be made to deal with butt swell, and the diameter and height at the inflection point had to be measured or at least estimated, making timber cruising costly. One advantage was the ease of integration for determining volumes. Although it dealt with butt swell better than single function equations, there were still substantial drawbacks to the improved accuracy.

A similar "dual-equation" system was later created and tested on 32 species and ecozones in British Columbia (Demaerschalk and Kozak 1977). After testing seven common taper models they concluded that they were all biased and this pattern of bias changed from one site class to another. This led them to create a model with attributes addressing the shortcomings of previous models, these being; continuity at inflection points, conditioning to result in a zero diameter at the tip of the tree, intersection of diameter inside bark at breast height, and not basing the equation on an outside bark diameter which is often highly affected by butt swell in many species. This new and improved equation breaks the tree into two geometrically different sections and predicts diameter inside bark at any height with much improved accuracy through the entire bole, except at the butt where swell continues to be a problem. The major disadvantage in this equation was that it was far too complicated for use with a calculator and required a computer which was not assessable to everyone at that time.

In 1980, Cao, along with Burkhart and Max examined integratable taper equations and how they relate to volume ratio models in an attempt to most accurately predict volume from any given height on a tree to a specified merchantable top diameter. The simple quadratic equations, Ormerod (1973), Demaerschalk (1973), Honer (1967), and Kozak *et al.* (1969), all performed poorly in diameter estimation as well as volume estimation. It was concluded that Max and Burkhart's 1976 equation predicted tree diameters very well, and after a few modifications, was the best model for predicting volumes to top diameters as well. For predicting volumes to various heights however, a new model based on Burkhart's 1977 taper equation was the most successful. This non-linear model estimated volume from heights instead of diameters. The primary conclusion from all this model testing was the simple notion that no one model can do it all, so when choosing a model, the desired outcomes must first be determined.

In the early nineties, the United States Forest Service wanted to find the best taper and volume equations that gave not only board feet, but cubic feet as well. With computer use becoming more common, they were eager to implement the more complicated models for better predictive ability. In the Southeast US, these issues were addressed very thoroughly by Clark et al. (1991). Recognizing the conclusions drawn in the Cao et al. 1980 paper, Clark et al. tested three different models which each seemed to have slightly different strengths. These were Max and Burkhart's (1976) and Cao's (1980) segmented polynomial equations and Schlaegel's (1983) form-class profile model. It was determined that a combination between Max and Burkhart's segmented polynomial and Schlaegel's form-class profile model was the single ideal equation for that US region and coefficients were determined for 58 different southern species. This equation had very good predictive abilities, its biggest disadvantage was that it required a measure of diameter at 17.3 feet, the top of the first log.

The method of using segmented polynomials for predicting diameters proved to have far less bias than earlier single function equations but they were not without disadvantages. The parameters were often hard to estimate, and integrating to find volume and/or merchantable height was often difficult or impossible (Kozak 1988). As Cao (1980) concluded, with so many equations to choose from at that point in time it was important to weigh the pros and cons of each, the desired end-product, and the availability of computers before choosing the best suited taper model.

2.4.2.2 Variable Exponent Taper Models

Kozak's 1988 variable-exponent taper equation was an important advancement in taper modeling because it eliminated the necessity of using several functions and replaced it with one tidy equation which employed a changing exponent (variable exponent) to signal the change in tree shape; these being, neiloid, paraboloid, and conic. Most previous equations quantified taper with just two bole shapes. After linearizing with a logarithmic transformation Kozak's 1988 equation can be written as:

$$\ln(d_i) = \ln(a_0) + a_1 \ln(D) + \ln(a_2)D + b_1\ln(X)Z^2 + b_2\ln(X)\ln(Z + 0.001) + b_3\ln(X)\sqrt{Z} + b_4 \ln(x)e^z + b_5\ln(X)\left(\frac{D}{H}\right) \quad [2]$$

Where: $X = \left(1 - \sqrt{\frac{hi}{H}}\right) \Big/ \left(1 - \sqrt{p}\right)$

p = (HI/H)*100
d_i = diameter inside bark
D = diameter outside bark at breast height
h_i = height from ground
H = total height of tree
Z = h_i/H

Using over 32,000 trees from 33 different species, this equation was tested by average biases and standard errors of estimates. It was found to perform much better than whole bole estimating systems. Although it performs much better than older techniques it must be noted that this equation cannot be integrated to calculate volume. Volumes must be found through numerical integration.

Effects of adding crown class, site class and breast height age variables to Kozak's 1988 equation was examined a few years later in Douglas-fir and other species (Muhairwe *et al.* 1994). They determined that the additional variables resulted in only marginal improvements in prediction abilities of diameter inside bark, total volume and merchantable height and, therefore, taking these additional measurements was not justifiable.

Kozak (1977) noted that the variable exponent equation has two theoretical problems. First is the high multicollinearity among some of the independent variables, particularly ones containing some transformation of the h_i/H regressor variable. Secondly, like all taper equations ever fitted, there are fairly strong autocorrelations on the multiple measurements taken within each tree. The later of these two issues will be discussed in more depth in the mixed modeling section.

In the 1980's, variable exponent equations for modeling taper gained popularity as many authors began fitting the form to their own data sets. These included Newberry and Burkhart (1986), Newnham (1988), and Newnham (1992). Newberry and Burkhart (1986) incorporated both form and taper changes into variable –form stem profile models for loblolly pine. This meant that an additional variable, such as crown ratio, tree age, height to base of live crown, site index, basal area or trees per area could also be used to strengthen taper equations. Coefficients were estimated for each additional stand and tree characteristics. No definite conclusions were drawn though, due to complications in the error structures of correlated data and perhaps too small of a sample size. Newnham (1988) showed that for plantation-grown red pine stands, his variable form model was more satisfactory than the segmented polynomial model of Max and Burkhart (1976). In 1992, Newnham again compared the improved variable form model to Max and Burkhart (1976), as well as Kozak's (1988) taper equation. In his comparison, 7367 trees, made up of four species, were fit with a variable form taper function in Alberta (Newnham 1992). This variable form model was very similar to Kozak's (1988) equation, the major difference being the varying exponent, which controlled tree shape. In Newnham's (1988) model it was allowed to change at different heights along the bole whereas in Kozak's (1988) model it was fixed within each stem section. It was determined that the variable exponent (Kozak 1988) and segmented polynomial (Max and Burkhart 1976) models performed consistently poorer in estimation of both upper stem diameter and stem volumes based on residual mean squares. Although Newnham (1992) could not conclude that his variable form equation performed better than Kozak's (1988) equation overall, he did prove that the variable form taper function had a lot of potential despite the slightly larger biases in merchantable volume, etc.

Another variable-exponent taper model, Equation [3], was created more recently by Garber and Maguire (2003). Their method was quite revolutionary in that it utilized nonlinear mixed effects and autoregressive error structures to correct for issues as mentioned earlier by Kozak. The random effects helped to reduce autocorrelation while a first-order autoregressive error structure provided more accurate variances, and therefore tests of significance, when inferring about the significances of specific covariates.

$$dib = a_1 D^{a_2} X^{\alpha_3 Z^2 + \alpha_4 \log(X) + \alpha_5 Z^{(-1/2)} + (\alpha_6 + \delta_6)\cos(Z) + (\alpha_7 + \alpha_8) DBH^X + \alpha_8 Z e^{-DBH/HT}} \quad [3]$$

Where: dib = predicted diameter inside bark at some height
D = diameter outside bark at breast height
X = $[1\text{-}Z^{0.5}]/[1\text{-}p^{0.5}]$
p = reference point = 1.37/HT (where 1.37 = breast height)
c = function of Z and other tree variables
Z = relative height = h\HT
a_1 and a_2 are parameters to be estimated

Comparing their model to traditional models on 94 ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*), and grand fir (*Abies grandis*) at different spacings in Central Oregon they found that the addition of random effects and correlation structures produced clear changes in parameter estimates and test statistics. Despite its success, they warned caution should be taken when examining trees with very small and large diameter to height ratios. As with most equations, the diameter at the base of a large tree can still cause problems.

2.4.2.3 Mixed Effects in Taper Modeling

Analyzing grouped data such as longitudinal data, repeated measures, and multilevel data has been long recognized as an issue in forest research. Mixed models, which incorporate both fixed effects from a population as well as random effects associated with individual experimental units randomly drawn from a population have become a very important tool in dealing with grouped data (Pinheiro and Bates 2000). Because data collection for taper equations generally involves multiple measurements being made on single trees there is always the complication of a predictive correlation that is not always adjusted for by fitting (Leites and Robinson 2004). In regression analysis it is assumed that the error terms are independent, identically distributed, normal random variables. The correlation inherent in taper data violates the assumption of independence and needs to be dealt with. Mixed effects modeling flexibly estimates the covariance matrix of the correlated data by allowing a non constant correlation among the observations (Lindstrom and Bates 1990). Now, being more frequently applied to taper equations, mixed effects modeling is proving itself to be a very useful tool.

Williams and Reich (1997) explored the error structure of taper equations by re-fitting Max and Burkhart's (1976) taper equation and testing the statistical significance of not ignoring the correlated errors. They found a small but significant bias of 1.05% when the correlated errors were ignored, meaning that the fit was actually improved by taking into account these blatant correlations.

A similar study was done in which a mixed-effects modeling framework was applied to Max and Burkhart's (1976) taper equation for loblolly pine (*Pinus taeda*) (Leites and Robinson 2004). They tested four different versions of that equation, (1) the original, (2) original with mixed effects, (3) original with crown variables (these being crown length and ratio) and fixed effects, and lastly, (4) original with crown variables and mixed effects. They found the inclusion of random effects in the original equation significantly improved the fit of the equation to the data. This supports the hypothesis that mixed modeling techniques can improve taper modeling. Adding crown variables also helped but there was still variation left unexplained.

Tasissa and Burkhart (1998) came to a similar conclusion concerning mixed modeling of taper when they used this technique to model taper of loblolly pine after thinning. They found a significant effect of thinning on stem taper and also saw a substantial decrease in Akaike's Information Criterion (AIC) when using random effects indicating large improvement over the ordinary least squares method.

Modeling stem taper of three Central Oregon conifers using nonlinear mixed effects, Garber and Maguire (2003) have further proved the usefulness of mixed modeling by using random subject effects with a first order continuous autoregressive error process (CAR(1)). Although mixed effects did reduce correlations considerably, it was not sufficient to eliminate them, making the addition of a CAR(1) necessary.

Statistical theory tells us that estimates are unbiased in the presence of autocorrelation, yet this is still a debated topic. Kozak (1997), speaking in regards to his 1988 taper equation, addressed the issues of multicollinearity as well as autocorrelations. Two equations were derived from the original 1988 version and were evaluated using Monte Carlo simulations. It was concluded that predictions were unbiased despite these two issues. However, the estimators were more variable when severe multicollinearity existed. This conclusion regarding autocorrelations seems to suggest that ignoring them is a valid option, yet in the introduction he warns of the consequences of not dealing with autocorrelations. These include estimators which no longer have a minimum variance property, underestimation of the mean square error and standard errors of parameter estimates, and thus an unreliability of statistical tests using t or F distributions, as well as unreliable confidence intervals.

Newberry and Burkhart (1986) describe error structures for two-stage modeling procedures and introduced the option of using “random function analysis” in the second stage by comparing it to ordinary least squares for loblolly pine in Eastern States. Due to difficulties in using the random effects, and because similar parameter estimates came from both methods, they decided that, “. . . the ordinary least squares second stage procedures are probably as appropriate as the random function procedures” (Newberry and Burkhart 1986).

Mixed modeling is not without its difficulties, yet it is clear that its use has improved diameter and volume estimations in forest mensuration, and it will only be used more in the future.

2.5 Concluding Remarks

Using sulfur to enhance the health and productivity of a crop is not a new idea. Both its nutritional and fungicidal qualities have been in use for thousands of years. However, its effectiveness in mitigating the impacts of SNC in an industrial setting is fairly unexplored. A few studies have produced promising results when they found improvements in needle retention and infection rates (Stone *et al.* 2004), pseudothecia counts (Stone *et al.* 2004), and even needle coloration (Chastagner 2002). But, in order to justify the time and expense involved in large-scale application to a forest, variables such as volume growth and taper need to be examined. Thankfully, recent advances in taper modeling, such as the variable exponent model form, and mixed modeling techniques, allow a more sophisticated and precise method of quantifying these changes. Equipped with the knowledge contained in this literature review, I will determine how sulfur application influences tree, crown, and needle attributes in Oregon Coast Range Douglas-fir.

3 Methods

3.1 Study Area

Within a 25 year old Douglas-fir plantation located in the Nilsen Creek drainage of the Oregon Coast Range, three two-acre units were chosen by Starker Forests, Inc. in 2000. Like much of the Coast Range, this plantation shows symptoms of Swiss needle cast. The site is located at 44º 43´ N, 123º 44´ W, in Lincoln County, Oregon at approximately 530 feet in elevation. Soils are 40% Preacher, 25% Bohannon and 20% Slickrock soil types. Bohannon and Slickrock are gravelly loams, whereas Preacher is clay to sandy loam. All three of these soil types were formed from colluvium weathered from sedimentary rock. Bedrock is located 35 to 58 inches below the surface. Douglas-fir is considered suitable for timber production in these soils (Soil Survey of Lincoln County Area, Oregon 1997).

Each of these three units was randomly assigned a treatment of either; 1) sulfur, 2) sulfur + nutrients, or 3) no treatment, referred to as a control. The sulfur treatment consisted of 10 gal/acre of liquid sulfur, 20 gal/acre of water and 8 oz. of tactic per 100 gallons. The sulfur applications in both the sulfur and sulfur + nutrient treatments were aerially applied twice in June, 2002 and twice again in June of 2003. The nutrient treatment was formulated specifically for this site and included calcium, magnesium, sulfur, potassium, boron, ferrous sulfate, copper sulfate, zinc sulfate and urea and was applied annually 2000 – 2004 except for 2003 when nutritional requirements were re-evaluated and adjusted accordingly. Specific concentrations, application rates, and application years are listed in Table 1.

Within each treatment ten 1/20th-acre plots were established at a predetermined azimuth on a two chain interval. Within each plot four trees, showing no significant defect, such as forks or conks, were selected at random and felled for taper analysis.

Table 1. Per acre application rates and concentrations in the sulfur and sulfur + nutrient treatments by year.

	Year					
	2000	**2001**	**2002**	**2003**	**2004**	**Total**
Nutrient Treatment						
Calcium (CaCO3)	540	540	540		1000	2620 lbs
Doloprill	1440	1440	1440			4320 lbs
Sulfur (90 - 92%)	25				35	60 lbs
Potassium (0-0-50)	250				300	550 lbs
Boron (14.3%)	15				15	30 lbs
Ferrous Sulfate (26%)	270					270 lbs
Copper Sulfate (23%)	10				15	25 lbs
Zinc Sulfate (36%)	20				10	30 lbs
Urea (46-0-0)	440					440 lbs
Sulfur Treatment						
Liquid Sulfur w/ tactic			20	20		40 gallons

The stand was planted on a 10x10 foot grid, resulting in approximately 430 trees per acre (TPA). When data were collected in 2004, there were approximately 407 TPA due to some natural thinning caused by canopy closure a few years prior. The mean total height, DBH, crown ratio, and crown width values from the 120 sampled trees are listed in Table 2.

Table 2. Minimum (Min), mean, maximum (Max), and standard deviation of selected tree attributes in 2004, n = 120 trees.

Attribute	**Min**	**Max**	**Mean**	**Standard Deviation**
Total ht (ft)	55.5	86.0	70.6	5.28
dbh (in)	4.1	13.2	8.2	1.7
Crown Ratio (%)	28.8	71.0	48.2	7.8
Crown Width (ft)	2.1	14.5	8.8	1.9
Sapwood Area (in^2)	1.5	58.4	18.5	9.5

To examine needle biomass and retention a subsample of 10 trees per treatment, 30 trees total, were selected from the above listed trees. The attributes of the sub-sampled trees are listed below in Table 3.

Table 3. Minimum (Min), mean, maximum (Max), and standard deviation of selected tree attributes of the sub-sampled trees in 2004, n = 30.

Attribute	**Min**	**Max**	**Mean**	**Standard Deviation**
Total ht (ft)	64.7	80.1	73.4	3.9
dbh (in)	7.5	14.0	10.0	1.3
Crown Ratio (%)	41.5	69.5	52.0	6.9
Crown Width (ft)	2.8	13.0	9.6	2.1
Sapwood Area (in^2)	12.1	58.4	25.6	10.9
Needle biomass (oz)*	2.5	28.4	12.0	5.8
Needle retention (years)*	2.6	3.9	3.2	0.3

* Total on 5-year-old sample branch

3.2 Data Collection

The four trees per plot were felled in April 2005, before the 2005 growth season began. The needle collection occurred shortly thereafter, and the remaining field work took place from June 27th to August 8th 2005. The needle samples were taken from one of the felled trees per plot. One branch from the 5th whorl from the top of each tree was cut at the branch collar, placed in a plastic bag, and labeled. Before removing any disks, the remaining branches (except the lowest live branch) were removed and a cloth tape was laid on the length of the bole and total height was measured in tenths of feet to the top of the terminal bud. Stump height was recorded and added to total height to obtain a true total height. The height of each disk (h) was then marked on the tree by taking out a small chuck of bark with an axe and measuring to the bottom (closest to the butt) side of the mark with the cloth tape. Approximately nine disks per tree were taken, these were located at: 1) stump height (approximately six inches from ground) 2)

DBH, 3) crown base, 4) and approximately six disks at every third interwhorl above DBH. These last disks were taken at interwhorls (half way between whorls) to avoid distortions in diameter caused by branch collar swell. Two perpendicular branches from the whorl containing the lowest live branch were then measured for crown width with a Spencer tape to the nearest tenth of an inch. There were a few instances when obtaining perpendicular branches was not possible due to breakage during felling so the next furthest branch (<180°) in that whorl was taken instead. Diameters inside bark at 19 ft, 38 ft, and 57 ft were measured to the nearest tenth of an inch to produce the small end diameters of the 19-foot logs that would have been taken from the tree in a thinning. A Stihl MS 290 chainsaw was used to remove disks so that the bottom of the disk aligned perfectly with the previously mentioned axe mark. The top of the disk was then labeled by plot number, tree number and disk number with a black Sharpie marker and all disks from one tree were placed into a plastic bag and transported to the Forest Mensuration and Silviculture Lab at Oregon State University.

The disks were laid out with their surfaces exposed on counter or floor space to dry out and prevent molding. It was determined after several re-measurements that shrinkage stabilized after two weeks so disks were left drying in the lab for at least two weeks before being prepared for measurements.

To prepare the disk surfaces for measurement, a diameter path across the disk was randomly picked, avoiding knots and other abnormalities. An electric planer was used to create a uniform surface by removing chainsaw marks and rough areas. Typically a two inch (planer width) wide strip across the disk was enough. The planer alone was adequate for most disks, but when the growth rings were very small a palm sander with 220 grit sandpaper was used to finish the surface. Using a straight edge and pencil, a measurement line was marked across the disk on the prepared surface, one radius was marked “A” and the other “B”.

After preparation, the disks were taken to the Wood Science Microscopy Lab. Growth ring widths were measured using:

- Velmex Unislide 24" measuring stage, Model# TA4030H1-S6
- AcuRite 0.001mm linear encoder, Model# 3852511724
- Nikon stereo scope, Model# SMZ-2T
- Metronics Quick Chek readout box, Model#: QC1000M-AR
- Measure J2X software Version 3.1, Release 25

To begin measuring, the Measure J2X program was opened, and the new series was given an ID and a start year of 2004. The measuring type was selected as youngest to oldest (App-FixLYOG). The radius "A" on the disk was then positioned on the measuring platform and lined up with the last year (2004) in the crosshairs. The platform was slowly advanced as a button was pressed at the end of each growth ring to record that measurement. The process was then repeated for the "B" radius on the same disk. Both series were checked to ensure that they each had the same number of rings.

After measuring all growth ring widths for each disk, diameter inside and outside bark were measured on all disks. Two diameter measurements were taken per disk, measured with a ruler to the nearest tenth of an inch. One measurement was done along the same line as the growth ring width measurements and the other was done perpendicular to this line. The same procedure was used to measure diameter outside bark.

3.3 Crown Analysis

Swiss needle cast directly impacts crown morphology. The size, shape and location of a crown can all be affected by the pathogen. Therefore, measurement of a selection of crown attributes between treatments may reveal differences in SNC impacts. Variables measured include sapwood area, crown ratio, crown width, needle biomass, and years of needles present on the sample branch.

A crown base disk was removed from each of the 120 trees and sapwood area (in^2) was measured in the lab. Sapwood area was indirectly obtained by subtracting heartwood cross-sectional area from total diameter inside bark cross-sectional area, assuming, of course, the disk was elliptical. To measure heartwood area, the disks were soaked in water for five minutes to increase the distinction in color between the sapwood and heartwood. Four heartwood radii measurements were measured on each crown base disk. Two of the measurements were along the same line as the growth ring width measurements and the other two were perpendicular to it. These measurements were taken with a ruler to the nearest tenth of an inch. To detect treatment differences, an analysis of covariance (ANCOVA) model was produced in SAS v. 9.1. Combinations of covariates were tested in the ANCOVA model to explain additional variation. Those tested were diameter inside bark at crown base, crown ratio, crown length, and diameter at breast height. Of these, diameter inside bark at crown base explained the most variation. This is most likely due to the fact that the diameter of the sapwood at crownbase is directly related to the diameter of the entire crownbase disk.

Crown ratio is frequently used as an indicator of tree health and growth potential. It is therefore relevent to determine if the treatments of sulfur, sulfur + nutrients and control had an effect on average crown ratio after adjusting for tree size. Crown ratio is measured in feet, from crown base to top of terminal leader, and then divided by feet of total height from ground to top of terminal leader. This is the ratio of crown length to total height. Crown base in this analysis is defined as the point on the bole where the lowest living branch exists. An ANCOVA model was created in SAS v. 9.1 with the GLM procedure to determine treatment differences in crown ratio with a total height covariate. Other covariates were tested yet none explained as much variation as total height. Because crown base height is usually more consistent in a closed canopy, even aged stand, it would follow that, in general, the tallest trees would have the greatest crown ratios. In this data set, the standard deviation of the mean crown base height (36.32) was 4.89, whereas the standard deviation of the mean total height (70.54) was 5.38. This reinforces the biological reasoning for total height being a more proper covariate in the crown ratio model.

Crown width was measured on the forty felled trees per treatment, by measuring the length of two perpendicular branches at crown base. The two crown radius measurements were then averaged to obtain crown width per tree. An ANCOVA model was created in SAS v. 9.1 with the GLM procedure to determine treatment differences with a covariate of sapwood area at crownbase. Following the pipe model theory, this covariate makes sense. As previously explained, a particular amount of sapwood area can support a proportional amount of leaf area. In this situation it is probable that perhaps a greater amount of leaf area might require a greater amount of lateral branch to contain it.

3.4 Needle analysis

The branches collected for needle analysis were kept in a freezer until lab measurements could be made. Once removed, the branches were clipped into five foliage age classes and retention was quantified. If a majority of an age classes needles were present, it was counted as a whole year. In the first age class which did not hold a majority of its needles the percent of needles present was counted and added to the number of age classes which did hold a majority of their needles. This method of quantification is somewhat crude in that it cannot describe what percentage of needles were present in the 'whole year', and, in addition, older age classes, which might have held a small percentage of needles still, were not counted at all. After being dried for 48 hours, the needles were then removed from the woody branch components and weighed to the nearest 0.01 grams. Similar ANCOVA models were also created in SAS for the needle biomass and retention.

3.5 Tree Form and Volume Analysis

3.5.1 Taper

In this study, Kozak's (1988) variable exponent taper equation was used to examine the effect of treatment on stem taper. The original model can be written as:

$$d_i = \alpha_0 dbh^{\alpha_1} \alpha_2^{dbh} X^{b_1 Z^2 + b_2 \ln(Z+0.001) + b_3 \sqrt{Z} + b_4 e^Z + b_5 (dbh/H)} \qquad [4]$$

where d_i, the dependent variable, is diameter inside bark at a particular height (h_i) on the tree bole, dbh is diameter outside bark at breast height, Z is relative height (h_i/H) where H is total height, and X is $(1-\sqrt{h_i / H})/(1-\sqrt{p})$. The inflection point, p, is the relative height at which the tree shape changes from a neiloid to a paraboloid. Demaerschalk and Kozak (1977) found that in all commercial species of British Columbia this value only ranged between 20 and 25%, so estimating p with the data is not necessary. For these data the inflection point was fixed at 25% of total height. Lastly, $a_0 - a_2$ and $b_1 - b_5$ are parameters to be estimated.

To draw proper conclusions about the effect of sulfur and sulfur + nutrients on taper, Kozak's (1988) taper model was refined. The α_2 parameter which helps to describe inside bark diameter from dbh was eliminated due to very high parameter correlations and an insignificant p-value. The redundancy of the Z variable in the exponent parameters led to an examination of the necessity of all three of these variables. It was determined that eliminating the b_2 parameter, improved the Akaike's Information Criterion (AIC), Bayesian Information Criterion (BIC), as well as the log likelihood ratio. Thus, further analysis was conducted without this variable. The final model form can be written as:

$$d_i = \alpha_0 dbh^{\alpha_1} \; X^{b_1 Z^2 + b_3 \sqrt{Z} + b_4 e^z + b_5 \left(\text{dbh}/\text{H}\right) + b_6 I_S + b_7 I_{SN}} \qquad [5]$$

To test for treatment effects, two treatment indicators were added to the variable exponent portion of the model. I_S is the indicator variable for the sulfur treatment (1 if trees are sulfur-treated, zero otherwise) and I_{SN} is the indicator variable for the sulfur + nutrient treatment (1 if trees are sulfur + nutrient treated, zero otherwise).

Most data sets used to develop taper equations inherently contain autocorrelation. Ignoring correlated errors is a valid option, yet this option results in: (1) estimators which no longer have a minimum variance property, (2) underestimation of the mean square error and standard errors of parameter estimates, and (3) unreliable statistical tests using t or F distributions, as well as unreliable confidence intervals (Kozak 1997). Because an accurate estimation of standard error for the treatment coefficient was essential to this analysis, autocorrelation was accounted for with a combination of a continuous autoregressive error structure (CAR(1)) and a random tree effect (a nonlinear mixed effects technique). These techniques have been applied to provide meaningful tests of significance in modern taper analyses (Garber and Maguire 2003, Williams and Reich 1997, Tasissa and Burkhart 1998).

Variance of the error term increased with diameter of tree disks, violating the assumption of constant variance. Therefore, a power variance function was incorporated into the fitting procedure (Pinheiro and Bates 2000). After examining a number of weighting functions, the power variance function with a weight of 0.3 significantly improved the fit of the data ($p = < 0.0001$). Evaluation of assumptions for testing parameters were assessed with residual and empirical autocorrelation plots at $\alpha = 0.05$ (Pinheiro and Bates 2000). Nested models with and without random effects, variance functions, and correlations structures were compared using likelihood ratio tests (Pinheiro and Bates 2000, Garber and Maguire 2003). Models were fitted with S-PLUS 7.0 (Insightful Corp.).

3.5.2 Volume

Three different methods of volume calculation were used in an attempt to detect treatment differences. First, the volumes of the 19’ logs were measured in cubic feet per tree and per acre. Secondly, these same nineteen-foot logs were complied by treatment using Scribner’s board foot rule per tree and per acre so that a dollar value could be attached to the volumes produced. Lastly, Kozak’s taper equation was numerically integrated and expressed as the average tree and volume per acre for each treatment using the estimates determined in the taper analysis.

Smalian's formula was used to estimate the cubic foot volume of the 19-foot logs that would have been taken in a thinning, had these trees not been used for taper analysis. Smalian's formula can be written as:

$$\frac{\left(DIBSE^{2} \times 0.005454) + (DIBLE^{2} \times 0.005454\right)}{2} * L$$

where DIBSE is the diameter inside bark at the small end, DIBLE is the diameter inside bark at the large end and L is the log length. The length was fixed at 19 feet in this case due to local market sorts and harvest method. Cubic foot volume was calculated for each log in each treatment down to a diameter of 4 inches DIBSE. All trees contained at least two logs above stump height, while a few produced three. An analysis of covariance was performed after a log transformation of the cubic foot volume to correct for non-constant variance. A dbh covariate was incorporated to adjust for tree size. This was necessary since the subject trees were randomly selected at each plot, and average tree size varied slightly, although not statistically so, between treatments (Control-Sulfur p-value = 0.6556, Control-Sulfur + nutrient p-value = 0.6648, Sulfur-Sulfur + nutrient p-value = 0.9898).

To quantify differences between treatments in terms of potential products and their value, Scribner board foot volume was determined for each tree. Board foot volumes were calculated based on the 1972 Scribner factor table to the nearest inch diameter (Bell and Dilworth 2002, p. 13). Nineteen-foot saw logs were taken to a 5" DIBSE, and 19-foot pulp logs to a 2" DIBSE were taken from the remainder. Values (in dollars) per tree were obtained through the use of the Oregon Department of Forestry Region 1, 2006, 2^{nd} quarter log price report. Sawlogs, assumed to all be 3-saw quality (5 – 7"), were listed as having a pond value of $595 per MBF while the pond value of pulp logs (utility) was $55 per MBF.

Because the cubic and boardfoot volume calculations were simply the sum of the logs produced, it was thought that perhaps using a taper equation to determine volume might ‘smooth out’ these course cut-offs caused by the merchantable length and scaling diameter constraints. As previously mentioned, one of the downfalls of the variable exponent taper model is the inability to integrate to determine volume. However, it is possible to numerically integrate each tree within each treatment to find average volumes by treatment. Numerical integration was conducted in S+ with Equation [5].

4 Results and Discussion

4.1 Crown and Needle Attributes

4.1.1 Sapwood area

An examination of residual graphs, including residual vs. predicted and a normal QQ plot revealed non-constant variance which increased as sapwood area increased. To compensate for this a natural log transformation was taken on the response variable, sapwood area. The transformed residual graphs were much improved. The tails on the normality plot are still light but no improvements could be made with additional transformations.

Due to an apparent curvature in the residual graph an attempt to square the independent variable, diameter inside bark at crown base (DIBcb), was also made. However, no significant improvements were made and the DIBcb variable without the square was actually better at accounting for variation in the model, therefore, the square was not utilized.

The median response for the control treatment was 16.6 in^2, sulfur was 15.8 in^2, and the sulfur + nutrient response was 16.6 in^2. In other words, the sulfur treatment has 5% less sapwood than the control (95% confidence interval -5% to +16%) while the sulfur + nutrient treatment has 1% more than the control (95% CI = -10% to +10%). Statistically, neither of the treatments were significantly different from the control ($p = 0.36$ and 0.93 respectively) and the sulfur treatment was not significantly different from the sulfur and nutrient treatment ($p = 0.32$). These results are confirmed by the boxplot of sapwood area by treatment (Figure 1). In all the following boxplots the center line represents the median, the boxes capture 50% of interquantile range (IQR), and the whiskers capture the last IQR. The outliers are represented by circles with a horizontal line through them. It should also be noted that these box plots display the data prior to adjustment caused by the covariates which were later added to some models.

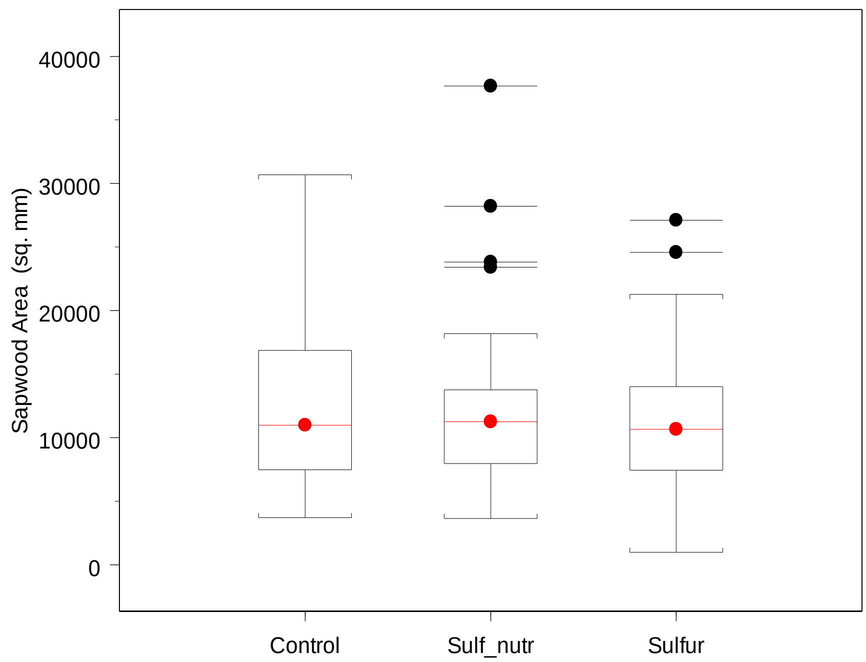

Figure 1. No difference among treatments was exhibited in sapwood area (mm^2) at the crownbase.

Considering how trusted sapwood area is as a predictor of leaf area (Waring *et al.* 1982), it is very surprising that there was no significant increase in sapwood between the treatments. The pipe model theory hypothesizes a functional relationship between the amount of sapwood area present and the amount of foliage existing above the point where sapwood is measured on the bole (Shinozaki *et al.* 1964). This implies that a change in foliage amount would require a proportional change in sapwood area for functional support. A quick conclusion might be that there is no significant increase in foliage above crown base in either of the treated stands, but the foliage biomass and retention results, presented later in this chapter contradict this conclusion. In older literature describing the relationship between sapwood area and leaf area, this relationship is linear (Long *et al.* 1981, Grier and Waring 1974). However, the slope varies based upon things such as species, site quality, and age. If the slope of the linear relationship between sapwood area at crown base and leaf biomass is very steep, then a slight increase in foliage caused by the sulfur + nutrient treatment would not be enough to show a statistically significant increase in sapwood area. This theory is only true if we assume that this is a cause and effect relationship where an increase in foliage produces the carbon necessary to form new sapwood. Many authors still debate if the opposite isn't true, where new sapwood is needed in order to support new foliage (Kershaw and Maguire 2000).

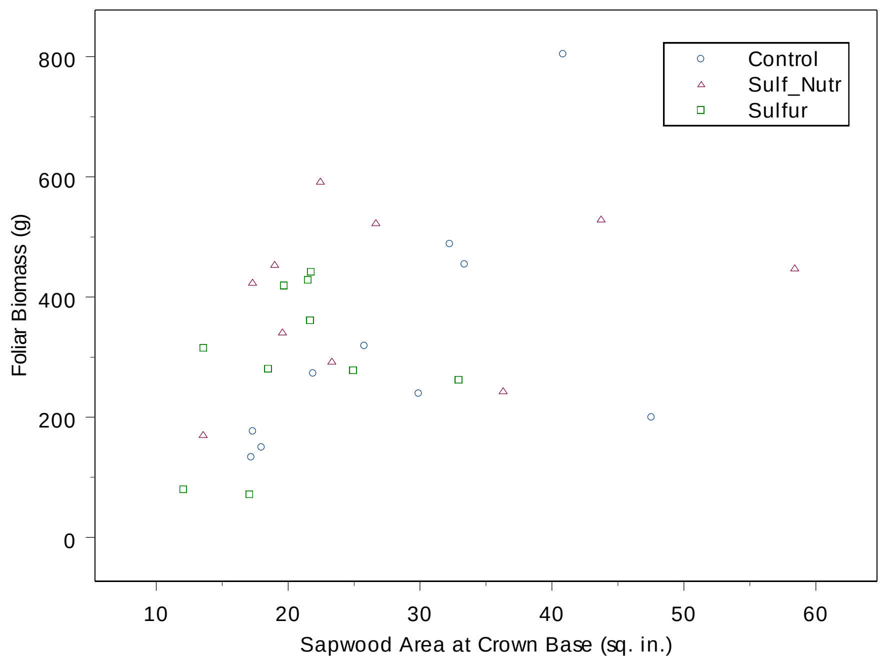

Figure 2. Scatterplot of foliar biomass by sapwood area at crown base where the treatments are represented by different shapes.

What is not taken into account in this discussion is the behavior of this theory in the face of disease. I predict that we see no statistically significant differences due to the fact that the premature loss of needles caused by SNC invalidates the assumptions which the pipe model relies on. Figure 2 displays the relationship between sapwood area at crown base and foliar biomass for this dataset. Sapwood area only explains 1%

of the variation in foliar biomass. This leads me to believe that perhaps SNC has caused this typically strong linear relationship to breakdown.

For the above analysis to be correct however, we must make the assumption that the 5-year-old branch is accurately representing the biomass of the entire crown. This may or may not be true. Because we did not count the number of branches on the crown of each tree, we cannot multiply the two variables to get a better measurement of total crown biomass. If we allow crown length to be a surrogate for number of branches though, we can create an approximation of total crown biomass, just to be able to explore this topic further. Figure 3 displays the relationship between total crown foliage biomass (crown length x foliar biomass of 5 year old branch) and sapwood area at crown base.

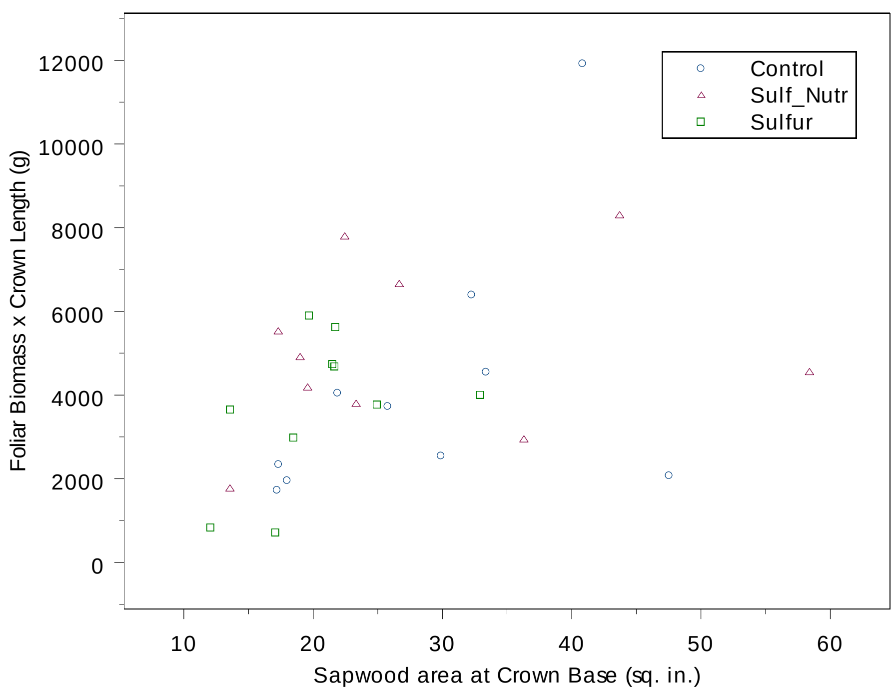

Figure 3. Scatterplot of total crown foliar biomass by sapwood area at crown base where the treatments are represented by different shapes.

Once crown size is taken into account, foliar biomass predicts 14% of the variation in foliar biomass (p = 0.0403). This is an improvement, yet not strong evidence, in my mind, of a reliable relationship that should be used to predict leaf area in the face of SNC infection.

4.1.2 Crown ratio

Adding a total height covariate to the crown ratio model helped account for 21% of variation in crown ratio. Plots of residuals and normality to check linear model assumptions of constant variance and normality showed these assumptions to be met. No outliers were identified as a problem.

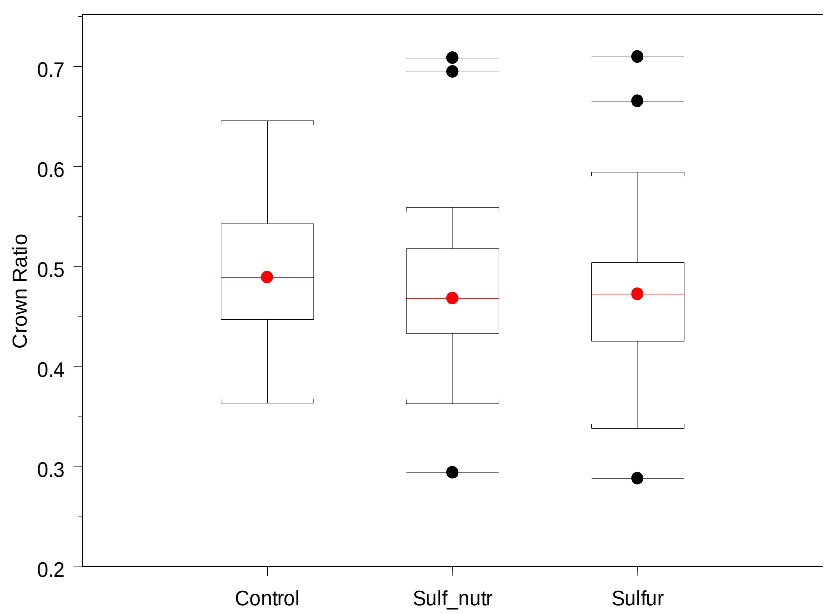

Figure 4. No difference in percent crown ratio was found between treatments.

Neither of the treatments had mean crown ratios significantly different from the control (control – sulfur comparison p-value = 0.14, control – sulfur + nutrient comparison p-value = 0.16). A boxplot of crown ratio by treatment lends further evidence to this conclusion (Figure 4).

In CR models, common covariates include DBH, total height, and some form of taper and/or competition (Temesgen *et al.* 2005, Maguire and Hann 1990, Ritchie and Hann 1987). This is because a larger crown ratio is generally expected to produce higher growth rates and greater taper for trees of a given species and age. The results here don't substantiate any clear conclusions on this topic.

Crown sparseness is a measure of leaf area density which uses crown length and sapwood area variables. After correcting for tree size with a DBH covariate, an ANCOVA model concluded that CL/SA is not different between treatments (control – sulfur + nutrient comparison p-value = 0.6228, control – sulfur comparison p-value = 0.5485). Figure 5 displays the similarities in a boxplot. Considering the insignificances of sapwood area and crown ratio between treatments, this is not surprising. Crown sparseness is often relied upon for quantifying disease impacts, or in this case, disease recovery. Weiskittel and Maguire (2004) studied the sparseness response to silvicultural treatments of fertilization, vegetation management and thinning. They found that only the thinned plots revealed a change in sparseness. This suggests that perhaps fertilization, as in the sulfur + nutrient treatment, should not be expected to change crown sparseness.

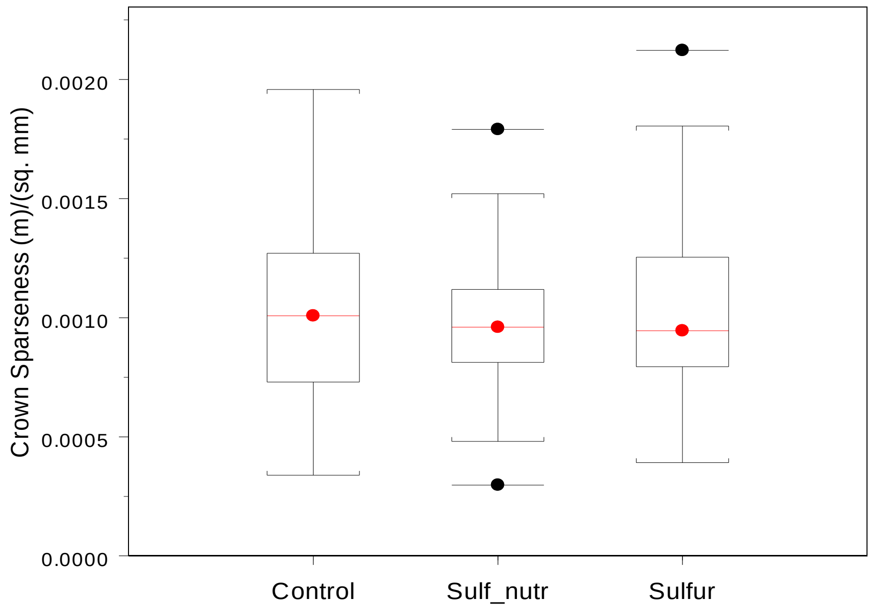

Figure 5. No difference in crown sparseness was found between treatments

4.1.3 Crown width

Of all possible covariates, sapwood area accounted for the most variation in crown width (29%), so the analysis was carried out with sapwood as the only covariate, as addition of other covariates increased the R^2 value only slightly. Scatterplots to check assumptions of constant variance and normality showed these assumptions to be met. Three potential outliers were identified in the scatterplot, however, there was no justification for excluding them, so they remained in this analysis.

Treatment means are summarized in Table 4. Similar to crown ratio there is no statistical significance (control – sulfur comparison p-value = 0.51, control – sulfur and nutrient comparison p-value = 0.85). A boxplot of crown width by treatment makes this conclusion apparent (Figure 6).

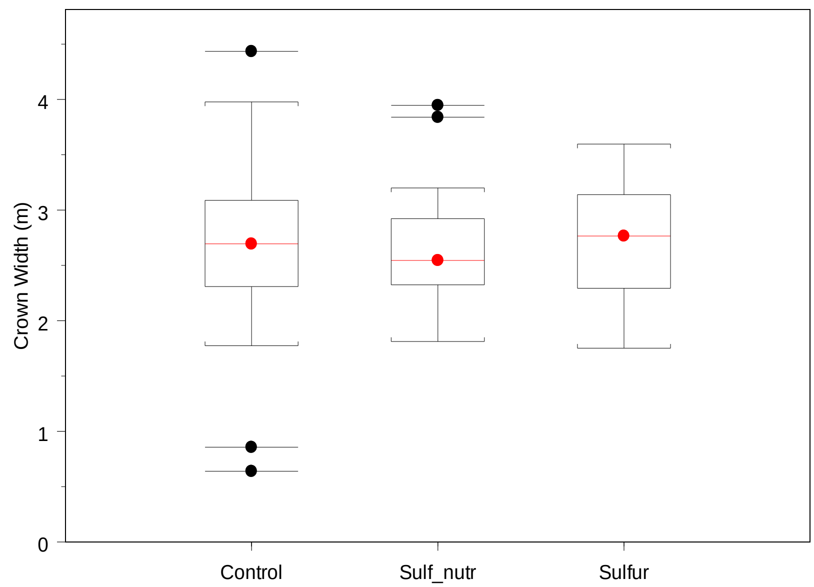

Figure 6. No difference in crown widths was found between treatments.

Mean responses by treatment for these crown attributes are given in table 4. It becomes apparent here that there are no clear patterns when it comes to crown attributes. The control treatment has the highest crown ratio, while the sulfur treatment has the widest crown, and the sulfur + nutrients treatment has the greatest sapwood area. Neither of the treatment means are significantly different from the control for any of these attributes.

Table 4. Mean crown ratio and width by treatment with 95% confidence intervals.

Crown Attribute	Control		Sulfur		Sulfur + Nutrients	
	Mean	+/- CI	Mean	+/- CI	Mean	+/- CI
Sapwood Area (in^2)	16.6	1.1	15.8	1.1	16.6	1.1
Crown Ratio (%)	49.74%	2.18%	47.40%	2.18%	47.57%	2.18%
Crown Width (ft)	8.7	0.5	9.0	0.5	8.6	0.5

Traditional measures of trees “size” including DBH, and total height, were not at all significantly different between treatments. The control had a mean DBH of 8.75 inches, sulfur treatment mean was 8.57, and sulfur + nutrient mean was 8.58, and none of the treatments were significantly different from one another (p-value = 0.6983, 0.9142, and 0.6204). Total height showed similar results. Control mean total height was 70.41 feet, sulfur treatment mean height was 70.28 feet, and the sulfur + nutrient treatment was 70.28 feet. Once again, none of these were statistically different from one another (p-values = 0.6983, 0.9142, and 0.6204). Because variation in tree size between treatments was so slight, all crown attribute models were initially fit without a covariate to determine if any treatment effect might prevail. An analysis of variance concluded that a treatment variable alone did not explain a sufficient amount of variation in the sapwood area, crown sparseness, crown ratio or crown width models, as indicated by insignificant p-values of the F-statistic ($p > F = 0.6414, 0.7567, 0.3516$, and 0.9503 respectively).

By examining differences in crown width it was hoped that it could reveal whether or not there might be differences in crown volume. Crown volume, as previously discussed, is a useful surrogate for photosynthetic active foliage. However, due to the statistical insignificance of crown width as well as crown ratio, developing a crown profile model was not justified. Many other analyses were carried out involving crown attributes but none of these produced significant differences between treatments. Elaboration on the details of these analyses is therefore not included. It is interesting to point out though, that the treatments had no effect on crown slenderness, the ratio of crown width to crown length, either ($p > F = 0.6023$).

4.1.4 Needle biomass and needle retention

In April of 2005, one entire branch was collected from one randomly selected tree per plot, resulting in ten branches per treatment. Analysis of covariance assessed the treatment effects on both needle biomass and retention on the five-year-old sample branch, after accounting for branch location (depth into the crown) and tree size (DBH). Graphical checks of model assumptions were made, and determined to be sufficient.

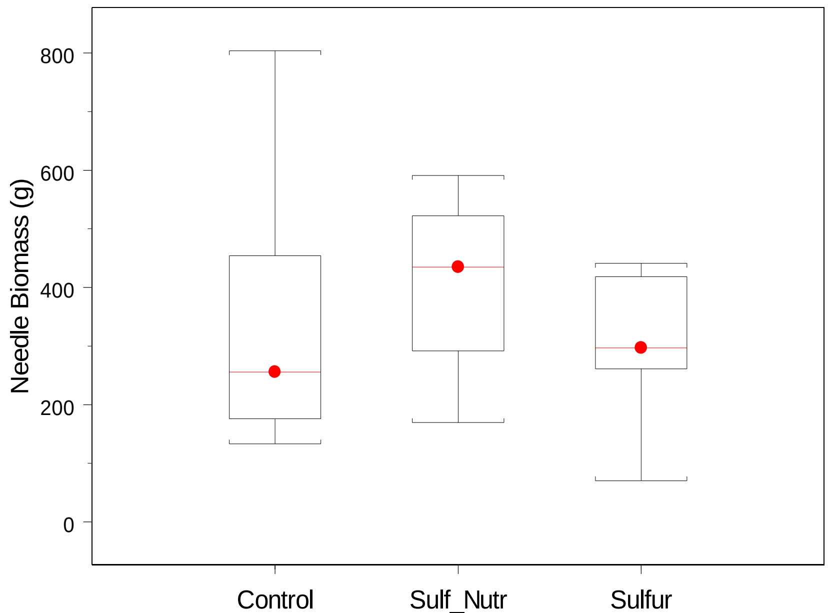

Figure 7. Sulfur + nutrient treatment shows improved needle biomass (g) over the control treatment, while the sulfur treatment does not.

As seen in the boxplot of needle biomass by treatment (Figure 7), the sulfur treatment does not have a mean foliage biomass significantly different from the control treatment ($p = 0.9094$), but the sulfur + nutrient treatment is marginally greater than the control ($p = 0.0599$).

The sulfur + nutrient treatment once again showed an improvement over the control when it came to years of needle retention (3.4 years vs. 3.0, $p = 0.0205$). This same statistical significance, however, is not seen between the sulfur and control treatments (3.2 years, $p = 0.2496$) (Figure 8).

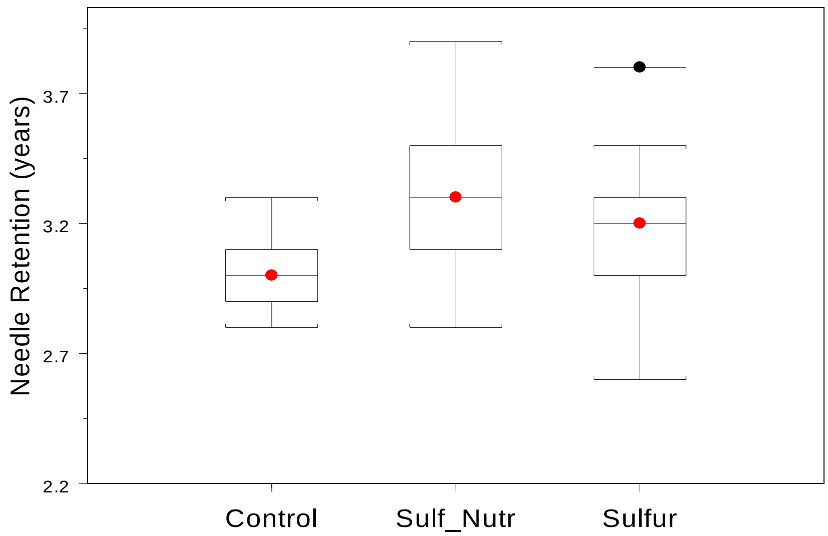

Figure 8. Sulfur + nutrient treatment shows a significant increase in needle retention (years) over control while the sulfur treatment is not statistically different.

Table 5. Mean needle biomass and mean needle retention response by treatment with corresponding 95% confidence interval.

Needle Attribute	Control		Sulfur		Sulfur + Nutrients	
	Mean	+/- CI	Mean	+/- CI	Mean	+/- CI
Needle Biomass (g)	297.08	87.39	303.98	86.12	415.88	86.38
Needle Retention (years)	3	0.2	3.2	0.2	3.4	0.2

The analysis was also carried out without the branch location and tree size covariates to determine their influences. The foliar retention conclusions remain unchanged without the covariates. The sulfur + nutrient treatment is still significantly different from the control (p-value = 0.0234) while the sulfur treatment is not (p-value = 0.2583). The foliar biomass conclusion, is however, influenced significantly by the covariates. Without them, the sulfur + nutrient treatment no longer has significantly more biomass than the control (p-value = 0.2959), and the sulfur treatment is still not different from the control (p-value = 0.6773). This is probably due to the fact that the branch location in the control treatment is slightly higher than in the sulfur + nutrients, and sulfur treatments, although not significantly so (p-values = 0.3248, and 0.3801 respectively).

Despite the insignificances seen in the crown attributes between treatments, there was an improvement in needle biomass and needle retention in the sulfur + nutrient treatment. This result suggests that the sulfur + nutrient treatment may increase foliage biomass and retention at the whole tree level. The increase in foliage biomass is likely a result of this greater needle retention (sulfur effect) and an increase in younger foliage development (nutrient effect). Although not significant, there was a slight increase in needle retention in the sulfur treatment suggesting a slight effect of sulfur on the pathogen. An increase in leaf area after fertilization has frequently been reported in forestry literature (Brix 1981, Zhang *et al.* 1997). But, needle retention has also been shown to decrease with fertilization and decrease with increasing site fertility (Pensa and Sellin 2002, Xiao 2003, Amponsah *et al.* 2005). Pensa and Sellin's (2002) findings confirmed the notion that trees living with low resource availability have greater needle longevity than compared with trees in fertile habitats. Supporting these conclusions, Xiao (2003) suggested needle longevity is a function of micro site environments more than genetics or other factors. Even more recently, Amponsah *et al.* (2005) found that annual fertilization decreased needle longevity by 23 - 30%. Because fertilization alone has traditionally caused a decrease in needle retention, our contradictory results of an increase in needle retention in the sulfur + nutrient may be due to the fungicidal effect the sulfur component has had on SNC.

Interestingly, these findings of increases in needle biomass and retention in the sulfur + nutrient treatment directly contradict earlier statements that there were no changes in leaf area as indicated by a lack of significant change in sapwood area. The first thing to point out is that the sample branches taken for the leaf biomass and retention analysis were taken from the 5th whorl from the top in all sampled trees. The 5th whorl down may or may not be representative of the response in the entire crown. Because SNC is known to more severely attack the top third of the tree crown, the greatest improvement in leaf area after treatment is most likely going to occur in the top third of the crown. In addition, because the treatment was aerially applied, it is also assumed that a higher proportion of the elemental sulfur would be retained by the upper portion of the crown. These two points alone may explain why a treatment effect was found in needle characteristics 5 whorls down, but not necessarily in the entire crown overall.

A SNCC study of fertilization of Douglas-fir with combinations of N, P, K and micronutrients, suggested that highly infected trees not be fertilized (Mainwaring *et al.* 2005). However the results here suggest that if nutrients are used in conjunction with elemental sulfur, needle retention and needle biomass may actually be improved in SNC infected trees.

4.2 Tree Form and Volume

4.2.1 Diameter distribution along the stem

Because growth ring widths were measured from every disk removed for the taper analysis, it was possible to determine growth increments pre-treatment (1996 - 2000) and post-treatment (2000 – 2004). Arranging these results, averaged by disk and treatment, into a graph allows one to see the growth along the entire bole (Figures 8 and 9). The stump disk was taken at approximately 6 inches above ground, DBH disk was taken at 4.5 feet above the ground, and the remaining disks (1 – 6) were taken at every third interwhorl until the top of the tree was reached.

In the pre-treatment period (Figure 9), the control shows the greatest average increment along the entire bole. Also in this time period, it is easy to see that all treatments have parallel curves except where the sulfur + nutrient treatment has slightly more growth than the sulfur treatment for disks 2 and 3.

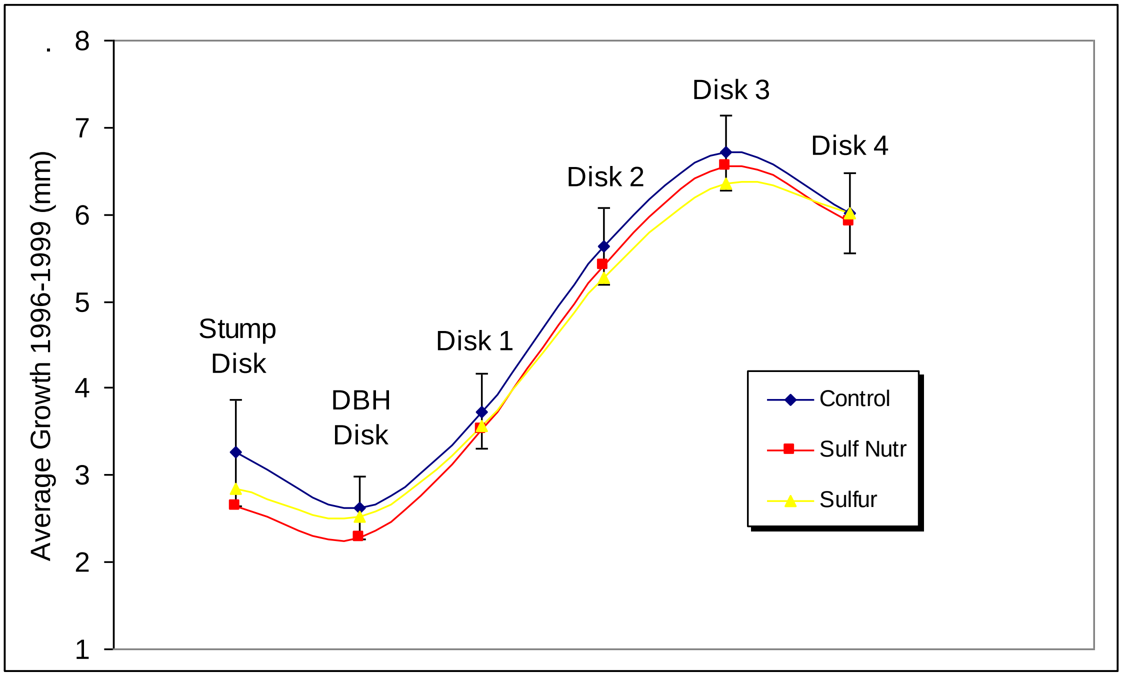

Figure 9. Mean pre-treatment (1996 – 2000) growth increments with confidence intervals (α = 0.05) about the control treatment mean (n = 120).

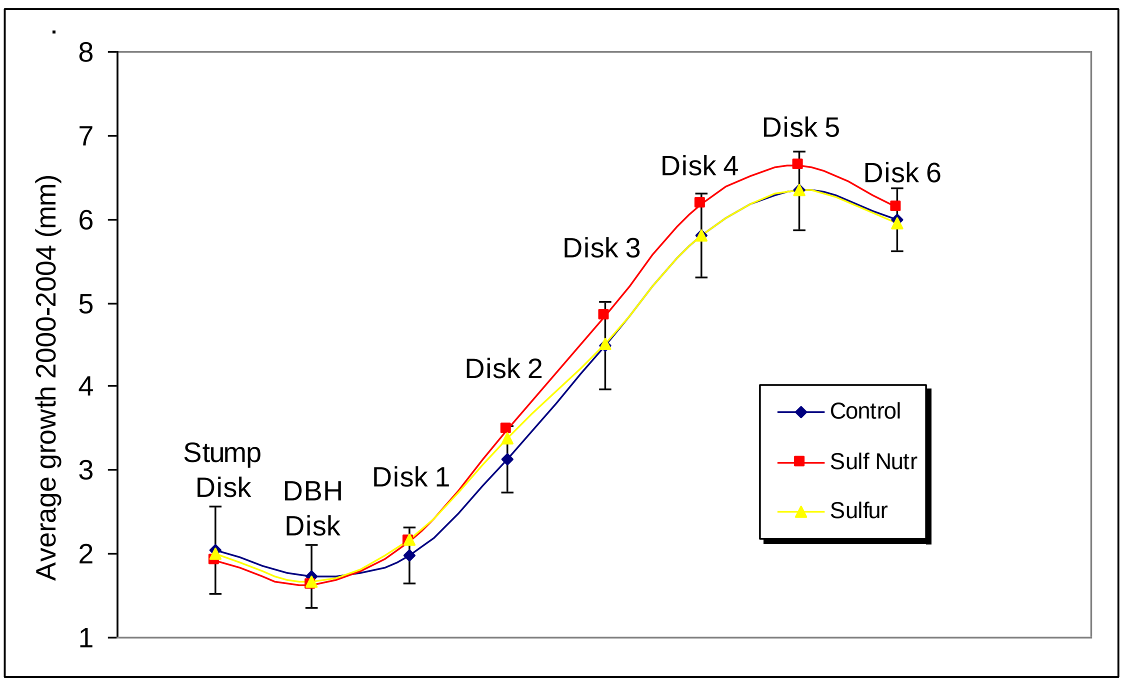

Figure 10. Average during-treatment (2000 – 2004) growth increment with confidence intervals (α = 0.05) about the control treatment mean (n = 120).

In the post-treatment period four years later (Figure 10), much change has occurred. Most notably, the sulfur + nutrient treatment saw an improved growth increment above DBH. The sulfur treatment also shows improvement in growth increment above DBH, but much less so. Despite these observed changes in growth increment along the stem, the confidence interval bars on the control treatment remind us that the growth increments in the treated stands are still not very different from the control.

After averaging the 2004 growth increment across all disks along the bole, and correcting for the year 2000 growth increment as well as the disk number, it is clear that the sulfur + nutrient treatment significantly improved growth increment ($p = <0.0001$), but the sulfur treatment alone did not ($p = 0.0991$). The sulfur + nutrient treatment had a mean 2004 growth of 0.16 inches, the sulfur treatment had a mean of 0.15 inches, and the control had a mean 2004 increment of 0.14 inches.

Similar results surface when a multivariate analysis of variance is conducted on the basal areas of the 1063 disks. The response variables in this situation are the relative basal areas of 8 disks along the length of the bole, where 'relative' refers to the basal area divided by the breast height basal area, acting as a covariate. This analysis is conducted using a mixed procedure (proc mixed) in SAS and an autocorrelation structure of lag 1. The tests of fixed effects revealed that there is in fact a treatment effect ($p = 0.0340$). More importantly, a test of the interaction between treatment and position of disk on the bole revealed there is significance ($p = 0.0007$). This implies that stem profile among treatments is significantly different because there is a significant change in relative basal area as position changes.

Examination of this raw growth increment data reinforces the conclusions drawn in the taper analysis which will be discussed next. Once other covariates and autocorrelations are accounted for, and results are smoothed out in a continuous as opposed to discrete method, the statistical significance of the taper in the sulfur + nutrient treatment is easily quantified.

4.2.2 Taper

In determining the best taper modeling technique, AIC, BIC, as well as the log likelihood ratio were compared between nested models with and without a random effect and a lag one continuous autoregressive error structure (CAR(1)) (Table 6).

Table 6. AIC, BIC and log-likelihoods are presented between taper models with and without a random effect and a CAR(1).

Error Structure[a]	Estimated Parameters	AIC	BIC	Log Likelihood
GNLS	10	8428	8478	-4204
GNLS with CAR(1)	11	7955	8009	-3966
NLME	11	8342	8397	-4160
NLME with CAR(1)	12	7958	8018	-3967

The simplest model, a generalized nonlinear least squares model (GNLS), without a correlation structure or random tree effect, had the highest values of AIC, BIC and log likelihood, proving it to be most inferior as was expected. Adding a continuous autoregressive error structure with a lag of one (CAR(1)) to the GNLS model improved the fit considerably. The nonlinear mixed effects model fit by maximum likelihood with a single random tree effect and a CAR(1), which was hypothesized to have the best fit, was not an improved fit from the GNLS with CAR(1) model ($p = 0.1688$, Table 7).

Table 7. List of likelihood ratio tests and corresponding p-values for determining best taper model error structure, where GNLS[a] with CAR(1) is determined to be the best, followed closely by NLME with CAR(1).

Test			Likelihood ratio	P-value
GNLS	**vs.**	GNLS with CAR(1)	475	< 0.0001
NLME	**vs.**	NLME with CAR(1)	386	< 0.0001
GNLS	**vs.**	NLME	88	< 0.0001
GNLS with CAR(1)	**vs.**	NLME with CAR(1)	2	0.1688

This leads to the conclusion that a first-order autoregressive process was adequate in accounting for the substantial inherent autocorrelation in this dataset. An examination of the autocorrelation plots between the GNLS and GNLS CAR(1) models displays this improvement (Figure 11).

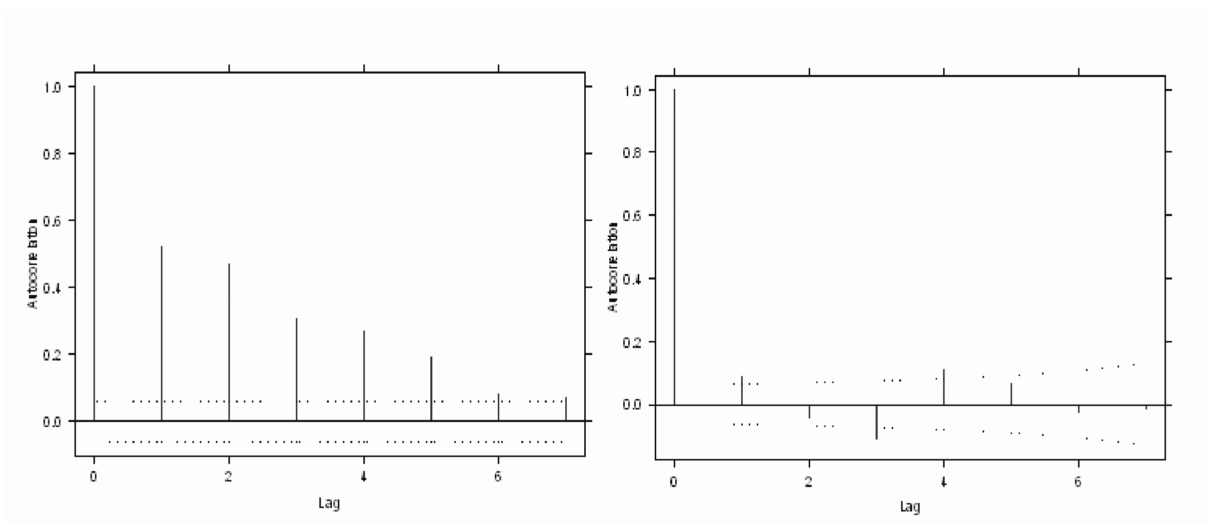

Figure 11. Autocorrelation plots for the original GNLS model form (left) and the final model form, GNLS with a CAR(1) (right).

Once the final model form, GNLS CAR(1), was selected, tests on the two indicator variables were completed. These tests suggested that relative stem profile in the sulfur treatment was not statistically different from the control treatment (e.g., b_6 was not significantly different from zero, p = 0.7160). However, the sulfur + nutrient treatment did have a significantly different stem profile than the control treatment as indicated by b_7 being significantly less than zero (p = 0.0246). To test if the sulfur treatment is significantly different from the sulfur + nutrient, a t-test was performed. The point estimator of this quantity, $b_6 - b_7$, and the estimated variance of this estimator, $s^2\{b_6\} + s^2\{b_7\} - 2s\{b_6, b_7\}$, were calculated. It resulted in a p-value of 0.4868, indicating that there is no significant difference between the sulfur and the sulfur + nutrients treatment. Table 8 summarizes the estimates and confidence intervals of the indicators.

Table 8. Point estimates (Est.) and confidence intervals for the coefficients of the treatment indicator variables, I_S (b_6) and I_{SN} (b_7).

Parameter	Estimate	Confidence Interval	
b_6	-0.0062	-0.0409	0.0285
b_7	-0.0386	-0.0732	-0.004

Because the sulfur + nutrient treatment shows a significantly improved taper, using a different set of taper coefficients is advisable when estimating volume in similarly treated stands. The sulfur treatment was pooled with the control as these were not significantly different and the indicators were left off for this determination of coefficient values (Table 9).

Table 9. Taper model coefficients with corresponding standard errors listed for the two significantly different treatments, control and sulfur + nutrients.

Control Treatment			**Sulfur + Nutrient Treatment**		
Parameter	**Estimate**	**Std. Error**	**Parameter**	**Estimate**	**Std. Error**
α_0	1.0609	0.1177	α_0	1.8422	0.3506
α_1	0.9442	0.0203	α_1	0.8427	0.0354
b_1	0.1403	0.0834	b_1	0.3942	0.1293
b_3	-1.1015	0.1011	b_3	-1.1917	0.1306
b_4	0.6266	0.0565	b_4	0.5599	0.0881
b_5	0.0132	0.0042	b_5	0.0180	0.0077

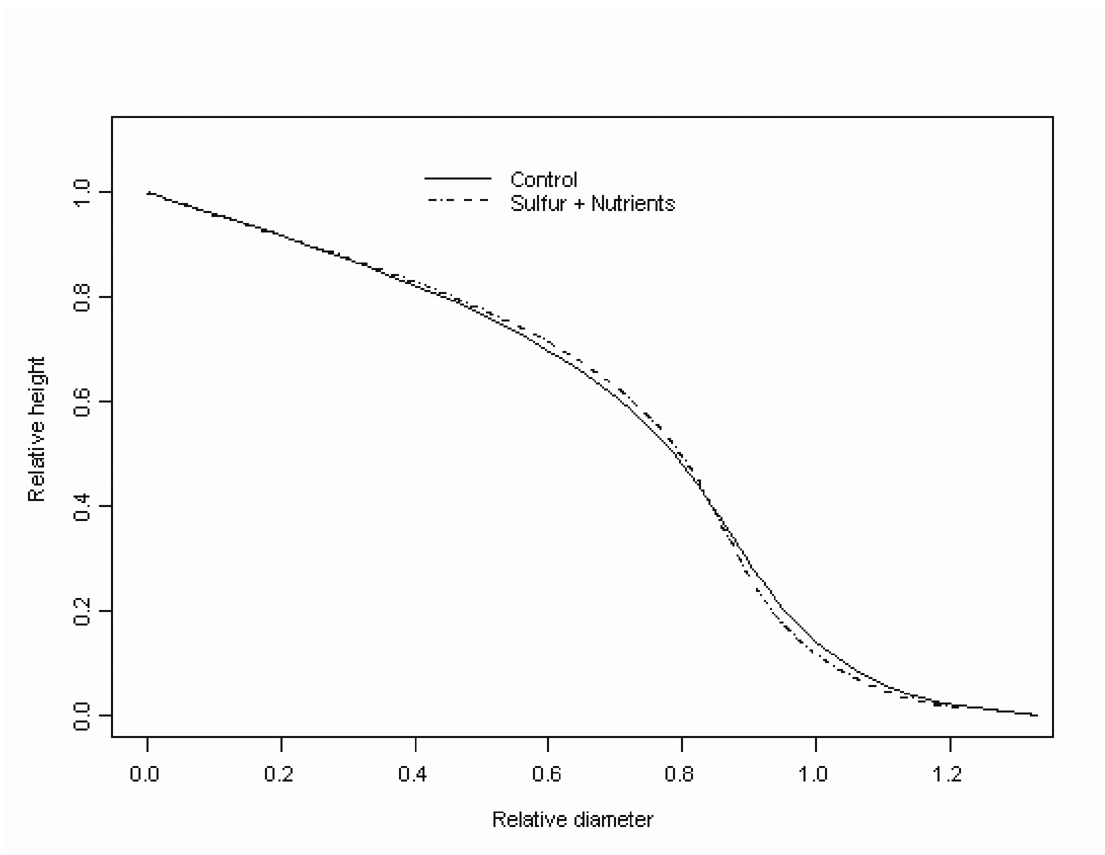

Figure 12. Stem profile difference between the control and sulfur + nutrients treatments at the overall mean dbh and total height.

The addition of the random tree effect in the taper model was not necessary (p = 0.1688). This result however, was contradictory to more recent studies in which mixed modeling significantly improved the model fit. Garber and Maguire (2003) found that when modeling stem taper in differing tree spacings, the combination of random effects and a first-order autoregressive process was necessary to reduce the effect of autocorrelation. Similar findings have been made while developing taper equations for coastal Douglas-fir as well (Aaron Weiskittel, Pers. Comm., Oregon State University, 2006). Tasissa and Burkhart (1998) also recognized and accounted for correlation among within tree observations with mixed modeling techniques but noted that some of the variables significant when correlation was ignored turned insignificant after correlation was accounted for and visa-versa. It is important to note that in this analysis a change in significance was also noticed. The sulfur + nutrient treatment remained significant after accounting for the variance with a power function (p = 0.0016), and adding a CAR(1) to account for autocorrelation (p = 0.0246). However, this treatment became insignificant once a random tree effect was added (p = 0.1364). Because the random effect was determined to be unnecessary, however, it was not utilized, leaving the sulfur + nutrient treatment to remain significant. Huang et al. (2000) knowingly chose not to utilize mixed modeling techniques when modeling taper with a variable-exponent model form, stating that whether the correlations are accounted for has little practical significance for prediction purposes. Gregoire *et al.* (1995) argued that model misspecification caused by erroneously including or excluding covariates due to their inaccurate error estimates can bias the model fitting process, therefore possibly damaging predictions. The results obtained here underscore the importance of accounting for autocorrelation in the best possible fashion, as this can drastically affect the significance of the treatment indicator coefficients.

Even in healthy trees, there are contradictions in the literature as to how fertilizers affect stem form. Many agree that after a fertilization treatment, taper will increase, decreasing form factor (Groot *et al.* 1984, Mead and Tamm 1988, Gordon and Graham 1986). Others have found though that fertilization allocates more growth higher on the stem, making the bole more cylindrical (Valinger 1992). And yet others have found that N fertilization does not statistically change stem form at all (Karlsson 2000). Because fertilization effects on taper are not even clear in healthy trees, the treatment effect on SNC infected trees is definitely arguable. Weiskittel and Maguire (2004) attempt to explain this relationship by suggesting that a decrease in leaf area (as caused by SNC) can cause an increase in taper. Speculatively, anything that can be done to combat SNC, will most likely begin to return leaf area to a previous level, causing taper to once again decrease. It has been shown in this analysis that the sulfur + nutrient treatment actually did improve needle biomass, retention and taper.

It is stated again and again in taper literature that tree bole taper is directly related to crown size and position. The results in this analysis, however, seem to contradict this popular theory. As earlier results concluded, there were no treatment effects in the analysis of covariances on sapwood area, crown ratio, crown width, etc. Given that the taper analysis found a significant difference between treatments, it leads me to believe that perhaps stem form is not directly mediated by any of the crown attributes, but by the needles. This seems particularly logical considering that the needle ANCOVA did reveal significances between the sulfur + nutrient and control treatments, just as the taper analysis did. To explore this idea, two commonly measured crown attributes, crown ratio and crown width, were added to the taper equation one at a time. Because the previous analysis determined that the generalized last squares fit model with a weighting function of 0.3, and a lag 1 continuous autoregressive error process dealt with the correlation structure best, it was used for this exploration of taper as well. Crown ratio was not a significant predictor of tree taper (p-value = 0.9165), however, crown width was marginally significant (p-value = 0.0529). The two needle measures, retention and biomass, were also added to the taper equation one at a time. The needle biomass parameter was not statistically significant (p-value = 0.4273) in the taper equation, yet the foliar retention parameter was very significant (p-value = 0.0007). As oppose to shedding light on the hypothesis, these results seem to complicate the matter. Crown width had some solid predictive abilities, yet needle retention was far better. These results somewhat support the hypothesis that needle characteristics influence tree taper more so than crown attributes. Table 10 displays the AIC, BIC, and loglikelihood values for the taper equation with the specified covariates added to the exponent. The lowest values are obtained by the taper equation with foliar retention parameter. A test between the taper model with no covariate, and the taper model with the foliar retention covariate confirmed that adding the foliar retention improved model fit (p-value of log likelihood ratio = 0.0007). The value of adding crown width to the taper equation was marginal (p-value of log likelihood ratio = 0.0519).

Table 10. AIC, BIC and log likelihood ratio values for the taper equation with each of the specified parameters added to the exponent.

Extra Taper Parameter	Estimated Parameters	AIC	BIC	Log Likelihood
Foliar Mass	10	7959	8008	-3964
Foliar Retention	10	7947	7996	-3964
Crown Ratio	10	7959	8008	-3969
Crown Width	10	7955	8005	-3968
None	9	7957	8002	-3969

The best fit taper model for this dataset, where R is foliar retention in years, can then be written as:

$$d_i = \alpha_0 dbh^{\alpha_1} \; X^{b_1 Z^2 + b_3 \sqrt{Z} + b_4 e^z + b_5 \left(\frac{dbh}{H}\right) + b_6 R} \qquad [6]$$

Crown ratio is commonly used in taper and volume equations (Garber and Maguire 2000, Burkhart and Walton 1985, Valenti and Cao 1986), yet this analysis shows that crown width was a better predictor. One possible reason why was mentioned by Hann et al. (1987). He commented that crown ratios tend to be smaller in long-crowned than in short crowned trees. Therefore, the variation that would have been explainable by crown ratio is already explained by the height diameter ratio, seen in this equation as "b_4(dbh/H)". In addition to this, I feel that this particular dataset did not have very much variation in crown ratio, being an even-aged closed canopy stand. Perhaps the insignificance of the crown ratio variable in the taper equation was due to the fact that a wide enough range of crown ratios were not measured. Biologically, I believe it makes sense that crown width at the lowest live branch was a better predictor of tree taper than crown ratio. Crown width is very closely related to tree spacing, and tree spacing is very closely related to stem taper. Early in tree taper research it was determined that open grown trees taper more than trees within a closed canopy. In this situation, crown width is acting as a tree-level surrogate for stand density. After some thought, it is actually surprising that crown ratio is so frequently utilized in taper modeling, when so many better variables exist. Perhaps it's frequent use is solely due to its ease of measurement.

4.2.3 Integrated tree volume

Because there is a significantly different taper in the sulfur + nutrient treatment, it follows that the volume in the sulfur + nutrient treatment may be significantly different from the control as well. By numerically integrating the variable exponent taper equation, and using the appropriate coefficients for each treatment on each tree, a determination of average volume by treatment can be made. Numerical integration was performed by splitting each tree up into one hundred segments of equal length, integrating and then summing the parts using S+ statistical software. Because the taper of the sulfur treatment was not statistically different from the control, these two treatments were combined and then integrated to be compared to the integrated sulfur + nutrient volumes. Results revealed that the sulfur + nutrient treatment had a mean tree volume of 24.68 cubic feet, where the combined sulfur and control treatments had an average volume of 24.49 cubic feet. After performing a pooled-variance two-sample t-test, it was determined that these two volumes are not statistically different ($p = 0.6087$).

4.2.4 Merchantable tree volume and valuation

To test if volume differences exist between treatments, log lengths and diameters were directly measured on the trees which were felled for taper analysis in the field. Because felling for taper analysis occurred just months before the actual first commercial thinning in the stand, this method of volume determination seemed highly practical. Nineteen foot logs were measured to a 4 inch top, and DIBSE as well as DIBLE were directly measured with a scaling stick on site.

Cubic foot volume, as quantified by Smalian's formula, to a 4-inch inside bark diameter, showed no significant differences among the treatments. After correcting for tree size with DBH and checking model assumptions, the control treatment had a mean tree volume of 12.1 ft^3, the sulfur treatment had a mean of 11.2 ft^3, and the sulfur + nutrient treatment had a mean of 11.6 ft^3 (control-sulfur comparison p-value = 0.0957, control-sulfur + nutrient comparison p-value = 0.3441). These values are notably less than the integrated volumes because the non-merchantable volume in the top and stump were not included in this method of volume calculation. Expanding these to a per acre basis also showed no significance. The control treatment still had the highest volume at 4,931 $feet^3$ per acre, sulfur treatment had 4,627 ft^3 per acre, and the sulfur + nutrient treatment had 4,645 (control-sulfur comparison p-value = 0.5593, control-sulfur + nutrient comparison p-value = 0.5780).

Because the slightest increase in DIBSE can be capable of moving a log from pulp to a saw log category, and pulp logs are worth appreciably less than saw logs, dollar values were calculated per tree based on the 1972 Scribner factor table and the bf prices as discussed in the methods section. Much like the results in the examination of cubic feet between treatments, this log valuation reveals that there are no treatment differences in the value of thinned trees after accounting for tree size with a dbh covariate (control – sulfur comparison p-value = 0.6850, control-sulfur + nutrients comparison p-value = 0.6969). Surprisingly, the control treatment actually has the greatest mean dollar value per tree ($ 25.98) although, this is not statistically significantly different from the other two treatments, where the average value of a sulfur–treated tree is $25.32, and a sulfur +

nutrient-treated tree is $25.35. On a per acre basis the conclusions are the same. If an entire acre from the control were harvested, the gross value would be $4,931, the sulfur treatment had a value of $4,627, and the sulfur + nutrient treatment would be worth $4645. Neither of these treatments had greater standing volume than the control on a per acre gross value basis (control – sulfur comparison p-value = 0.5593, control-sulfur + nutrients comparison p-value = 0.5780)

4.2.5 Volume Change from 1999 to 2004

Because the growth rings on each disk were measured, change in volume from 1999 to 2004 can also be compared between treatments. The 1999 diameter and the 1999 height of one tree per plot was used, and the pre-treatment cubic foot volume was calculated. The volume of the tree at time of felling (2004) was also calculated on the same trees in the same manner. After correcting for tree size with a 1999 DBH covariate, it was determined that the change in volume from 1999 to 2004 was not different between treatments. (control – sulfur comparison p-value = 0.2390, control-sulfur + nutrients comparison p-value = 0.8348). The greatest mean change in volume occurred in the sulfur + nutrient treatment (6.46 ft^3), while the least change in volume occurred in the sulfur treatment (5.66 ft^3).

Without a significant increase in volume obtained in the first thinning due to the treatment effect, justification for the treatment in an industry setting is difficult. A lack of treatment effect could be due entirely to the fact that only four years have passed since initial nutrient applications were made, and only two years since the sulfur was applied. Volumes were quantified by numerical integration of the taper equation, cubic foot volumes with Smalian's formula, as well as Scribner board foot measurements. All methods concluded that no volume differences existed four years after initiation of the treatment.

4.3 Stand-Level Changes

It was speculated during data collection that the treatments may have caused stand changes in trees per acre (TPA), basal area per acre (BA), site index (SI), and/or diameter distributions. To explore this idea TPA, BA, and SI were quantified by treatment from 2000 (pre-treatment) to 2004 (post-treatment). Table 10 summarizes the mean TPA, BA, and SI by treatment as well as displays percent change from 2000 to 2004.

Table 11. Average number of trees per acre, square feet of basal area per acre, and site index by treatment from 2000 to 2004.

Stand	Control			Sulfur			Sulfur + Nutrients		
Attribute	2000	2004	Change	2000	2004	Change	2000	2004	Change
TPA	420	404	-3.80%	422	404	-4.30%	444	414	-6.80%
BA	176	207	17.60%	176	199	13.30%	173	203	17.50%
SI	104	104	0.48%	102	104	1.04%	102	102	-0.63%

Figures 13, 14, and 15 graphically display the information in Table 10. The sulfur + nutrient treatment, which begins with a higher initial TPA in the year 2000, experiences the fastest rate of decrease in TPA, as well as the fastest increase in BA. The sulfur treatment appears to have the same rate of TPA decrease as the control, but the increase in BA appears to be slightly less than in the control treatment.

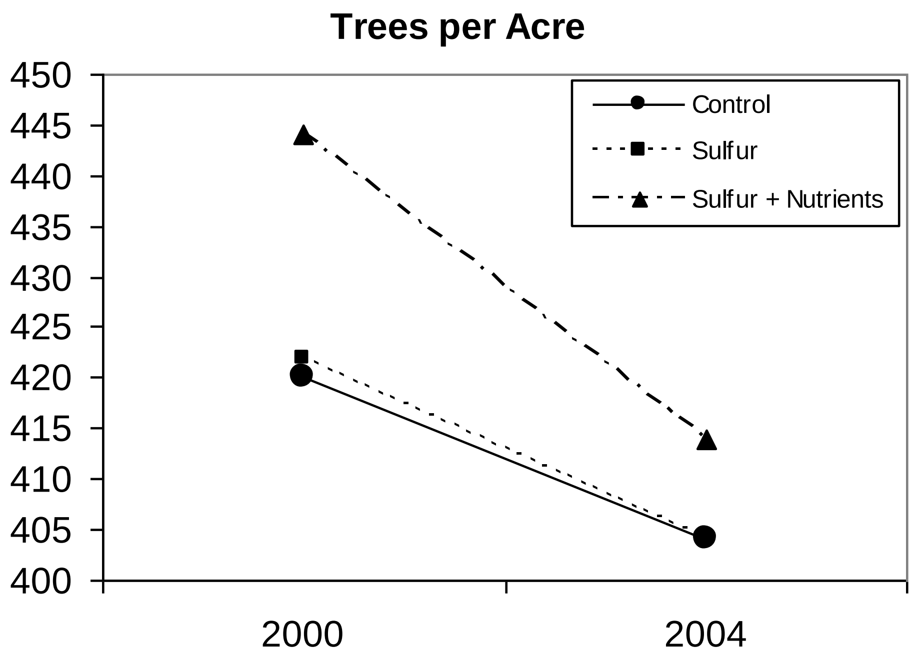

Figure 13. Trees per acre by treatment from 2000 to 2004, where the sulfur + nutrient treatment appears to have a greater, although not statistically significant, rate of decrease.

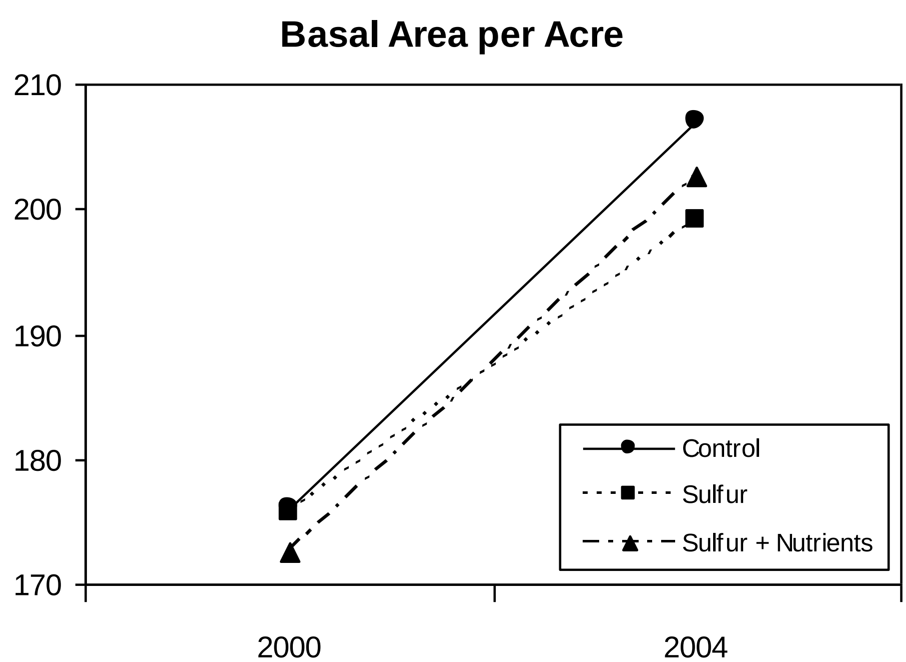

Figure 14. Basal area per acre by treatment from 2000 to 2004, where none of the treatments show statistically different rates.

To determine if any of the changes in TPA and BA in the treated stands are significantly different from the control, a Kruskal-Wallis test was performed. This procedure was chosen due to its robustness to non-normality and non-constant variance as well as other assumptions. This test, performed with a response variable of difference in TPA from 2000 to 2004, resulted in a p-value of 0.1553 indicating that the observed differences in change in TPA between treatments is not statistically significant. The Kruskal-Wallis test was also used to test if difference in BA growth from 2000 to 2004 was different between treatments. This test revealed that there is no statistically significant difference in BA change between treatments (p-value = 0.4937).

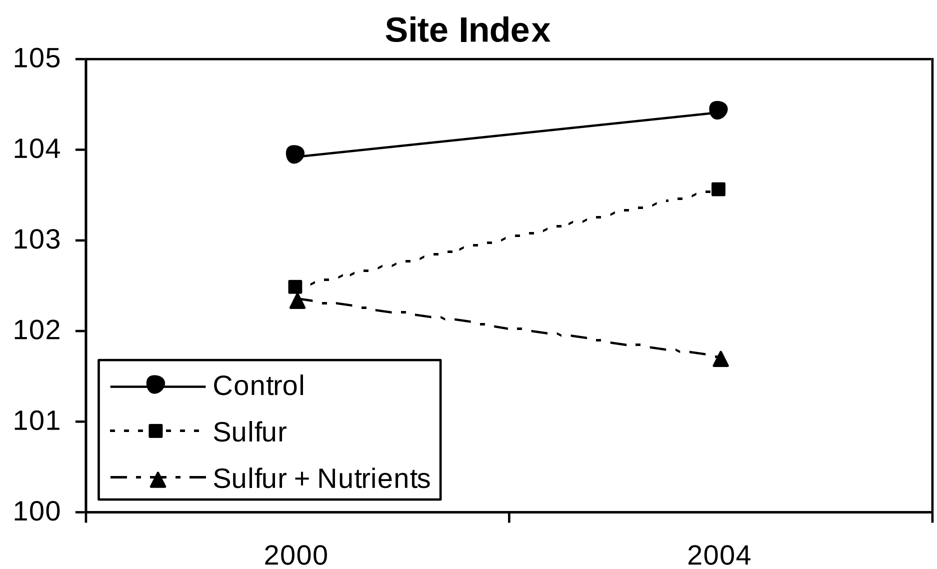

Figure 15. Site index by treatment from 2000 to 2004, where no statistical differences between treatments exist.

Site index is frequently used as an indicator of site productivity. In Oregon Coast Range Douglas-fir, King's site index equation (1966) is most commonly used as this metric. However, due to the young age of the stand, these values were terribly inflated since King's curve uses a base-age of 50 years (177 in the control, 175 in the sulfur treatment, and 171 in the sulfur + nutrient treatment). For this reason, a different site index curve was chosen. Flewelling *et al.* (2001) created a density dependent site index curve for young Douglas-fir stand with a base age of 30, which is much better suited to this stand. The most dominant tree from each plot was chosen, and the change in site index from 2000 to 2004 was compared between treatments with an analysis of variance procedure. A test on the multiplicative variable between treatment and year reveals there is no significant change in site index between treatments (p-value = 0.7332). Treatment does not explain a significant amount of variation in this model indicating that SI's are not different between the three treatments (p-value = 0.1732). Figure 15 makes it apparent that the sulfur and control treatments experience an increase in SI whereas the sulfur + nutrient treatment actually experiences a non-significant 0.6% decrease in SI. This is most likely due to the fact that the sulfur + nutrients treatment had a greater decline in TPA than the other two treatments.

This examination of SI also brings up another very important point. It is common knowledge that stands of high site indices are not expected to respond to nutrient treatments as well. Because these treatment areas are located on very high site ground, this lends further explanation to the lack of volume growth effect. If these stands were of poorer site class, I would expect a more substantial treatment effect in at least the sulfur + nutrients treatment.

Diameter distributions were also examined by treatment from 2000 to 2004. The resulting histograms are in Figure 16. As expected, all three treatments experienced diameter growth at breast height in the four-year period, as evidenced by the histograms. A Kruskal-Wallis rank sum test was performed on differences in diameter from 2000 to 2004, the null hypothesis being that the three treatment means are equal. This test resulted in a p-value of 0.2040, meaning there are no significant differences in mean diameter change between the three treatments. If the nutrient treatments did cause a greater differentiation in DBH, detecting this with a non-parametric test on the treatment means may not reveal that change anyhow. The spread of diameters could change significantly without changing the mean of the diameters. The histograms show that the shape of the frequency distribution goes from a bell shape to an almost more bimodal shape in the sulfur and sulfur + nutrients treatments. However, the same sort of change is occurring in the control, so no sure conclusions are drawn from diameter distribution observation.

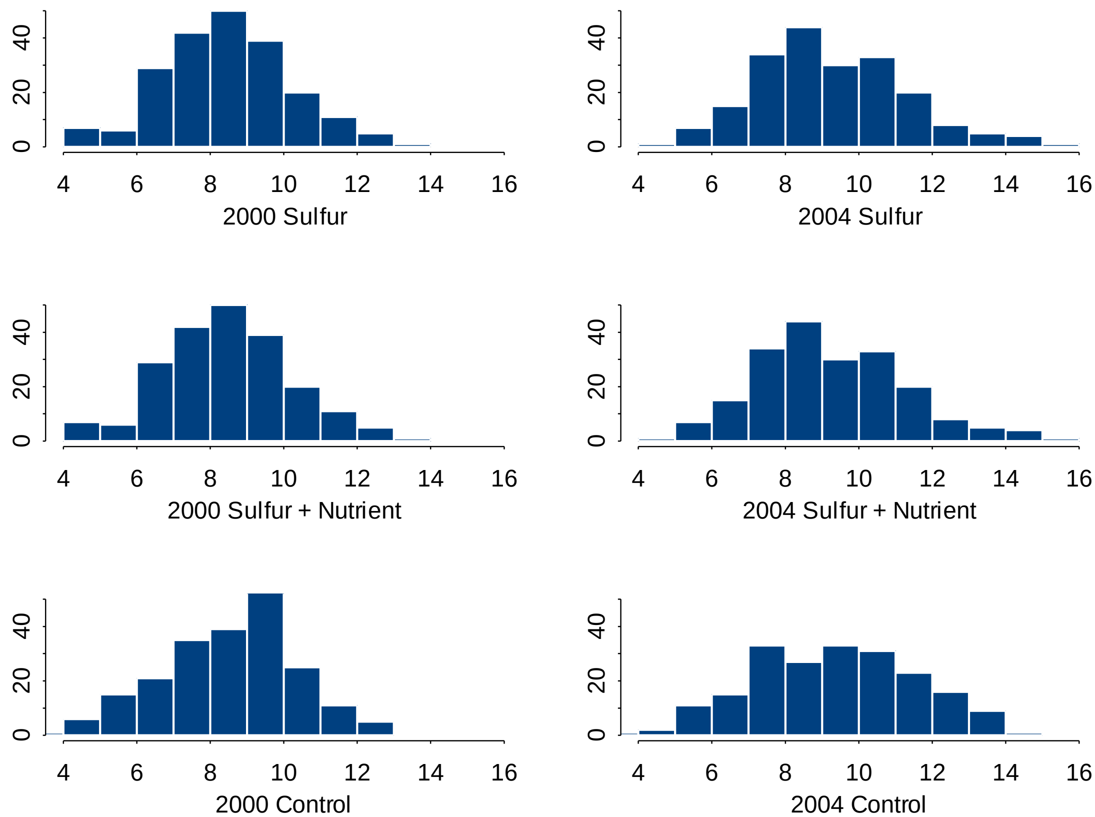

Figure 16. Diameter distributions by treatment from 2000 (pre-treatment) to 2004 (post-treatment).

The effects of fertilization on stand development have frequently been documented. While studying the effects of N fertilization on a lodgepole pine stand, Yang (1998) noticed that high N loadings increased self-thinning mortality and accelerated stand development. He even suggested that fertilization be advantageously used as a tool for managing overstocked stands. Similarly, Groot *et al.* (1984) noticed that response to N fertilization in a jack pine stand was greatest in the largest diameter trees. Logically, this leaves fewer resources to the smaller trees, making them weaker until stem exclusion occurs. Unlike these sources however, the SNC infected Douglas-fir from this experiment did not show a decrease in TPA from pre to post treatment. Groot *et al.* (1983) added that the growth response did not begin until the second growing season after treatment. For the sulfur + nutrient treatment, which was initiated in 2000, it seems as if there might have been a BA response, but the sulfur treatment was not initiated until 2002, leaving an inadequate two years for this sort of a response to surface. It is therefore concluded that the lack of increase in BA as well as a lack of difference in TPA may be due to an insufficient time period for response. If measured again in a few years, it may be possible to find a more substantial reduction of TPA in the sulfur + nutrient treatment, as well as a higher rate of BA, but this is, of course, is speculation.

5 Conclusion

Volume, taper, and selected tree attributes were examined on 120 Douglas-fir trees for response to treatments of 1) sulfur, 2) a sulfur + nutrient, or 3) a control, which received no treatment. Mixed results were found throughout the analysis when comparing the sulfur + nutrients treatment to the control, but for the most part, volume, taper and other attributes compared between the sulfur and control were not statistically different. Tree attributes such as crown ratio, crown width, and sapwood area at crown base showed no statistical significant differences between treatments while both foliage mass and years of needle retention showed improvement in the sulfur + nutrient treatment only. Using a modified Kozak's (1988) variable exponent model form with a continuous autoregressive error structure, taper analysis indicated that the taper of trees within the sulfur + nutrient treatment showed an improved taper compared to the control. Not surprisingly, the taper within the sulfur treatment was not statistically significant from the control. It was surprising however, that the sulfur + nutrient treatment has not shown significant increase in cubic foot or board foot volume after adjusting for tree size differences between treatments. Table 12 summarizes the overall results.

Table 12. Statistical significances (S) and non-significances (NS) between the sulfur treatment and the control (Sulfur) as well as between the sulfur + nutrient treatment and the control (Sulfur + Nutrient).

Tree Attribute	Sulfur	Sulfur + Nutrient
Foliar biomass	NS	S
Needle retention	NS	S
Sapwood area	NS	NS
Crown Ratio	NS	NS
Crown Width	NS	NS
Avg. BA growth	NS	S
Taper	NS	S
∫ Volume	NS	NS
BF $ Value	NS	NS

Often, when comparing the sulfur treatment to the control an improvement in the attribute was revealed, but this was never quite statistically significant. This leads me to conclude that perhaps much of the insignificant improvements were due to a lack of a proper response time period. In a similar study of N and S fertilization of *Pinus radiata*, both the S and N treatments showed similar growth to the control for about two years after the fertilizer application, but an improvement in growth was witnessed after the initial two year period (Lambert 1986). Situations such as this are frequently noted in fertilization literature. Because the questions that this study addresses are of great interest and value to forest management in the Oregon Coast Range, reevaluating these results after a few more years would absolutely be worth while.

Lack of a more significant response could also have something to do with the degree of SNC severity before treatment. There is a significant lack of research which quantifies the average years of needles held in Oregon Coast Range Douglas-fir prior to the discovery of SNC. Presently, Filip et. Al (2000) believe that a healthy Douglas-fir normally holds 3 - 4 years. In this study, the control held 3.0 years of needles. The question then becomes, just how infected is this stand? By simple observation, the crowns do appear more sparse than typical. This is, of course, very subjective, but no metric of SNC severity was taken prior to treatments. In addition to the SNC severity, I believe site fertility may also have also predisposed the stand to a less-than-expected response. It is common knowledge that high site class stands which are fertilized generally experience little to no basal area growth effect, and as previously discussed, this is a high site class stand.

Short of harvesting all Douglas-fir on the West side of the Oregon Coast Range and replanting with Sitka spruce and Western hemlock, silvicultural solutions to infestations of Swiss needle cast are not promising given these results. To craft an effective solution, I believe focusing on the underlying cause(s) of the current SNC epidemic is the key. Previous work has identified the primary causes to be off-site planting (Hansen *et al.* 2000), climatic changes (Stone and Coop 2006), and nutritional imbalances (Waring *et al.* 2000).

While the increased abundance of Douglas-fir in the coastal spruce zone of Oregon is undoubtedly partially responsible for the outbreak of SNC, the only management conclusion this leads to is removing or reducing the composition of Douglas-fir from this zone. While many foresters work to include other species in the artificial regeneration of harvested sites, others feel it is not necessary. Despite the increasing severity of SNC on these sites, the volume lost to this disease still does not financially outweigh planting species which will produce less valuable sawlogs.

Annual aerial surveys have been taking place along the PNW coast since 1996 when SNC was first recognized as an emerging crisis. Aerial surveys from the spring of 2006 reveal that 325,000 acres are moderately to severely infected: the second most widespread severity level since 2002 when 387,000 acres were infected (Kanaskie *et al.* 2006). Recent research within the SNCC has also discovered that severity is most closely linked to the previous average summer relative humidity, and the February to March degree-days (Stone and Coop 2006). Considering relative recent climate trends, these results are nothing but logical, and alarming. From 1966 to 2006, the average change in winter (December to January) temperatures has been approximately a 1.6 to 3.2 ºF increase, and in the same time period, the April to June precipitation has increased 4 – 6 inches (Stone 2006). If these climate trends continue, SNC severity will only worsen. Although identifying the climatical cause of SNC outbreak is of importance, it reveals very little in the way of management options, besides identifying planting sites which can minimize summer humidity and winter warmth.

It seems as though only the causal theory of nutritional imbalances can lead to more immediate solutions, avoiding stand-replacing options. As this work concludes, an improvement in needle retention, needle biomass and taper may be obtained within a few years by a combination of aerially applied sulfur and micro- and macronutrient treatments. The literature review revealed that fertilization treatments alone, especially those based on N, reveal mixed results (e.g., Brix (1981) vs. Balaster and Marshall (2000)). It has even been suggested that SNC stands not be fertilized (Mainwaring *et* *al.* 2005). Additionally, literature shows that needle retention generally decreases with nutrient treatments alone. The increase in needle retention and biomass, as seen in this study, is thought to be a consequence of adding elemental sulfur to the nutrient applications. For these reasons and more, a combination of elemental sulfur and specifically prescribed micro- and macronutrients is recommended for the improvement of foliage, taper, and growth in SNC infected Douglas-fir stands of the Oregon Coast Range.

To capture the full potential of the treatment effects, I believe monitoring of these plots should be continued. When these subject trees were felled the sulfur had only been applied for two consecutive years, and the nutrients had only been applied four years. Because there is a significant improvement in needle biomass, retention, and taper, it is suspected that volume growth and stem form may still improve in the future, but this is yet to be determined.

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