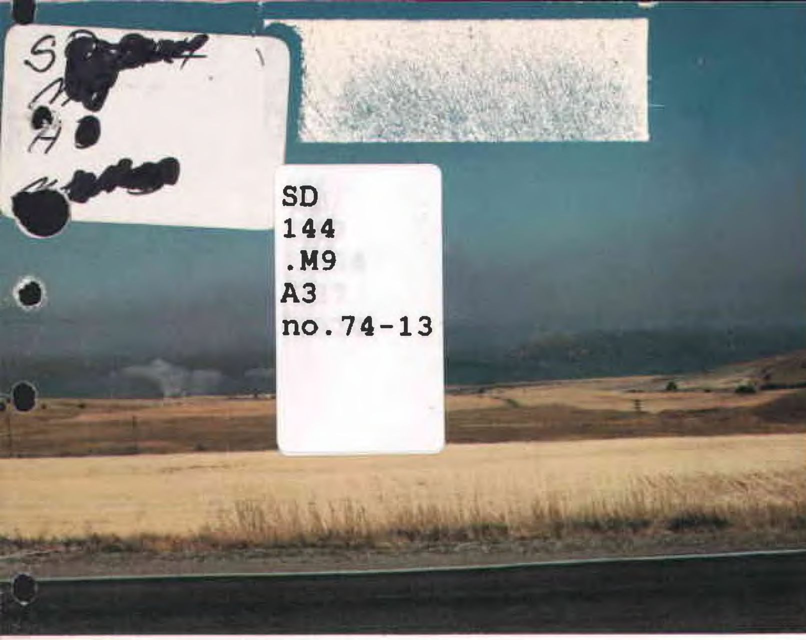

SULFUR DAMAGE TO DOUGLAS-FIR

NEAR A PULP AND PAPER MILL IN WESTERN MONTANA

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by

Clinton E. Carlson

This study was accomplished with the cooperation of the State of Montana Department of Health and Environmental Sciences, Missoula County Health Department, Hoerner Waldorf Corporation, U. S. Plywood, State of Montana Department of Natural Resources, and the U. S. Forest Service.

Cover Photographs

Upper left--Plume emitted by the Hoerner Waldorf pulp and paper mill at Missoula, Montana. The white component is primarily steam. The bluish-gray stratum extending horizontally from the main plume contains particulate and various gaseous sulfur compounds including mercaptans, hydrogen sulfide, and sulfur dioxide. Damage to Douglas-fir occurred on the mountains behind the mill.

Upper right--Sulfur damage to current year (1973) and older needles. Note the needle tip burn syndrome and loss of needles on older internodes.

Lower left--Damage to a Douglas-fir stand near the pulp mill. Many of the affected trees lost nearly 100 percent of their foliage.

Lower right--Damage to individual Douglas-fir trees. Note the loss of needles and the tendency for the inner and lower crowns to be affected more than the outer and upper portions. This probably represents a concentration effect.

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by

Clinton E. Carlson, Mark D. McGregor, and Norman M. Davis[1/]

ABSTRACT

Serious needle browning not caused by parasitic fungi or insects occurred on Douglas-fir over 5,200 acres of forested lands during the winter of 1972-73 near the Hoerner Waldorf pulp and paper mill at Missoula, Montana. Severity of damage increased at decreasing distance from the pulp mill. Total foliar sulfur content ranging from .00 to .63 percent was found in the area, with highest concentration found in the most severely affected area. Average sulfation rate, a measure of total atmospheric sulfur, was greatest (1.52 mg $SO_3/cm.^2/day$) in the severely affected area and least (.96 mg $SO_3/cm.^2/day$) in the lightly affected area. Symptoms on the foliage and tree as a whole were similar to those caused by excessive airborne sulfur compounds including H_2S and SO_2. Histological analyses of affected foliage showed the mesophyll cells, which plasmolyzed and collapsed, to be affected first, followed by hypertrophy and collapse of parenchyma in the vascular system. These symptoms were basically similar to those reported for pine tissue fumigated with reduced sulfur and sulfur oxides. It is concluded that sulfur was the most likely cause.

Potential impact, defined as the volume of merchantable Douglas-fir that may die if the situation persists, amounted to nearly 2.5 million board feet in moderately and severely damaged stands. If sulfur emissions are not reduced, this impact may become real.

The entire affected area was stereo-photographed in true color and color infrared at a scale of 1:8000. This photography clearly showed the damage and is a permanent record of the incident.

1/ Plant pathologist, entomologist, and soil scientist, respectively, USDA Forest Service, Region 1, Missoula, Montana.

INTRODUCTION

In mid-February 1973, a Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) branch showing severe disease symptoms on the foliage was collected near the Hoerner Waldorf pulp and paper mill (Fig. 1) and brought to our laboratory.[2/] More than half the needles were missing, and many of the remaining needles were either completely or partially dead. Necrosis (browning) was evident in varying patterns. Tip burn or necrosis at the needle tip was common. Also, a necrotic band medially along the dorsal side of the needle was often found. About 2 weeks later, a similar sample collected by Jess McDonald, a private landowner in the area, was delivered to us by Wes Kellie, silviculturist, Lolo National Forest. Preliminary laboratory analyses of these specimens indicated that neither parasitic disease nor insects were causal agents.

A field trip was made to the affected area early in March 1973 by Clinton E. Carlson, plant pathologist and William M. Ciesla, entomologist.[3/] Field observations confirmed that fungi and insects were not the primary damaging causes. A rather peculiar damage syndrome was noted on affected trees--damage appeared to progress from the inside of the crown to the outer portions, and from the bottom of the tree to the top. Thus the top and outside of many affected trees were green while the interior portions were brown and very sparse. At that time it was determined that the area affected was rather extensive; therefore an aerial reconnaissance was requested. An aerial survey was made late in March 1973, and the visibly affected area was mapped. Subjective classifications of damage severity as interpreted from the air were made:

Severe - intense browning on 50-100 percent of the trees, entire area appearing quite brown.

Moderate - browning on 25-50 percent of the trees, area appearing greenish-brown.

Light - browning on less than 25 percent of the trees, area appearing faded green.

2/ Specimens were collected by Rudy Lood, biological technician, Forest Insect and Disease Branch, Division of State and Private Forestry, Region 1, USDA Forest Service.

3/ Forest Insect and Disease Branch, Division of State and Private Forestry, Region 1, USDA Forest Service.

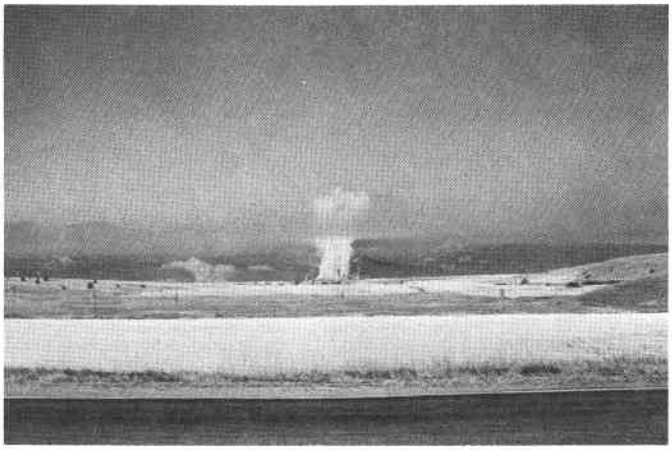


Figure 1.--Plume from the Hoerner Waldorf pulp and paper mill. Note lateral dispersion of fumes about 500-800 feet above valley floor. Damaged area is in the mountains behind the mill. Much of the severely damaged area apparently coincides with the lateral dispersion level.

Douglas-fir on 1,240 acres were found to be severely damaged, 1,120 acres moderately damaged, and 2,840 acres lightly damaged. In all, trees on 5,200 acres of land showed damage symptoms visible from the air (Fig. 2).

The pulp mill is situated on the valley floor at 3,100 feet mean sea level, 17 miles northwest of Missoula, Montana. A mountainous area with coniferous forest exists about 1 mile west of the mill. The habitat type (Daubenmire and Daubenmire, 1968) over a large portion of the damaged area is *Pseudotsuga menziesii - Physocarpus malvaceus*.

As shown in figure 2, the damaged area is located immediately west of the Hoerner Waldorf pulp and paper mill. The most severe damage was found close to the mill, with moderate and light damage farther away, respectively. In an Environmental Impact Statement prepared at Hoerner Waldorf's expense, Berg, et al. (1973) show that during 1973 the pulp mill emitted about 520 pounds of total reduced sulfur (as H_2S) per day and 5,000 pounds of sulfur dioxide (SO_2) per day. Injury by sulfur dioxide to trees around industrial sources is well documented. Nemec (1932) observed injured and dead trees affected by SO_2 from a paper mill in Czechoslovakia. Scheffer and Hedgcock (1955) documented extensive SO_2 damage to conifers near smelters at

Anaconda, Montana, and Trail, British Columbia. Linzon (1958) found severe damage to white pine foliage and reduced diameter growth caused by sulfur oxide from a smelter complex. Injury to needles in these areas, as in the Hoerner Waldorf area, generally was evident by tip necrosis, banding, or complete death. Because of the proximity of the damage to the pulp mill, the significant amount of sulfur emitted by the mill and the nature of the injury on the needles, it was hypothesized that airborne sulfur emitted by Hoerner Waldorf was the causal agent.

Early in May 1973, a special committee, including representatives of Hoerner Waldorf, University of Montana, State of Montana Air Quality Bureau, U. S. Plywood, Missoula County Health Department, State of Montana Department of Natural Resources, a small private landowner, and the U. S. Forest Service (Appendix I) were called together to discuss the problem. The input of this group was utilized in developing the final study outline. As a result, the following items were considered for study in relation to the hypothesis that sulfur was the causal agent:

1. Foliar analyses to determine total sulfur, to quantify sulfur-type damage, to identify foliage-feeding insects, and to observe histological reactions within the affected tissues.

2. Air analyses to determine SO_2 concentrations, total reduced sulfur, and meteorological conditions.

3. Soil conditions in the affected area.

4. Aerial photography of the affected area.

5. Potential impact on the timber resource in the affected area.

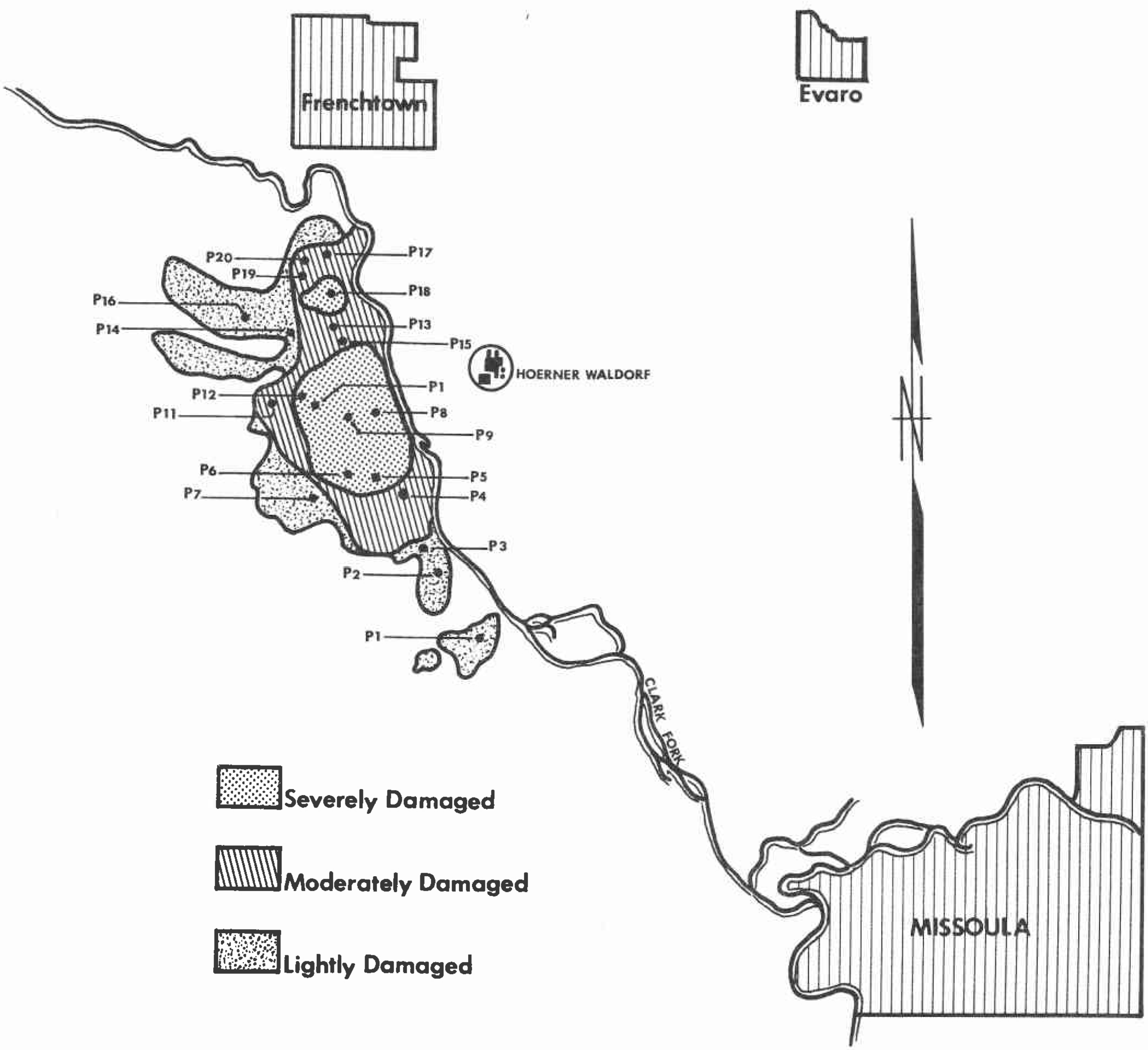
MATERIALS AND METHODS

Foliar and Air Analyses for Suspected Sulfur Damage

Twenty sampling sites distributed throughout the damaged area were selected by a Hoerner Waldorf representative and U. S. Forest Service employee[4/] (Fig. 2). Plots 1, 2, 3, 7, 14, and 16 were in the area previously defined as lightly damaged; plots 4, 12, 13, 17, 19, and 20 were in the moderately damaged area; and plots 5, 6, 8, 9, 10, 11, 15, and 18 were in the severely affected area. In addition, two control

4/ Marvin McMichaels, Hoerner Waldorf, and Clinton Carlson, U. S. Forest Service.

FIGURE 2 Damage Strata and Plot Locations for Sulfur Study



sampling sites were selected south of Plains, Montana, and two near Twin Creeks in the Blackfoot Valley east of Missoula on similar habitat types, species composition, and soils as found near the pulp mill.

At each plot two Douglas-fir and one ponderosa pine (*Pinus ponderosa* Laws.), generally dominant or codominant on the site, were selected and permanently identified for sampling. Then from each tree several branches, in aggregate having 2-4 pounds of foliage, were collected at midcrown facing the pulp mill. This foliage, on which several variables related to sulfur damage would be measured, was placed in a plastic bag and transferred to cold storage at the end of the day. At an appropriate time samples were taken to the Insect and Disease Laboratory, Region 1, for analysis.

A laboratory quantification of injury on foliage previously collected was then attempted, based on the symptom expressions of needle casting and necrosis. All branches gathered from each tree were cut into internode segments based on year of origin (1968-1972). Then, from 20 randomly selected segments of each year from each fir tree,[5/] the proportion of needles missing on each segment was estimated and classified as follows:

Percent needles missing	Class
76 - 100	1
51 - 75	2
26 - 50	3
0 - 25	4

Next, the needles from the Douglas-fir were stripped from each segment and kept separate by year of growth and tree number. Fifty needles were randomly selected and the proportion showing symptoms of sulfur damage was recorded. The presence of needle fungi was constantly watched for, although no counts were made.

Next, 10 Douglas-fir needles showing symptoms of damage were selected for histological analysis. Again, they were maintained by year of origin and tree number. Only needles showing distinct tip burn were used. From the damaged needles a 2-millimeter segment was cut from

5/ Quantification of damage was not done on ponderosa pine because needle browning was insignificant compared to that found on Douglas-fir.

the transition zone,[6] killed and fixed in formalin-aceto-alcohol, dehydrated in tertiary butyl alcohol, and embedded in paraffin. Sections averaging 10 microns in thickness were cut on a rotary microtone. For some specimens both longitudinal and transverse sections were made. All sections were stained with Feulgen's and counterstained with fast green. Observations were made through a Leitz Ortholux phase contrast microscope and photographed with an Aristophot system.

Approximately 20 grams of needles, including symptomatic and asymptomatic specimens, originating in 1970, 1971, and 1972 were weighed separately by year of origin from each tree sampled, dried in a forced draft oven at 80 degrees Farenheit, and ground to pass a 40-mesh screen. Foliage from ponderosa pine as well as Douglas-fir was analyzed for total sulfur. The dried and ground specimens were then sent to CH_2M/Hill Corporation, Bellevue, Washington, and analyzed for total sulfur. The method described by Blanchar et al. (1965) was used for determining total sulfur.

Two methods were used to determine the amount of airborne sulfur present in the study area. The first involved establishment of a system of sulfation plates (Huey, 1968). Sulfation plates are small plates coated with lead dioxide which, when exposed to either oxidized or reduced airborne sulfur, react with that sulfur, permitting quantitative analyses to be made. Two plates were installed at each plot location; one on a Douglas-fir and one on ponderosa pine, each of which had previously been sampled for foliar analysis. The plates were scheduled to be changed monthly or bimonthly as time warranted for the duration of the study period.

In the second method, concentrations of ambient sulfur dioxide, but not reduced sulfur, were measured with bubbler samplers. A constant volume of air was drawn through an aliquat of tetrachloromercurate. Two sampling devices were used: one was a portable battery-operated M.S.A. bubbler capable of sampling for 3-4 hours, the other was a 110-volt PEDCO machine that would sample for a 24-hour period. The latter was operated at various times on Jess McDonald's property near plot No. 17, where electrical power was available. The former, being portable, was operated at varying locations within the study area.

All sulfation plates and bubbler samples were analyzed by the Air Quality Bureau of the State of Montana.

6/ The transition zone is that area at the junction of necrotic and green tissue. It includes green, yellow, and brown tissue.

Wind direction and speed were measured near plot No. 11 in the severely affected area using an MRI model 1072-1 battery-powered instrument. This instrument was capable of recording data for approximately a 2-month period before the batteries and chart needed changing. Wind roses were computed from this data by the State of Montana Air Quality Bureau.

Foliar Analyses for Insect Damage

Field samples were collected from each of the 20 plot locations in the study area as well as from the four control areas. At each plot, four 15-inch branches were removed from midcrown from each of 10 Douglas-fir trees, two of which were sampled previously for sulfur damage. Branches were collected with extendable pole pruners with catch bags attached to prevent larvae from being lost when disturbed. Collected branches were placed in plastic bags and kept separate by plot and tree number. At the end of each work day all samples were transferred to cold storage prior to laboratory analyses.

In the laboratory, each branch was examined for the presence of defoliating insects, particularly western spruce budworm, *Choristoneura occidentalis* Freeman. Those found were removed and placed in Petri dishes labeled as to sample number. Then they were identified and sorted by an entomologist. Along with counts of defoliating insects, the number of defoliated and nondefoliated current year's buds were determined for each sample.

Soil Analyses

An inventory of soils was done in the study area and on the Blackfoot control plots, with particular reference to soil characteristics, water-holding capacities, and their ability to support tree growth under conditions of stress. Soils at the Plains control plots were not studied. All information collected was projected from data on similar soils outside the study area, as only incomplete data was available for soils within the study area. A field surveillance trip was made into the area to verify the interpretations made. No soil samples for laboratory analyses were collected in the study area.

Aerial Photography

To aid in delineation of visible damage and to provide a permanent record of this incident, the entire affected area was aerially photographed in infrared and true color at a scale of 1:8000. Complete stereo coverage was obtained.[7]

7/ This service was provided by the Division of Engineering, USDA Forest Service, Region 1, Missoula, Montana.

Potential Impact

Because Douglas-fir is an important lumber species in Region 1, it was desirable to know the volume of this species of timber affected in the study area. Using available resource photography, the moderately and severely damaged areas were stratified by stand types. The lightly affected area was not surveyed because of time and financial limitations. Then standard compartment examinations (Stage II - USDA Forest Service, Region 1, Timber Management Handbook) were made within each stand. Douglas-fir trees sampled were classified as:

1. Lightly affected to not damaged--some brown needles, less than 25 percent needles missing, crown nearly full.

2. Moderately affected--25-50 percent needles missing or brown, crown noticeably thin.

3. Severely affected--50-100 percent of needles brown or missing, crown very thin.

A moderately and a severely affected tree are shown in figure 3.

Height and diameter information for merchantable trees was transferred to a sale cruise tally sheet and volume information was summarized on the Forest Service computer by the damage classes defined above.

Figure 3.--Left - A Douglas-fir moderately damaged.
Right - Douglas-fir severely damaged.

RESULTS

Foliar and Air Analyses for Suspected Sulfur Damage

Results of determination of the proportion of needles missing, proportion of needles showing symptoms, foliar sulfur concentrations, and sulfation plate analyses for Douglas-fir are listed in Appendix II by the damage strata in which the plots were located. The distance and difference in elevation from the pulp mill are also given. Each value for proportion needles missing is an average of the indexes assigned to the 20 segments on which observations were made. Values for each of the other variables represent one determination and are not averages. The means and statistical significance as determined by an unpaired "t" test at the 95 percent level are given in table 1. Mean values are graphed in figure 4.

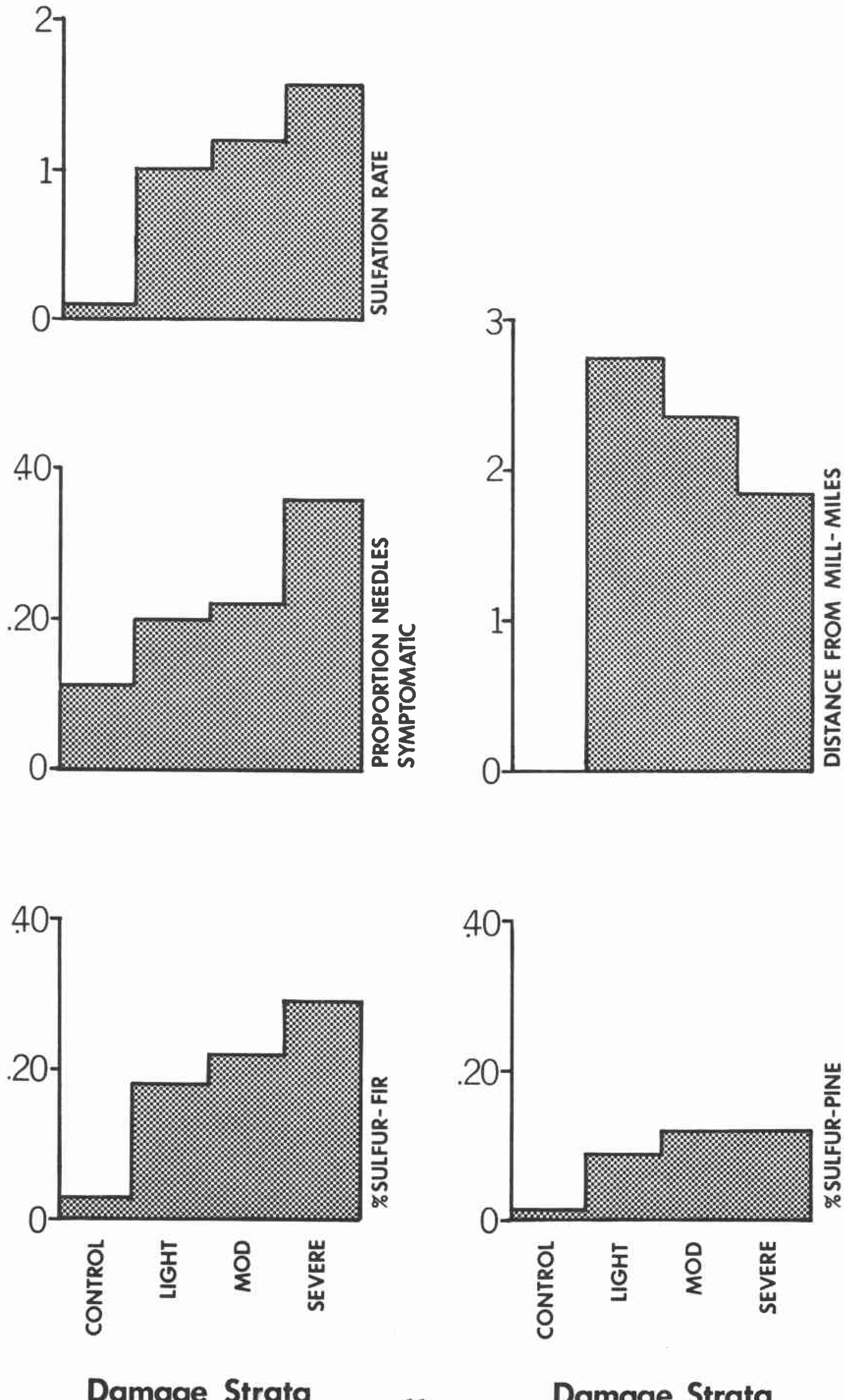
Table 1.--Statistical significance of means for different variables by damage class, Douglas-fir and ponderosa pine

	Control	Light	Moderate	Severe
Needle loss	2.81	2.63	2.41	2.20
Symptoms	.11	.20	.22	.36
Total sulfur (DF)	.03[1/]	.18	.22	.29
Total sulfur (PP)	.01	.09	.12	.12
Sulfation rate	.09	.96	1.17	1.52
Average plot distance from mill		2.75	2.36	1.86
Average plot difference in elevation		383	407	525

Means not underscored by the same line are significantly different at the 95 percent level.

1/ Percent sulfur based on the dry weight of the tissue.

FIGURE–4 Relationship of Several Variables to Damage Strata



The average indexes of proportion needles missing for the control, light, moderate, and severe damage strata irrespective of segment age, respectively were 2.81, 2.63, 2.41, and 2.20. Lower indexes indicate a greater proportion of foliage missing. As shown in table 1, the control values were significantly different from the moderate and severe, and the light values were significantly different from the severe. It was not statistically possible to distinguish between adjacent classes. Generally there was a trend for younger growth segments on most affected trees to retain more needles than older segments, but this was not tested statistically.

The means for proportion of needles showing sulfur symptoms were .11, .20, .22, and .36 for control, light, moderate, and severe classes, respectively. Only the light and moderate classes were statistically indistinguishable. These means were computed using data from all years of growth. Again, there was a trend for older needles to be more symptomatic than the younger, but this was not tested statistically.

The means for total sulfur in foliage, again computed without regard to foliage age, showed a significant increase as severity of damage increased. Respectively, control, light, moderate, and severe means were .03, .18, .22, and .29. Each was statistically different from the other. There was a definite trend for older needles to contain more sulfur than the younger.

The amount of sulfur in the air, as measured by the Huey sulfation plate method for the period May-October 1973, showed a constant increase as damage increased. Reported in micrograms of SO_3/ sq. cm/day, the means were .09, .96, 1.17, and 1.52 for the control, lightly, moderately, and severely affected areas. There was no significance between the light-moderate and moderate-severe classes.

Within the study area, plots in the severely affected area were significantly closer to the pulp mill than were those in the moderately and lightly affected areas. There was no significant difference in distance between plots in the moderately and lightly affected areas. On the average severely affected plots were 1.86 miles from the mill, moderately affected plots were 2.36 miles, and lightly were 2.75. Difference in elevation was highly variable and was not a significant factor for the damage strata.

Because injury appeared to be minor, measurements of damage on ponderosa pine were not done; however, chemical analyses of total sulfur were done. These values are listed in Appendix III by damage class as defined by injury to Douglas-fir. As indicated in table 1, the means for pines in the control, light, moderate, and severe classes were .01, .09, .12, and .12 percent, respectively. There was no significance between the light, moderate, and severe means but all were significantly different from the controls.

The relationship of percent sulfur in Douglas-fir to the sulfation rate during July-August at each plot in the study area without regard to damage strata is shown in figure 5. The data indicate a curvilinear relationship. Shape of the curve was ocularly estimated; no attempt was made to develop a mathematical model to fit the data. As the sulfation rate increased, the sulfur content of Douglas-fir foliage also increased.

Figure 6 shows that total sulfur in Douglas-fir foliage decreases at increasing distance from the pulp mill, and figure 7 indicates that sulfation rate also decreases as a function of increasing distance. Again, these data best fit a curvilinear format. Percent sulfur in Douglas-fir in relation to elevation was highly variable and no meaningful graph could be developed.

Data from bubbler sampling for sulfur oxides is shown in table 2. The results are quite variable, ranging from 0.0 to 0.04 parts per million. On May 22, 1973, values were higher than on other sampling days; however, we expected this because a strong inversion occurred that day. Four samples taken on that day were obtained along the road to plot No. 11. The results in relation to elevation are shown in figure 8. As elevation increased, so did the concentration of sulfur dioxide. Because of the small sample size, regression and correlation coefficients were not computed.

A wind rose for the period May-November 1973 is shown in figure 9. As mentioned previously, the wind station was located near plot No. 11 in the severely affected area. Three main vectors are indicated--northwest, east, and southeast. Data were extracted from field charts for 1-hour intervals.

All of the Douglas-fir needles on which histology was done showed a distinct pathological syndrome unlike any caused by infectious disease. The mesophyll was always damaged before elements in the vascular cylinder were affected. Mesophyll parenchyma first granulated as the chloroplasts broke down, then plasmolyzed and collapsed. Then, within the vascular cylinder, the albuminous cells of the phloem, phloem elements, and transfusion parenchyma hypertrophied and eventually collapsed. In the final stage of necrosis the endodermis also collapsed. Typical specimens are shown in figures 10 and 11.

Table 2.--Results of bubbler sampling for sulfur dioxide

Date	Location	Elevation	Time interval (hours)	SO_2 (p.p.m.)
5/22	1/8 mile S of Plot #8	3,240	1	.00
5/20	1/8 mile S of Plot #8	3,240	50 min.	.00
5/22	1/8 mile NW of Plot #8	3,400	1	.01
5/21	1/8 mile NW of Plot #8	3,400	1	.00
5/21	1/8 mile NW of Plot #8	3,400	1	.00
5/22	1/8 mile N of Plot #9	3,740	1	.03
5/22	1/8 mile N of Plot #9	3,740	1	.03
5/20	1/8 mile N of Plot #9	3,740	1	.02
5/19	Plot #6	3,760	1	.00
5/20	Plot #6	3,760	1	.00
5/20	Plot #6	3,760	1	.00
5/20	Plot #6	3,760	1	.00
5/20	Plot #6	3,760	1	.00
5/21	Plot #6	3,760	1	.00
5/22	Plot #11	3,800	1	.04
5/22	Plot #11	3,800	1	.02

Table 2.--Results of bubbler sampling for sulfur dioxide (con.)

Date	Location	Elevation	Time interval (hours)	SO_2 (p.p.m.)
5/21	Jess McDonald property 1/8 mile W of Plot #17	3,180	18.8	.01
5/22	"	"	21.3	.01
5/18	"	"	21.4	.00
5/19	"	"	21.2	.00
5/20	"	"	21.3	.00

In relation to the area of the transition zone from which the sections came, the following was observed:

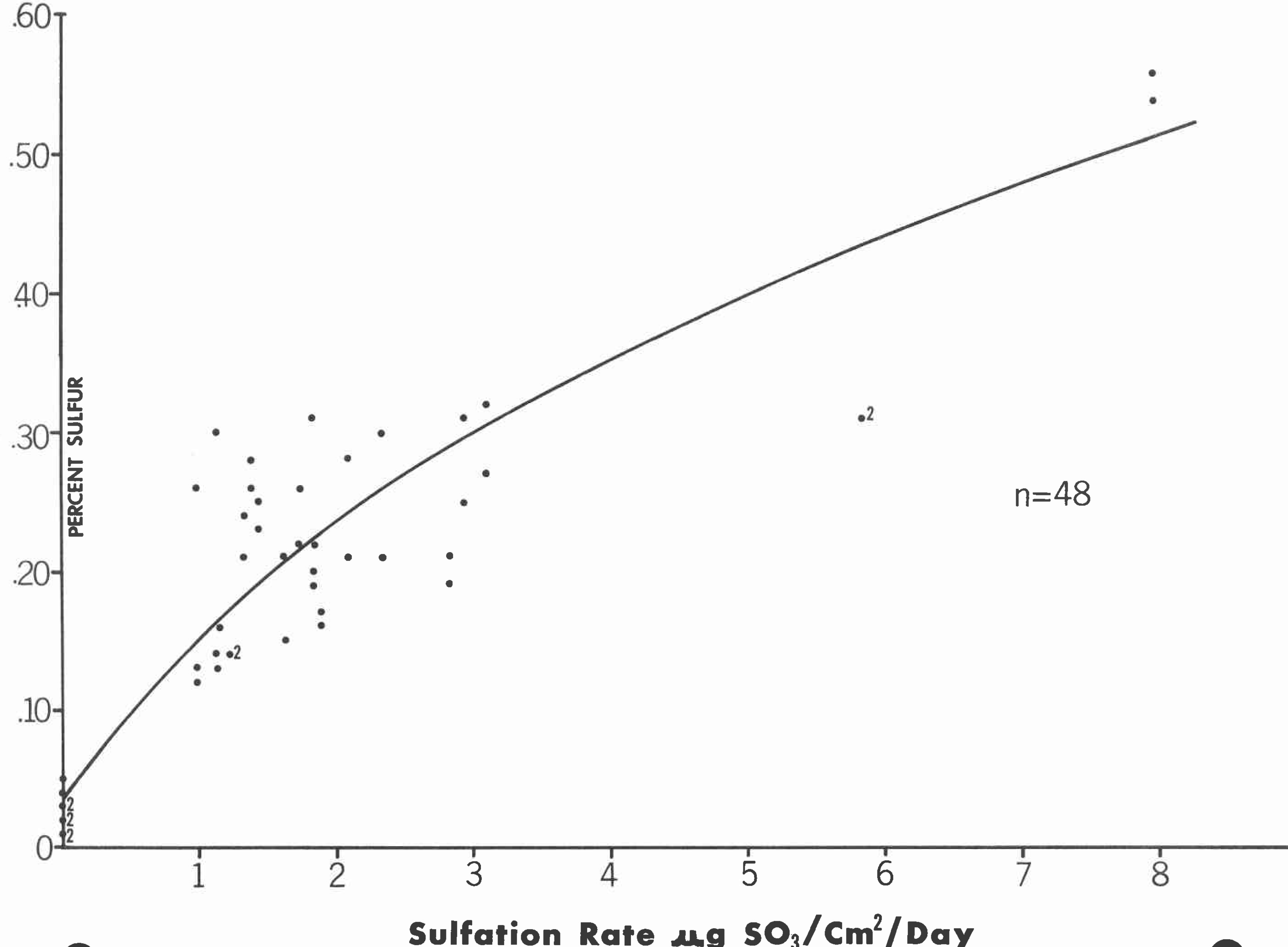
1. Green-yellow - initial breakdown of chloroplasts and plasmolysis of mesophyll cells.

2. Yellow - some collapse of mesophyll cells, hypertrophy of phloem elements and parenchyma, albuminous cells, and transfusion parenchyma.

3. Necrotic - collapse of mesophyll, endodermis, and albuminous cells.

Often, affected tissue in the vascular cylinder stained yellow in contrast to the blue-green observed in healthy tissue.

FIGURE-5 Relationship of Percent Sulfur in Douglas-Fir Foliage to Sulfation Rate



FIGURE–6 Relationship of Percent Sulfur in Douglas-Fir to Distance From Pulp Mill, Miles

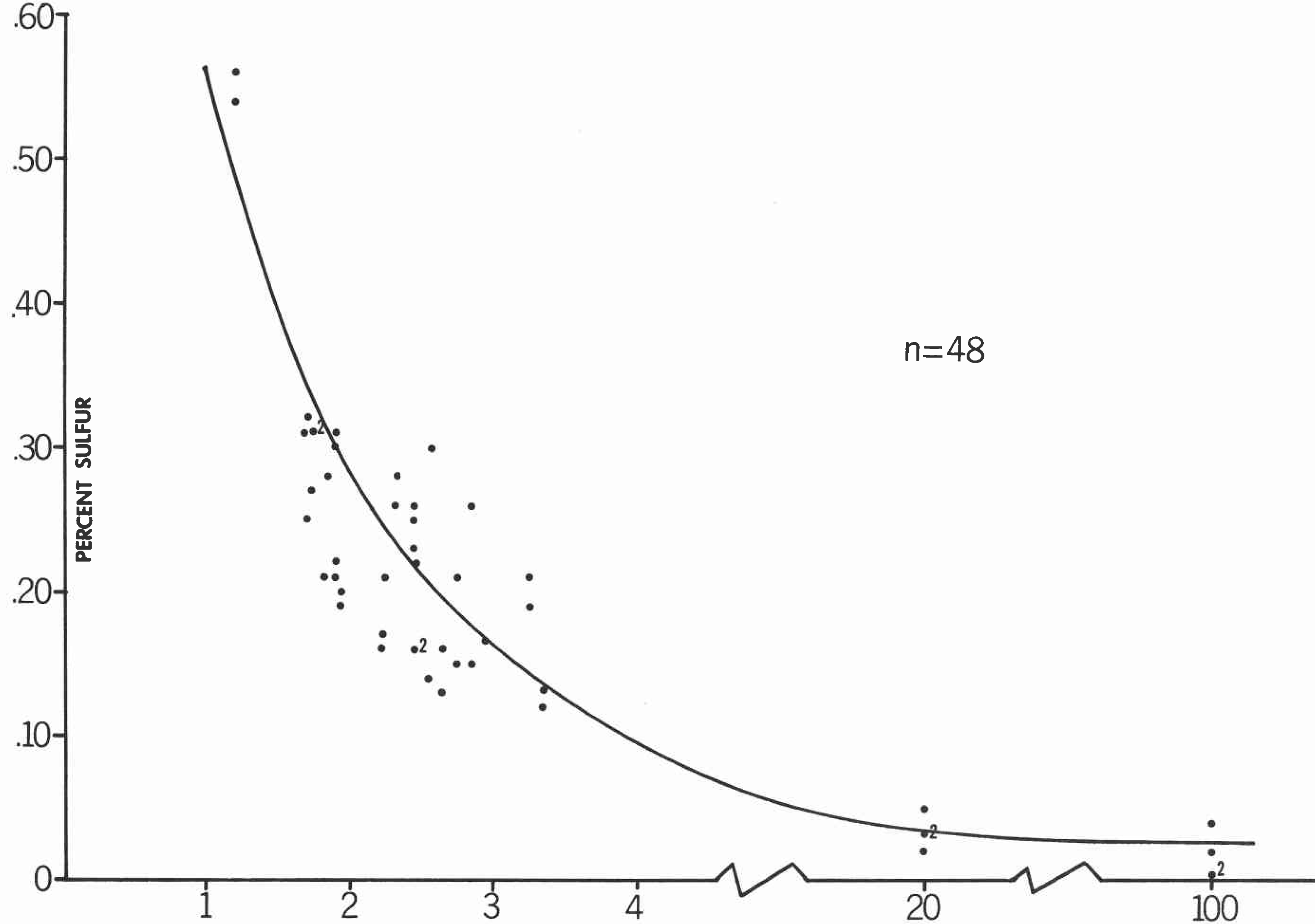


FIGURE-7 Relationship of July-August, 1973 Sulfation Rate to Distance from Pulp Mill

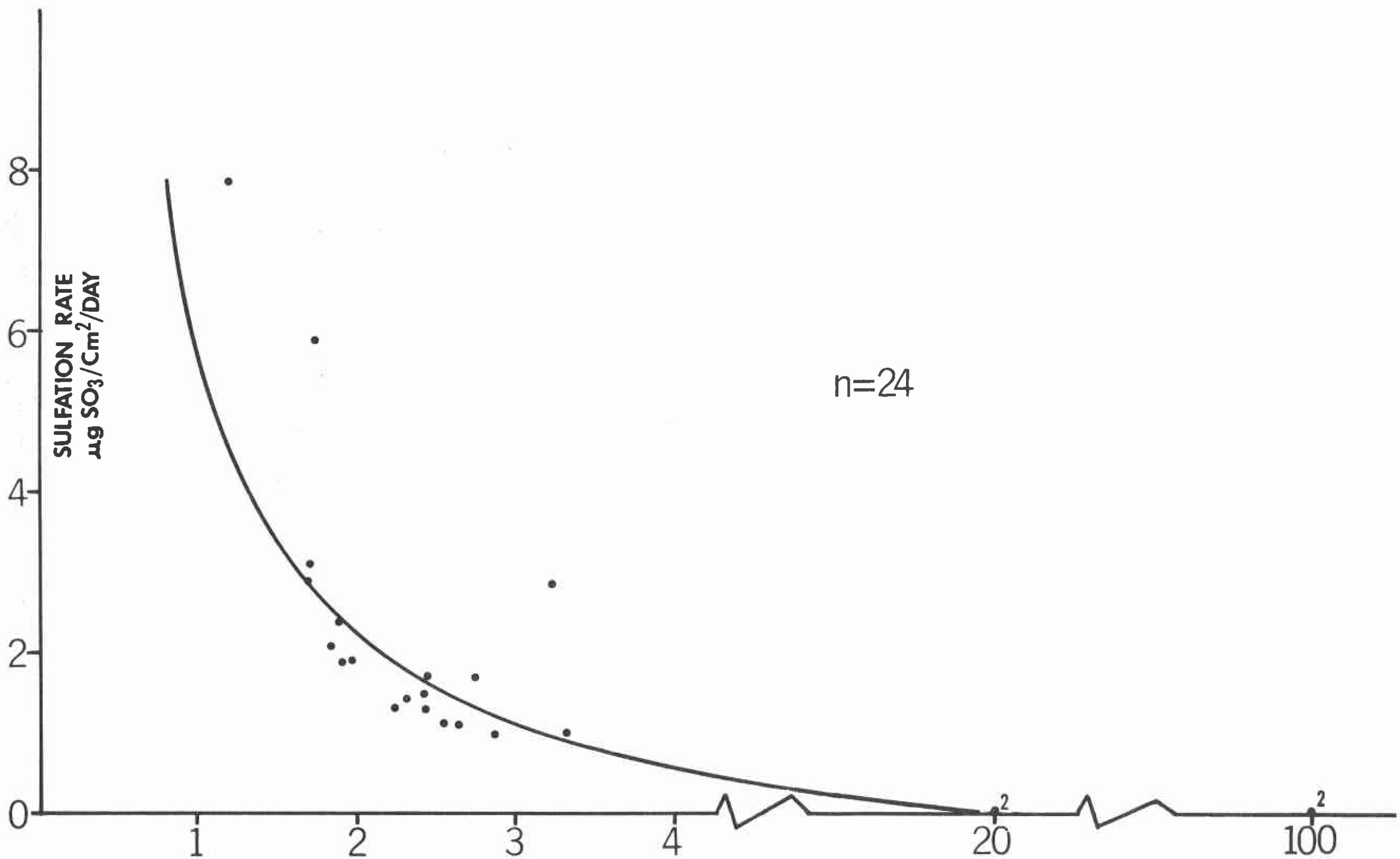


FIGURE –8 SO_2 Samples Taken on Wind Tower Road

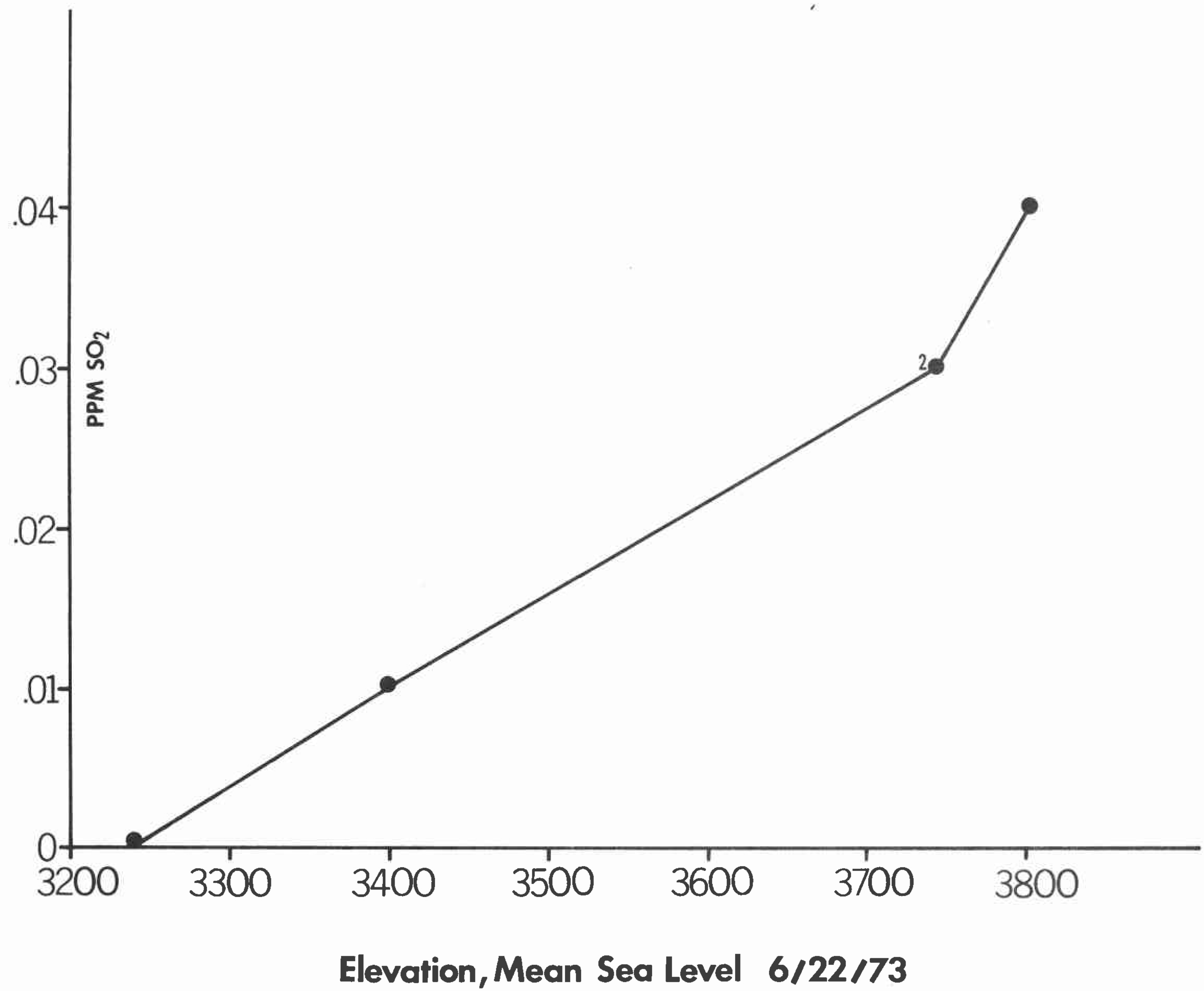
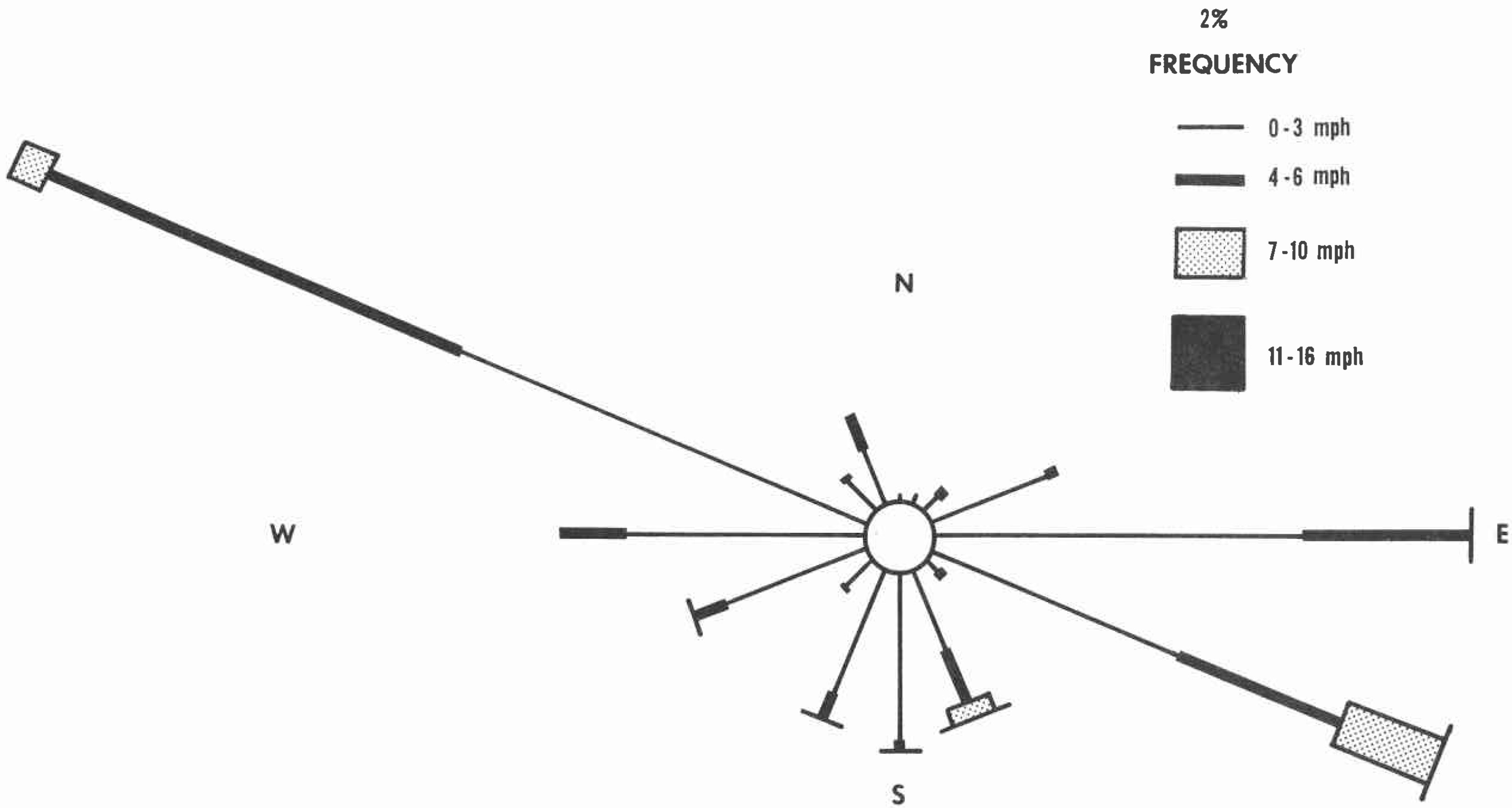


FIGURE-9 Rock Creek South Wind Rose



These data were collected with an MRI 1072-1 located on a mountain ridge 2 miles west-northwest of the Hoerner-Waldorf plant in the Missoula Valley near plot No. 11. Results were taken from data collected during the period May through November 1973. Data were extracted from charts for 1-hour intervals.

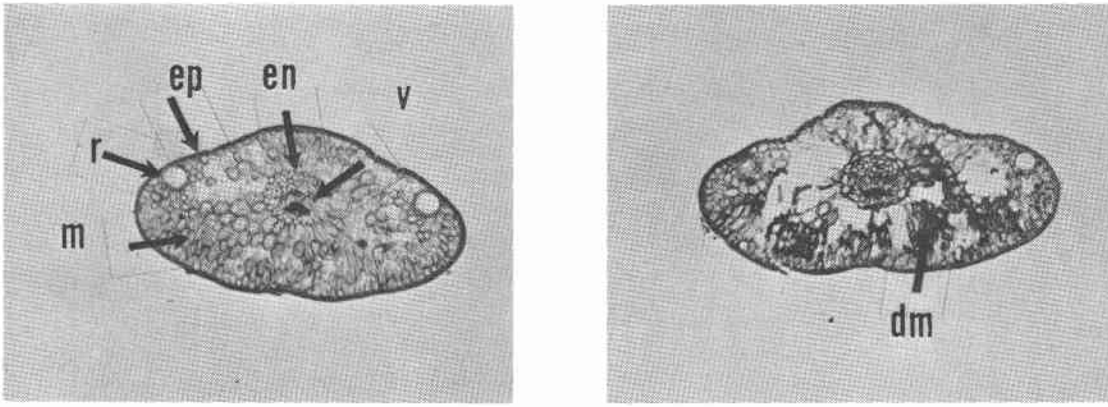


Figure 10.--Left - Cross section of a healthy Douglas-fir needle.
ep - epidermis, m - mesophyll, r - resin canal,
en - endodermis, v - vascular cylinder. X40

Right - Cross section of a damaged Douglas-fir needle.
The densely stained mesophyll depicts the damaged area, dm.
Most of the affected mesophyll cells have collapsed.
Yellow portion of transition zone. X40

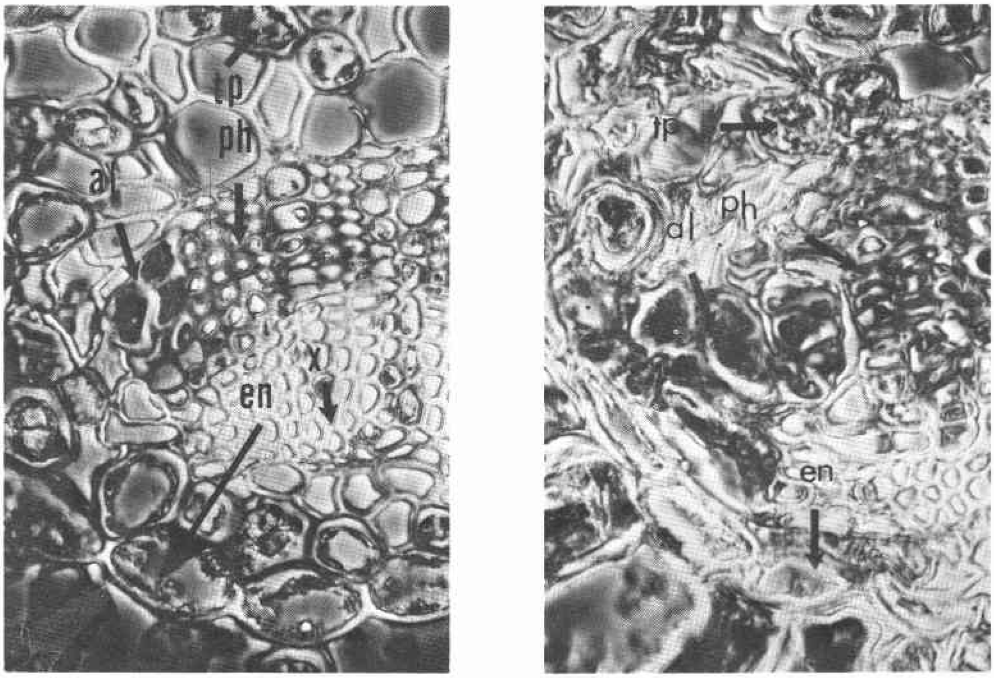


Figure 11.--Left - Transverse section of a healthy Douglas-fir needle. Closeup of vascular cylinder. en - endodermis, ph - phloem, x - xylem, tp - transfusion parenchyma, al - albuminous cells. X700

Right - Damaged Douglas-fir needle. Note that albuminous cells and transfusion parenchyma have hypertrophied extensively, crushing adjacent tissue. Phloem is nearly destroyed, and endodermis has collapsed. Yellow part of transition zone. X700

Foliar Analyses for Insect Damage

Data for the insect analyses is given in Appendix IV. About 12 percent of the 1973 Douglas-fir buds had been damaged by defoliating insects in the study area. To be visible from the air, about 25 percent of the buds need to be defoliated. The main defoliating insect present in the study area was the western spruce budworm, *Choristoneura occidentalis* Free., averaging 2.7 larvae per 100 buds. This is about twice that found on the control plots, but is considered a low level. The most defoliation was found at plot 20 where about 42 percent of the buds were damaged by budworm. Other defoliators were virtually absent except at plot 18 where 2.2 Douglas-fir tussock moth larvae, *Orgyia pseudotsugata* McD., per 100 buds were found.

Soil Analyses

Appendix V gives information on physical, chemical, and hydrologic properties of individual soils and some general information on vegetation and vegetative response to soil-moisture regimes. In general, the soils in the study area have very low to medium available moisture-holding capacities. They occur in low to mid-elevational zones where climate becomes limiting with elevations generally less than 4,500 feet and average annual precipitation is less than 25 inches. This combination results in frequent occurrence of soil moisture stress (evapotranspiration losses are great compared to incoming precipitation) especially during the summer months. In addition, the soils occurring on southerly- and westerly-facing slopes have high surface temperatures and are very droughty throughout most of the summer months. Difficulties with tree reproduction and revegetation are not major problems on most of these soils. Periods of moisture stress are usually limited to late summer.

The control plots in the Blackfoot area are located on Winkler soils that have properties very similar to the Winkler gravelly loam found near the Hoerner Waldorf pulp and paper mill. The major difference is that the control plot soils are on slopes of less than 10 percent. As mentioned before, soils of the Plains control plots were not examined.

Aerial Photography

Although damage was plainly visible on the true color photography, color infrared enhanced the contrast between the various damage strata and produced a more distinct picture. This photography confirmed the interpretations of damage strata made in the aerial survey (figure 2) and became a permanent record of the damage.

Potential Impact

Trees on 2,453 acres were evaluated for potential impact. The board foot volume of merchantable trees in the moderately and severely affected area is given in table 3 by individual tree condition. The total volume of Douglas-fir was 3,108,891 board feet, of which 672,205 board feet (22 percent) was in healthy to lightly affected trees, 1,779,469 board feet (57 percent) was in moderately affected trees, and 657,217 (21 percent) was in trees severely affected. The potential impact is defined as that volume of merchantable timber that may be killed due to repeated occurrences of defoliation. (Growth loss probably occurred but was not measured.) In this case, we can assume that the moderately and severely affected Douglas-fir comprise the potential impact, representing a total of 2,436,686 board feet, or 78 percent of the Douglas-fir volume on the 2,453 acres surveyed.

The average number of trees per acre by tree damage class for stands sampled in the moderate and severe damage strata is given in table 4. Of the Douglas-fir crop trees, about one-half (57.1 trees per acre) were moderately-severely injured while the remainder (61.0 trees per acre) were called healthy-lightly affected. However, 90 percent (374.4 trees per acre) of the excess trees were in the healthy-lightly class and 10 percent were moderately-severely injured.

Table 3.--Potential impact of sulfur damage on merchantable Douglas-fir on 2,453 acres

Tree condition	Species	Net board foot volume: Total	Net board foot volume: Per acre	Trees per acre	Average d.b.h.	Average height
Healthy-light	W. larch	31,774	13	0.6	8	45
	P. pine	1,665,337	679	39.6	8	47
	D. fir	672,205	274	12.5	9	48
Moderate	D. fir	1,779,469	725	42.7	8	48
Severe	D. fir	657,217	268	19.0	8	46

Total volume	4,806,002
Total D. fir volume	3,108,891
Percent D. fir	65
Percent healthy-light D. fir[1/]	22
Percent moderate D. fir	57
Percent severe D. fir	21
Total D. fir volume in moderate and severe	2,436,686
Percent D. fir in moderate and severe	78

1/ Based on total volume of Douglas-fir.

Table 4.--Average number of trees per acre by tree damage class in the moderately and severely affected damage strata

Tree designation	Tree damage class: Ponderosa pine			
	Ponderosa pine	Douglas-fir		
	Healthy-light	Healthy-light	Moderate	Severe
Total	137.9[1/]	435.4	62.2	36.0
Crop	58.0	61.0	40.3	16.8
Excess	79.9	374.4	21.9	19.2

1/ Average trees per acre

DISCUSSION AND CONCLUSIONS

Unthrifty conifers in the vicinity of Hoerner Waldorf's Missoula pulp mill have been observed for a number of years. Gordon (1969) observed foliage necrosis on ponderosa pine and Douglas-fir west of the pulp mill as early as 1963. He ascribed necrosis on ponderosa pine several miles south and northwest of Missoula as having been caused by sulfur from the pulp mill.

In 1973 the condition of the Douglas-fir in the study area suddenly worsened, while ponderosa pine showed little damage. The obvious questions posed were:

1. Why did damage suddenly increase, and

2. Why did Douglas-fir manifest the most pronounced symptoms?

It would seem that through a period of years of exposure to sulfur from the mill, both species would show a gradual decline. Thus, it is logical to assume that some adverse selective factor prominent late in 1972 or early 1973 was the agent. Because of a shortage of natural gas during this period, Hoerner Waldorf had to use fuel oil to keep the plant in operation. The burning of fuel oil releases sulfur dioxide to the atmosphere. Officials of the company[8/] indicated that possibly enough sulfur dioxide was released early in 1973 to have approached ambient concentrations known to cause injury to plants. Linzon (1972)

8/ Personal communication with Larry Weeks and Marvin McMichaels.

published the following information in relation to ambient concentration of SO_2 that will cause damage to vegetation:

Period of exposure (average for)	U.S. Bulletin 1619 (1967) (mg/m^3)	(p.p.m.)
1 hour	1,963	.75
8 hours	1,178	.45
1 day	785	.30
1 week	445	.17
1 month	262	.10
1 year	79	.03

The data generated by our study very strongly implicate excessive airborne sulfur emitted by the Hoerner Waldorf pulp and paper mill as the causal agent of the foliar damage observed on 5,200 acres of Douglas-fir near the pulp mill. When viewed from the air or observed on the aerial photographs, the most severely damaged area was closest to the pulp mill, the moderately affected area was somewhat farther, and the lightly damaged area was the greatest distance. The sulfation rate (a measure of atmospheric sulfur), the proportion of foliage showing symptoms, the proportion of needles missing, and the percentage of sulfur found in the needles were all greatest in the severely affected plots and least in the lightly affected and control plots.

Estimates of the proportion of foliage showing symptoms and proportion of foliage missing must be considered conservative. One criterion for sample tree selection was that trees had to have enough foliage so sulfur analyses could be made. Thus, in many cases trees that were completely defoliated were passed up as sample trees. The relation between sulfation rate (atmospheric sulfur) and sulfur in Douglas-fir needles indicated that needle sulfur concentration was a function of airborne sulfurs and that both were directly related to damage. Meteorological data indicated that the wind blew from the east about 30 percent of the time, likely moving sulfur-laden air into the forested mountains west of the mill.

The concentration of SO_2 in the study area at the time damage occurred likely will never be known; however we do know, based on the bubble sampling done, that concentrations reach 0.04 p.p.m. SO_2 for at least a 1-hour period. Under inversion conditions that occur during mid-winter in the Missoula Valley, that value could be much greater for an extended period of time. Thus, we consider SO_2 highly suspect as a contributing cause. Winter damage and drought have been suggested as possible causes, but the work of Scheffer and Hedgcock (1955) would not support that supposition. In their publication, they distinguish between sulfur dioxide, winter, and drought-induced symptoms on needle-bearing trees. The symptoms found on Douglas-fir in the pulp mill study area most closely match those given for sulfur dioxide:

1. Needle discoloration - reddish or brownish.

2. Extent of discoloration of individual needles - often incomplete, in the form of bands.

3. Seasonal occurrence of discoloration - any time during mild weather.

4. Maturity of affected needles - middle aged and older needles affected first.

5. Character of injury to branches - Branches die progressively from bottom of tree to the top and needles from the inner parts of branches to the ends.

6. Geographic distribution of injury - Severity of injury is related to distance from smelter and to topographic features, tending to confine sulfur dioxide.

All of these conditions were met in the study area.

The case against winter damage as a cause is supported by Carlson and Meyer (1973). In a mixed stand of ponderosa pine and Douglas-fir near Missoula, Montana, they found the pine severely affected as evidenced by nearly 100 percent needle browning, while adjacent Douglas-fir showed little or no symptoms. Conversely, in the pulp mill study area, it was the Douglas-fir that was damaged most severely with the pine showing only mild symptoms. Furthermore, Scheffer and Hedgcock (1955), based on field observations, rated Douglas-fir as more susceptible to sulfur dioxide than ponderosa pine, just as we found in the pulp mill study.

The case for SO_2 as the cause is further supported by the results of the histological analyses. Solberg and Adams (1956) described parenchyma hypertrophy of pine needles fumigated by hydrogen fluoride and sulfur dioxide. Gordon (1973), working with ponderosa pine needles, found that albuminous cells of the phloem enlarge following fumigation with SO_2 and H_2S, and that the inactive phloem collapsed early. The mesophyll cells showed granulation, and the endodermis collapsed in the late stage of damage. Stewart et al. (1973) found that early collapse and plasmolysis of the outer mesophyll of pine needle tissue was histologically distinct for salt and SO_2 damage and would be useful in diagnosis of cause. They also found phloem abnormality but not hypertrophy of transfusion parenchyma in response to SO_2. Our histology of Douglas-fir in the Hoerner Waldorf area showed the same syndrome that Solberg and Adams (1956), Gordon (1973), and Stewart et al. (1973) found in pine. Because there is no chance that either salt or fluoride could have caused the histological syndrome in the study area and because the syndrome was similar to that caused by SO_2 in pine, we assume that SO_2 was responsible. However, there is a need for controlled fumigation studies to be done on Douglas-fir in which necrosis caused by various agents could be compared to that caused by reduced and oxidized sulfur.

A reasonable hypothesis for the sudden appearance of damage is that since the pulp mill began operation in 1957, vegetation nearby has been accumulating above normal amounts of sulfur. With this abnormally high background level of sulfur concentration in the needle tissue, an overdose during a period of time in which the tissue was susceptible could have resulted in enough additional sulfur being accumulated in a short period of time to cause visible injury. A study by Grill and Haertel (1969) supports this hypothesis. In experiments with spruce (*Picea abies* (L.) Karsten) foliage, they found that the number of damaged cells did not increase in proportion to ambient concentrations of SO_2. Instead, damage, after an initial rise, remained unchanged in relation to increasing amounts of SO_2, then rose abruptly to 100 percent. This indicated that the needles could metabolize a considerable amount of sulfur, but that an upper limit was reached at which the sulfur became highly phytotoxic. They also found that older needles (4-year) were more susceptible to damage than were the younger (1-3-year). In addition, their experiments suggested a significant hazard to needles during warm periods and/or solar irradiation in the winter.

Why Douglas-fir was primarily damaged and not ponderosa pine is not known. The reason would have a metabolic basis in relation to accumulation of sulfur. Possibly ponderosa pine was not metabolically active during the time that fir was and during which SO_2 concentrations were high.

Gordon (1969) found necrotic ponderosa pine needles up to 10 miles and more south and northwest of the pulp mill. Through histological procedures he ascribed the injury to sulfur from the pulp mill. We found most damage within 3 miles of the pulp mill; time and monetary considerations restricted our study to this area. However, it is highly possible that necrosis to conifer foliage occurred to varying degrees at greater distances from the sulfur source.

The State of Montana standard for ambient sulfur oxide is (State of Montana, 1967):

0.02 p.p.m. - maximum annual average.

0.10 p.p.m. - 24-hour average, not to be exceeded over 1 percent of the days in any 3-month period.

0.25 p.p.m. - not to be exceeded for more than 1 hour in any 4 consecutive days.

The State of Montana standard for reactive sulfur (sulfation) (State of Montana, 1967) is:

0.25 milligram - sulfur trioxide per 100 square centimeters per day, maximum annual average.

0.50 milligram - sulfur trioxide per 100 square centimeters per day, maximum for any 1-month period.

Our sampling for SO_2 did not reveal any violations of State standards. The monthly standard for reactive sulfur was exceeded only in five cases (Appendix II) throughout the study period. All of the measurements of ambient sulfur were taken after the damage occurred. However, if on the average, ambient sulfur concentrations before and during the time that damage occurred were similar to those found after the damage incident, then perhaps the standards set to protect vegetation are too lenient. A re-evaluation of secondary standards may be in order.

The soil survey indicated that although soils in the damaged area were somewhat droughty, soils both up and down the valley and in the control plots were similar and supported similar but undamaged stands. Therefore, we do not consider soils a primary factor in causing the damage.

The survey for defoliating insects clearly showed that spruce budworm was not a significant factor in causing defoliation in the study area. In fact, the type of damage caused by budworm and other defoliators is clearly different from that noted near the pulp mill. Douglas-fir tussock moth was detected on plot No. 18, and by fall of 1973 about 100 acres of Douglas-fir in that vicinity were visibly defoliated. Again, this damage was distinctly different from that which occurred early in 1973.

The potential impact of nearly 2.5 million board feet of Douglas-fir in just moderately and severely damaged stands is important to consider. If sulfur oxide emission increases in the future as indicated by Hoerner-Waldorf's impact statement for plant expansion it is very likely that the moderately and severely affected trees will receive continuing or heavier doses of SO_2 and will die and become a real loss. The area of damage likely would expand. Most of this volume is on private land (Champion International) but about 400 acres of public land administered by the Lolo National Forest also are affected. Some of the timber already is dead and should be salvaged. If damage continues to occur, then salvage operations should be expanded. If damage does not continue, there probably are enough excess trees left in a healthy-light condition to replace crop trees that die.

Based on the results found in this study, we conclude that the most probable primary cause of the foliar damage on Douglas-fir near the pulp mill was sulfur emitted from the Hoerner Waldorf pulp mill. The exact compound is not known; however, while symptoms of sulfur dioxide were evident, it is feasible that a combination of reduced sulfurs and sulfur oxides was responsible. If the pulp mill expands and the use of fuel oil is increased, then SO_2 concentrations also will increase and damage to vegetation in the area can be expected to intensify. This damage would have a significant economic and esthetic impact on the timber resource in the affected area.

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APPENDIX I

HOERNER WALDORF AIR POLLUTION STUDY COMMITTEE
May 1, 1973

Chairman

Steve Kohler	Montana Division of Forestry

Members

William M. Ciesla	U.S. Forest Service, Missoula, Montana
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Leo Cummins	University of Montana
Jim Lowe	University of Montana
David Maughan	Montana Air Quality Bureau, Helena
Larry Halman	Montana State Department of Health and Environmental Services, Helena
Ernie Corrick	Champion International
Bob LeProwse	Champion International
Wayne Hite	Champion International
Marvin McMichaels	Hoerner Waldorf Corporation
Jess McDonald	Small landowner

APPENDIX II

Data for Several Variables Measured in Hoerner Waldorf Study

Damage strata	Plot & tree No. [1]	Dist. [2]	Diff elev. [2]	Index of proportion needles missing, Year of internode 68	69	70	71	72		Proportion foliage symptomatic, Year of foliage 68	69	70	71	72		% total sulfur content, Year of foliage 70	71	72		Sulfation rate ug sulfur/cm² /day May	June	July/Aug.	Sept/Oct.		
Light	01DF02	3.24	240	1.6	3.0	2.3	3.4	3.3		.74	.02	.06	.04	.00		.26	.19	.11		1.87	0.1	2.5	2.1		
	01DF03			2.0	2.4	2.2	1.8	2.3		.44	.50	.34	.06	.04		.28	.19	.15		1.12	1.1	3.2	2.5		
	02DF05	2.74	220	1.6	2.4	1.7	2.0	3.2		.14	.04	.06	.48	.14		.30	.05	.10		.62	0.0	1.8	1.0		
	02DF06			2.8	2.4	2.0	2.2	3.1		.00	.00	.00	.26	.08		.26	.26	.12		1.12	0.0	1.5	1.0		
	03DF11	2.47	340	2.0	2.1	1.8	2.0	2.2		.54	.12	.10	.04	.06		.28	.24	.13		2.04	0.0	1.6	1.0		
	03DF12			3.2	2.7	2.2	2.3	2.3		.12	.08	.10	.06	.00		.32	.28	.13		.15	0.1	1.9	0.9		
	07DF22	2.47	780	3.5	3.6	3.6	3.7	3.4		.72	.68	.00	.00	.02		.18	.15	.08		.20	0.3	1.2	0.7		
	07DF23			3.3	3.2	2.1	3.2	3.5		.00	.00	.08	.04	.00		.18	.14	.08		.05	0.0	1.3	0.5		
	14DF44	2.28	260	2.3	2.2	1.6	2.2	3.0		.72	.52	.06	.06	.04		.30	.20	.12		.39	1.0	1.3	0.9		
	14DF45			1.5	1.3	1.5	1.8	1.9		.12	.12	.08	.08	.06		.32	.26	.11		.03	1.0	1.4	0.9		
	16DF50	3.32	460	3.0	3.2	3.1	3.8	3.4		.76	.74	.12	.82	.14		.17	.15	.07		1.41	0.2	1.3	0.7		
	16DF51			3.7	3.8	3.8	3.7	3.7		.34	.76	.06	.04	.14		.14	.11	.04		.20	0.2	0.7	1.2		
	Σ	16.52	2,300	30.5	32.3	27.9	32.1	35.3	158.1	4.64	3.58	1.06	1.98	.72	11.98	2.99	2.22	1.24	6.45	9.30	4.0	19.7	13.4	46.4	
	x̄	2.76	383	2.5	2.7	2.3	2.7	2.9	2.6	.39	.30	.09	.17	.06	.20	.25	.19	.10	.18	.78	0.33	1.64	1.12	.97	.03
Moderate	04DF13	1.75	180	2.5	2.8	2.7	2.6	2.7		.66	.10	.06	.08	.06		.39	.32	.19		2.56	3.2	5.5 [3]	2.7		
	04DF15			3.0	3.8	3.5	3.7	3.6		.06	.04	.02	.02	.00		.39	.35	.20		.13	2.8	6.2 [3]	2.3		
	12DF37	2.64	880	2.9	2.2	3.9	3.3	3.0		.40	.42	.32	.20	.06		.20	.12	.07		.08	0.0	1.2	0.7		
	12DF38			2.6	2.9	3.0	3.0	3.0		.20	.14	.18	.20	.08		.21	.15	.11		.89	0.0	1.1	0.7		
	13DF40	1.86	260	2.6	2.6	2.6	3.0	2.8		.54	.22	.38	.62	.48		.30	.23	.11		.05	1.0	2.2	1.1		
	13DF41			1.6	2.1	2.2	2.2	2.5		.06	.02	.10	.04	.00		.38	.31	.11		.32	0.1	2.0	1.0		
	17DF08	2.47	180	1.4	1.0	1.4	1.2	1.9		.08	.00	.02	.00	.02		.28	.24	.17		.42	0.1	1.4	1.4		
	17DF09			2.2	1.5	1.6	1.1	1.4		.38	.38	.56	.00	.00		.28	.23	.15		.16	0.0	1.5	1.5		
	19DF55	2.57	440	1.7	1.4	2.1	2.4	2.0		.90	.90	.48	.16	.06		.38	.23	.30		1.04	0.1	1.1	1.0		
	19DF56			3.3	3.4	3.5	3.4	3.2		.16	.30	.06	.04	.04		.24	.19	.00		.77	0.0	1.2	1.1		
	20DF58	2.89	500	2.2	1.5	1.8	2.3	2.0		.92	1.00	.74	.08	.16		.29	.22	.27		.77	0.0	0.8	0.8		
	20DF59			2.0	1.6	1.7	2.0	1.7		.06	.04	.04	.02	.06		.17	.15	.13		1.20	0.0	1.2	0.9		
	Σ	14.18	2,440	28.0	26.8	30.0	30.2	29.8	144.8	4.42	3.56	2.96	1.56	1.02	13.52	3.51	2.74	1.81	8.06	8.39	7.3	23.4	15.2	54.29	
	x̄	2.36	407	2.3	2.2	2.5	2.5	2.5	2.4	.37	.30	.25	.13	.08	.23	.29	.23	.15	.22	.70	0.61	1.95	1.23	1.13	.04
Severe	05DF17	1.90	760	2.2	2.0	2.4	2.6	3.1		.52	.52	.84	.54	.22		.39	.30	.21		.18	0.50	2.6	0.9		
	05DF18			2.8	2.8	2.1	2.2	2.8		.34	.46	.04	.14	.12		.27	.22	.15		.05	0.0	2.1	1.0		
	06DF19	1.90	780	1.8	1.4	1.9	1.7	2.5		.20	1.00	.34	.32	.04		.39	.30	.23		.08	1.1	2.2	0.9		
	06DF20			1.8	1.2	1.0	1.2	1.2		.18	.30	.20	.12	.02		.29	.21	.16		.08	1.1	1.5	0.6		
	08DF25	1.20	140	1.0	1.0	2.2	2.7	3.4		.20	.84	.10	.26	.38		.63	.60	.45		5.62 [3]	4.6	6.9 [3]	2.9		
	08DF26			1.0	1.0	1.9	3.8	3.1		.50	.50	.54	.10	.04		.63	.57	.41		1.15	3.4	9.0 [3]	3.0		
	09DF28	1.71	680	2.2	1.6	1.6	1.8	1.5		1.00	.64	.20	.16	.10		.16	.32	.37		.89	1.6	3.1	0.8		
	09DF30			2.6	1.5	2.0	2.7	1.9		.80	.98	.94	.24	.28		.34	.31	.30		.03	1.6	3.1	1.0		
	10DF31	1.95	540	2.7	2.0	2.5	2.6	2.5		.86	.86	.64	.32	.24		.28	.20	.12		.03	1.0	2.2	0.6		
	10DF33			2.2	1.7	2.3	1.8	2.5		.94	.84	.44	.02	.02		.24	.20	.14		.03	0.0	1.5	1.0		
	10DF34	2.24	740	3.3	3.0	2.8	2.8	3.0		.86	.78	.46	.04	.02		.22	.16	.10		.60	0.0	1.9	1.0		
	11DF35			3.4	2.2	2.6	1.9	1.9		.30	.24	.04	.06	.04		.22	.17	.13		.03	0.9	1.9	1.0		
	15DF46	1.70	240	1.3	1.6	2.4	1.9	2.8		.74	.66	.32	.10	.06		.40	.28	.16		.06	0.8	3.1	1.7		
	15DF47			2.8	3.2	2.8	1.9	2.4		.32	.52	.10	.08	.08		.41	.30	.20		.12	0.5	2.8	1.7		
	18DF53	2.32	320	1.0	1.6	1.6	2.6	3.3		.50	.60	.24	.10	.06		.35	.28	.15		1.07	0.6	1.4	2.0		
	18DF54			1.6	2.2	2.8	2.2	2.7		.92	1.00	.38	.18	.06		.27	.37	.18		1.75	0.1	1.4	1.4		
	Σ	14.92	4,200	33.7	30.0	34.9	36.4	40.6	175.6	9.18	10.74	5.82	2.78	1.78	30.30	5.49	4.79	3.31	13.59	11.77	17.8	46.7	21.5	97.77	
	x̄	1.87	525	2.1	1.9	2.2	2.3	2.5	2.2	.57	.67	.36	.17	.11	.38	.34	.30	.21	.28	.74	1.11	2.92	1.34	1.53	.05
Control	C1DF61			2.8	3.9	3.0	3.4	3.7		.00	.00	.00	.00	.00		.03	.04	.00		.03	.00	.00	.00		
	C1DF63			3.2	3.4	2.8	2.8	3.1		.10	.30	.44	.14	.08		.01	.01	.01		.20	.00	.00	.00		
	C2DF65			2.9	3.3	2.2	2.2	3.3		.32	.10	.12	.04	.54		.06	.04	.03		.10	.00	.00	.00		
	C2DF66			2.9	2.8	2.4	2.7	2.8		.46	.03	.03	.04	.24		.00	.00	.03		.07	.00	.00	.00		
	C3DF67			3.4	2.8	3.6	3.0	3.1		.22	.08	.04	.04	.04		.10	.07	.05		.10	.00	.00	.00		
	C3DF68			1.7	2.0	3.6	2.3	1.8		.28	.28	.20	.16	.04		.03	.01	.02		.10	.00	.00	.00		
	C4DF71			2.2	2.1	1.9	2.6	3.0		.00	.00	.00	.00	.00		.06	.03	.00		.13	.00	.00	.00		
	C4DF72			2.4	2.2	2.9	3.2	3.0		.12	.06	.00	.04	.00		.06	.03	.00		.23	.00	.00	.00		
	Σ			21.5	22.5	22.4	22.2	23.8	112.4	1.50	.85	.83	.46	.94	4.58	.35	.23	.14	.72	.86	.00	.00	.00	.86	
	x̄			2.7	2.8	2.8	2.8	3.0	2.8	.19	.11	.10	.06	.12	.11	.04	.03	.02	.03	.11	.00	.00	.00	.03	.00

1/ 01DF02 = Plot No. 1, Douglas-fir, tree No. 2.
2/ Pulp mill is reference point.
3/ Violation of Montana Standard.

APPENDIX III

TOTAL SULFUR IN PONDEROSA PINE BY DAMAGE CLASS

Damage class	Plot No.	Year of tissue		
		1970	1971	1972
	01PP01	0.13	0.13	0.05
	02PP04	.13	.11	.08
	03PP10	.13	.10	.05
Light	07PP24	.03	.03	.02
	14PP43	.13	.10	.07
	16PP49	.13	.10	.03
	Σ	.68	.57	.30
	$\bar{X}$	.11	.10	.05
	04PP14	.26	.21	.13
	12PP39	.08	.00	.06
	13PP42		No data	
Moderate	17PP07	.12	.09	.06
	19PP57	.17	.12	.07
	20PP60	.13	.13	.11
	Σ	.76	.55	.43
	$\bar{X}$	.15	.11	.09
	05PP16	.10	.10	.05
	06PP21	.07	.05	.05
	08PP27	.11	.18	.07
Severe	09PP29	.21	.18	.12
	10PP32	.08	.06	.05
	11PP36	.16	.13	.10
	15PP48	.16	.32	.09
	18PP52	.15	.12	.07
	Σ	1.04	1.14	.60
	$\bar{X}$	.13	.14	.08
	C1PP62	.00	.00	.03
	C2PP64	.00	.00	.00
Control	C3PP69	.04	.02	.01
	C4PP70	.00	.00	.00
	Σ	.04	.02	.04
	$\bar{X}$	.01	.01	.01

APPENDIX IV

POPULATIONS OF DEFOLIATING INSECTS ON HOERNER WALDORF STUDY PLOTS

Plot No.	Total buds	Green buds	Damaged buds	Percent buds damaged	No. of spruce budworm	Spruce budworm per 100 buds	Dioryctria	Tussock moth	Sawfly	Other defoliators
1	1,855	1,772	83	4.5	23	1.2	0	0	0	0
2	1,405	1,294	111	7.9	30	2.1	2	0	0	1
3	1,988	1,831	157	7.9	37	1.9	3	0	3	3
4	2,463	2,222	241	9.8	78	3.2	6	0	1	0
5	3,723	3,351	372	10.0	86	2.3	9	0	2	1
6	4,034	3,762	272	6.7	57	1.4	3	2	1	3
7	1,518	1,320	198	13.0	51	3.4	2	0	1	2
8	2,195	1,819	326	15.2	86	4.0	4	3	3	3
9	3,163	2,380	763	24.8	203	6.4	7	2	0	1
10	3,421	3,022	399	11.7	105	3.1	5	0	2	1
11	3,004	2,770	234	7.8	56	1.9	10	0	3	3
12	4,335	3,839	496	11.4	136	3.1	5	0	2	0
13	3,450	3,290	160	4.6	40	1.2	0	0	4	2
14	3,290	3,125	165	5.0	31	.9	1	0	6	1
15	2,421	2,211	210	8.7	61	2.5	4	0	1	2
16	1,959	1,812	147	7.5	38	1.9	5	1	0	12
17	1,438	1,189	249	17.3	50	3.5	1	0	2	0
18	2,828	2,113	715	25.3	93	3.3	3	63	2	1
19	2,933	2,403	530	18.1	83	2.8	2	3	0	0
20	851	498	353	41.5	40	4.7	0	0	0	0
Total	52,224			11.9		2.7				

POPULATIONS OF DEFOLIATING INSECTS ON
HOERNER WALDORF STUDY PLOTS (con.)

Plot No.	Total buds	Green buds	Damaged buds	Percent buds damaged	No. of spruce budworm	Spruce budworm per 100 buds	Dioryctria	Tussock moth	Sawfly	Other defoliators
Control 1	5,332	4,916	416	7.8	84	1.6	0	0	1	0
Control 2	3,463	3,260	203	5.9	50	1.4	2	0	0	0
Control 3	1,250	1,160	90	7.2	12	1.0	1	0	0	0
Control 4	2,423	2,278	145	6.0	27	1.1	1	0	0	0
Total	12,468			6.9		1.4				

APPENDIX V

ESTIMATED PHYSICAL, CHEMICAL AND HYDROLOGIC PROPERTIES OF SOILS AND VEGETATIVE DATA TABLE

Column 1, soil mapping unit No. This is the number used on the soils map to identify soil areas.

Column 2, soil unit name and classification. The soil unit gives the name or names of major soil series within the unit and the dominant range in slope percentage. The dominant soil in each unit is classified according to the system adopted by the National cooperative soil survey. The classification will be useful to anyone interested in researching the soils in detail.

Column 3, depth to bedrock, gravel, etc. These are average depths.

Column 4, depth from surface. This column lists the average depths of the major horizons of a representative profile that are to be described in columns 5, 6, 7, and 9.

Column 5, USDA texture. Textural system based on relative amounts of sand, silt, and clay in soil material less than 2.0 mm in diameter, giving rise to basic soil textural names such as sand, sandy loam, and clay. The basic textural name is given a "coarse" (gravelly, cobbly, etc.) modifier if it contains approximately 15 percent or more coarse material larger than 2.0 mm. It is a classification system developed by the USDA.

Column 6, permeability, relates only to movement of water downward through undisturbed and uncompacted soils. It does not include lateral seepage. The estimates are based on soil characteristics that influence porosity of the soil.

Column 7, available water capacity. The capacity of soils to store water available for use by most plants. It is commonly defined as the difference between the amount of soil water at field capacity and the amount at wilting point. It is expressed in the table as inches of water per inch of soil.

Column 8, available water capacity, expressed as inches/60-inch profile or to limiting layer. Also included is a relative rating expressed as:

low	1 to 6 inches
medium	6 to 9 inches
high	9 and over

Column 9, reaction pH. This is the estimated range in field pH values for each major horizon. Reaction is the degree of acidity or alkalinity of a soil, expressed as a pH value.

Column 10, dominant aspect. An expression of the typical aspect of occurrence. Does not mean a particular soil will occur only on the aspect listed.

Column 11, elevation range. This is the approximate elevation range of a particular soil within the study area.

Column 12, average precipitation. This is a range in precipitation projected for each soil from "High Elevation Precipitation Map - Overlays" data published by SCS. Map atlas prepared by: USDA Forest Service, Division of Soil, Air, and Water Management.

Column 13, period of soil moisture stress. This is a general evaluation of present moisture regime based on monthly precipitation records, potential evapotranspiration, micro climatic influence such as slope aspect, soil moisture holding capacities, and habitat type.

Column 14, primary rock type, based on data from "Geology Map of Montana - 1955" and limited field observations.

Column 15, habitat type. Climax for soil unit by Daubenmire classification. The range for a soil unit will include two to three contiguous H.T.'s.

Estimated Physical, Chemical, and Hydrologic Properties of Soils

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Soil mapping unit No.	Soil unit name and classification	Depth to bedrock, gravel, etc.	Depth from surface	USDA texture	Permeability	Available water capacity In/in. soil	Available water capacity In/60-inch profile or limiting layer	Reaction pH	Dominant aspect	Elevation range	Average precipitation	Periods of soil moisture stress	Primary rock type	Habitat type
38E	Perma soils, 18-45% slopes (andic ustochrepts, loamy-skeletal, mixed, frigid)	60+	0-12	Cobbly loam	Moderately rapid .6-2	.17	Low	6.6-7.8	N,E	3000-4000	15-20"	High-during mid and late summer	Mixed-gravelly & cobbly alluvium	DF-CARU
			12-60	Very gravelly loam	.6-2	.06-.08	3.92-4.88	6.6-7.8						
180F	Repp gravelly loam, very steep (typic ustochrepts, loamy-skeletal, mixed, frigid)	60	0-60	Very gravelly loam	Moderate 0.6-0.8	.05-.14	Low 3.6-4.8	7.4-8.4	S	3000-4200	15-21"	Very high-during most of summer	Limestone & quartz-ite	DF-AGSP, DF-CARU PP-AGSP
189B	Totelake cobbly loam, 2-8% slopes (andic ustochrepts, loamy-skeletal, mixed, frigid)	60+	0-16	Gravelly loam	Moderately rapid .6-2	.10-.14	Low to medium 3.8-6.3	6.1-7.3	Nearly level	3000-3500	15-18"	High-during late summer	Mixed-gravelly & cobbly alluvium	DF-SYAL DF-CARU DF-PHMA
			16-60	Very gravelly sandy loam	2-6	.05-.09		6.1-7.3						
282D	Trapp soils, 10-30% slopes (typic eutroboralfs, loamy-skeletal, mixed)	60+	0-12	Very gravelly loam	Moderate .6-2	.07-.12	Low to medium 3.5-6.02	7.9-8.4	S,W	4100-4200	20-23"	High-much of summer	Limestone & quartz-ite	DF-CARU OR-PHMA
			12-38	Very gravelly clay loam	.6-2	.06-.10								
			38-60	Very gravelly loam	.63-2	.05-.09								
284F	Holloway gravelly loam 30-60% slopes (andic cryochrepts, loamy-skeletal, mixed)	60+	0-10	Gravelly loam	Moderately rapid 1-2	.12-.14	Low 3.7-5.4	5.1-6.5	N,E	3200-4500	16-23"	High-short periods during late summer	Argillite & quartz-ite	DF-PHMA
			10-60	Very gravelly fine sandy loam	1-2	.05-.08		5.6-6.0						

Estimated Physical, Chemical, and Hydrologic Properties of Soils (con.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
						Available water capacity								
Soil mapping unit No.	Soil unit name and classification	Depth to bedrock, gravel, etc.	Depth from surface	USDA texture	Permeability	In/in. soil	In/60-inch profile or limiting layer	Reaction pH	Dominant aspect	Elevation range	Average precipitation	Periods of soil moisture stress	Primary rock type	Habitat type
382F	Whitmore gravelly loam, 30-60% slopes (typic cryochrepts, loamy-skeletal, carbonatic)	60+	0-17	Gravelly loam	Moderate 0.6-2	.08-.13	Low 3.5-5.6	7.4-8.4	N	3200-5000	16-25"	High-during mid and late summer at lower elev.	Limestone & quartzite	DF-PHMA, DF-SYAL, DF-CARU
	Winkler-Sharrott Association, steep		17-72	Very gravelly loam	2-6	.05-.08						High during late summer at higher elevation		
483F	Winkler gravelly loam (udic ustochrepts) loamy-skeletal, mixed frigid)	40+	0-20	Gravelly loam	Moderately rapid .6-2	.12-.16	Low to medium 4.4-6.8	6.1-7.3	S,W	3500-5000	18-25"	High-most of summer	Argillite & quartzite	DF-CARU, DF-SYAL, DF-AGSP
			20-83	Very gravelly sandy loam	.6-2	.05-.09		5.6-6.5						
	Sharrott gravelly loam (lithic ustochrepts loamy-skeletal, mixed, frigid)	20	0-14	Gravelly loam	Moderately rapid to bedrock .6-2	.10-.14	Very low 1.4-1.96	5.6-6.5	S,W	3500-5000	18-25"	Very high-most of summer	Argillite & quartzite	DF-CARU DF-AGSP
			14+	Hard bedrock, fractured argillite & quartzite										
938B	Perma loam, cold 2-4% slopes (andic ustochrepts, loamy-skeletal, mixed frigid)	60+	0-20	Loam	Moderately rapid .6-2	.18-.22	Medium 6-7.6	6.6-7.8	Nearly level	3200-4000	15-20"	High-during late summer	Mixed-gravelly & cobbly alluvium	DF-CARU, DF-SYAL
			20-60	Very gravelly loam	.6-2	.06-.08		6.6-7.8						

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