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Changes in a Douglas-fir (Pseudostuga menziesii (Mirbel) Franco) forest as a result of fluoride fumigation

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CHANGES IN A DOUGLAS-FIR (*PSEUDOSTUGA MENZIESII* (MIRBEL) FRANCO)
FOREST AS A RESULT OF FLUORIDE FUMIGATION

By

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ABSTRACT

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Changes in a Douglas-fir (Pseudostuga menziesii (Mirbel) Franco) Forest as a Result of Fluoride Fumigation (81 pp.)

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This study was initiated to elucidate changes in plant community structure and composition that may occur after prolonged fluride fumigation of a Douglas-fir forest. The investigation was conducted in five experimental plots along a three kilometer fluoride gradient NNW from an aluminum reduction plant at Columbia Falls, Montana. Five life-form strata, tree, tall-shrub, short-shrub, herb, and moss layers were analyzed by use of percent cover and height measurements.

Reduction in total percent cover was observed in tree, tall-shrub and short-shrub layers in areas closest to the fluride source. Conversely, high fluoride levels were associated with an increase in total percent cover of the two lowest strata: the herb and moss layers. Diversity of the lower strata was inversely related to the dominance of the larger growth forms. With increasing fluoride concentrations there was a marked decrease in diversity of the tree, combined shrub and moss strata, but an increase in herb stratum diversity. The height of fluoride-sensitive tall and short shrubs was suppressed in severely polluted plots, whereas herb layer height increased, most notably among the graminoids. The increase in total percent cover, diversity and height of the herb stratum was attributed to increases in understory light intensity, soil moisture, niche area and fluoride resistance of graminoids and exotic species. Areas most exposed to chronic fluoride fumigation will eventually be reduced to shrub-grassland communities.

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Chapter 1

INTRODUCTION

The plant community represents an assemblage of individuals whose presence and organization are a result of chance, time and the selective forces of the environment. Since it is the highest level of biological organization achieved by plants, it reflects all events that have occurred from its inception. Major species changes in the community are initiated at the time of significant disturbances (Henry and Swan, 1974). The function of the plant community is intimately tied to its structure, i.e., the spacial organization of individuals forming a stand (Meuller-Dombois and Ellenberg, 1974). Hence, the study of the structure and composition of plant communities sheds light on ecosystem function and the effect of certain environmental events to which they have been exposed.

Community response to perturbations is governed by the intensity and duration of the disturbance and the stability of the plant association (Cocking, 1973; Allen and Forman, 1976; Woodwell, 1970). Plant communities exposed to chronic disturbances are suspended in a state of stress, whereas short-lived disturbances incur damages and usually are repaired by secondary succession. Several studies related to plant community perturbation have shown that those communities exposed to chronic or repeated artificial disturbances exhibit reduction in structural complexity (Woodwell, 1970). In these communities, the pattern is one of elimination or diminution in height of the larger more upright forms of vegetation.

Soluble fluorine is a phytotoxic element, non-essential to plant growth (Bidwell, 1974), to which most plant communities have had little exposure. In regions where fluoride pollution is a problem, plant communities are threatened by this source of stress.

In 1972, approximately 150,000 metric tons of atmospheric fluoride were emitted from industrial sources in North America (Environmental Protection Agency, 1972). Steel refineries, metal smelting operations, brick manufacturing, phosphate fertilizer production and coal combustion are the largest contributors to atmospheric fluoride pollution in the United States (Weinstein, 1977). In view of the current U.S. legislation to promote coal-fired power generation, the demand for agricultural fertilizers and the abundance of certain metals like aluminum, the pervasion of fluoride as a stress on ecosystems is a pressing problem.

Unfortunately the control of industrial by-products harmful to human health and continuity of ecosystem function is not a self-imposed phenomenon but evolves as conformance to federal and state regulations. Unenforceable air quality standards in Montana and legal variances from these standards only serve to aggravate the problem. For these reasons it is in our best interest to study areas where air pollution is a chronic, insidious disturbance. It is this type of artificial disturbance that is allowed to continue indefinitely.

In 1968, Anaconda Aluminum Company was emitting 7,500 pounds of fluoride per day--an amount sufficient to cause rapid die-off of sensitive vegetation near the facility (Carlson and Dewey, 1971; Gordon, 1974). The vegetation in the region has been exposed to an average dosage of 4,000 pounds of fluoride per day for twenty-one years. Average emissions were 2,470 pounds of fluoride per day in 1976 (Bolstad, 1977). Such long-term exposure to fluoride can significantly alter community structure.

The objectives of this study were to measure and describe changes in Douglas-fir forest vegetation as a result of its interaction with hydrogen fluoride gas and fluoride particulate emissions. The study was conducted in the vicinity of the Anaconda Aluminum Company (AAC) reduction plant in Columbia Falls, northwestern Montana.

Chapter 2

LITERATURE REVIEW

It has long been recognized that plant species exhibit varied tolerances to fluoride (Zimmerman and Hitchcock, 1967; Carlson and Dewey, 1971; Rhoads, 1974). Several interrelated factors contribute to the capacity of plants to endure long-term fluoride fumigations. These factors can be classified as two types: plant attributes and environmental attributes.

Plant Attributes

Genetic resistance. An important plant attribute is genetic resistance to fluoride. There is a paucity of scientific research dealing with the genetic traits which account for species tolerance to fluride, but several researchers have determined that resistance is, in fact, a genetic characteristic (Ryder, 1971; Rohmeder and von Schoenborn, 1968; Hepting, 1966). This discovery is based largely on the observation that there is great variability within species in response to fluoride exposure. Work with several tree species, notably Eastern white pine (Pinus strobus), indicates that there is enough genetic variation within large populations to provide biological indicators as well as resistant strains to specific toxicants (Berry, 1966; Robbins et al., 1973).

There are no reports in the literature which cite conditioning or hardening effects in which plants become more resistant to fluoride after exposure to sublethal doses. Physiologists have found that in certain plants stress resistance can be passed on to progeny for several generations as if they were inherited (Bidwell, 1974). However, decreased vigor in first generation soybean (Glycine max) seedlings from seeds of fluoride-fumigated parents has been observed (Pack, 1971). Apparently fluoride-induced stress can be passed on to progeny.

Growth form. Growth form is an equally significant factor determining susceptibility to fluoride. Knabe (1969) conducted a field study in which clones of plants spaced systematically from ground level to twelve meters in height were exposed to fluoride from an aluminum smelter. In all plants fluoride accumulation rose with increasing height from the ground. The greatest difference was between ground level and 4.3 meters, suggesting that reduced wind velocities might be one explanation for the observed differences in fluoride concentrations. In addition, Knabe found that exposed plants filtered more fluoride than those that were sheltered. Gordon et al. (1977) has repeatedly illustrated the scavenging properties of taller, more exposed individuals (Gordon and Tourangeau, 1977; Tourangeau et al., 1976). The highest foliar concentrations of fluoride are found in the uppermost parts of the plant and on the side facing the pollution source (Gordon, 1976). As a result, smaller, less exposed individuals are less predisposed to fluoride accumulation and injury than are taller growth forms.

Plants reproducing vegetatively are potentially less susceptible to long-term fluoride exposure. Data showing decrease in flower production (Brewer et al., 1966), inhibition of pollen tube germination (van Hook, 1972; Facteau et al., 1973, Sulzbach and Pack, 1972), dwindling pollinator populations (Lezovic, 1969) and reduced fruit production (Pack and Sulzbach, 1976; Hitchcock et al., 1963) illustrate the disadvantages of the annual growth form as compared to the perennial habit.

Leaf morphology. There are only a few reports in the literature of morphological adaptations of the leaf exhibiting tolerance to gaseous fluorides. Gaseous fluorides are believed to follow the transpirational stream of the leaf, entering through the stomata and migrating to the leaf tip and margins (Jacobson et al., 1966). Hendrix and Hall (1957) demonstrated that "low stomatal frequency and/or small well size were associated with resistant varieties whereas more sensitive varieties tended to possess higher stomatal frequency and/or well size." Zimmerman and Hitchcock (1956) found no correlation between stomatal frequency and fluoride resistance. Jacobson et al. (1966) presented evidence to suggest that fluoride injury avoidance was manifested in the ability of certain leaf types to relocate fluoride to inactive parts of the leaf or to distribute fluoride in such a way as to avoid concentrating fluoride in small areas. *Kalanchoë daigremontiana* leaves are able to move fluoride from the interior of the leaf towards the surface (epidermal tissues and cuticle). Evidence for this process was obtained by removal of fluoride from the surfaces of leaves of plants that had obtained fluoride exclusively from the soil. Jacobson et al. (1966) also found that plants with pubescent leaves absorb more fluoride in dust particles that accumulate there than in the interior of the leaf.

Wiebe and Poovaiah (1973) presented the most exciting hypothesis regarding leaf morphology and fluoride injury avoidance. They propose that xeromorphic leaves are relatively more resistant to fluoride.

> In our studies the solution-grown plants were somewhat more succulent than soil-grown plants of the same age. They were also more sensitive to injury, requiring shorter fumigation times and lower fluoride contents to produce injury comparable to that of the soil-grown plants. Our soil-grown plants were watered daily, but this apparently was not enough to prevent some moisture stress, partial stomatal closure, and the development of a more xeromorphic structure.

Zimmerman and Hitchcock (1956) also reported that inducing moisture stress in plants before exposure to fluoride (HF) rendered these individuals more resistant to fluoride. They do not associate this phenomenon with xeromorphy but describe it as a "conditioning" process. Further, this conditioning process was not associated with decreased absorption of fluoride in the leaf; stomatal closure was not the mode of fluoride injury avoidance.

Keller (1973) has attributed the relative resistance of conifers to particulate fluoride injury to the heavy cuticle on their needles. However, fluoride may delay the formation of epicuticular waxes on the lower surfaces of *Abies alba* needles (Bligny et al., 1973).

Phenology. The severity of injury incurred by plants may in part be regulated by the stage in development of the plant (Zimmerman and Hitchcock, 1956). Gas chamber studies of milo maize (*Sorghum* sp.) reveal decreases in productivity when fumigated with fluoride during the period of tassel-shooting and anthesis (Hitchcock et al., 1963). Young emergent leaves appear to be most susceptible to injury and older leaves the least (Zimmerman and Hitchcock, 1956). Long-term exposure to fluoride may render the older foliage more prone to injury. This is clearly seen in needle pathologies of ponderosa pine (*Pinus ponderosa*) correlating ppm fluoride and exposure time to percent total needle necrosis (Tourangeau et al., 1977).

Environmental Attributes

Physical parameters. Evidence is accumulating in support of the idea that changes in the nature of the abiotic environment of plants before, during or after exposure to fluoride may reduce or accentuate injury to vegetation. Rohmeder et al. (1967), after testing 7,000 resistant spruce (*Picea* sp.) shoots in greenhouse experiments, found "that the higher the relative humidity, the higher the light intensity, or the higher the assimilative intensity, the greater the damage to forest trees by fluoride." In gladiolus (*Gladiolus* sp.) leaves, necrosis was more pronounced at 21^{o}C or 26^{o}C than at 16^{o}C, and although injury increased as temperature increased, fluoride accumulation decreased (Maclean and Schneider, 1971). Sunflower, conversely, showed no visible injury, and fluoride accumulation was highest at 26^{o}C. When soybeans (*Glycine max*) are exposed to high temperatures, high light intensity or moisture stress after fluoride fumigation, fluoride injury is most severe (Wiebe and Poovaiah, 1973). In a field study, apricot trees stressed by competition from weeds incurred more fluoride injury than did trees grown in well-tended plots (Oelschlager and Moser, 1969).

Substrate factors. Plants grown in nutrient deficient substrates or hydroponic solutions may exhibit increased susceptibility to airborne fluoride (Maclean et al., 1976; McCune et al., 1966; Adams and Sulzbach, 1961). In addition, fluoride accumulated from the substrate in the root causes a reduction in nutrient assimilation (Navara and Golab, 1968). Navara (1968) also found that "airborne fluoride-induced alterations in the plant metabolism are manifested mainly by alteration of the water balance of plant tissues." The decrease in suction tention of the crowns of several fluoride-fumigated trees and shrubs has also been observed (Gottfried, 1970).

Accumulation rates of fluoride from the soil can be depressed with increased content of lime, clay and organic matter (Hansen et al., 1958). Garber et al. (1967) found no effect on fluoride uptake from soil when sodium or calcium were added to potted plants. The availability of fluoride in the soil solution seems to be most critical to fluoride uptake sufficient to induce injury in the plant (Garber et al., 1967; Gisiger, 1964; McCune et al., 1966).

Fluoride compounds. HF, SiF_4, H_2SiF_6 and F_2 are the gaseous and the most phytotoxic forms of fluoride (Weinstein, 1977). Particulate fluorides are less phytotoxic but will increase in toxicity with increasing solubility, relative humidity and water on leaf surfaces (Weinstein, 1977; Keller, 1973). Hydrofluoric acid is another highly toxic form known to cause growth abnormalities, e.g., excessive lateral bud formation and excessive terminal stem growth (Gordon, 1972). Synergistic effects of HF and SO_2 can render an individual more susceptible to foliar injury than the effect of either pollutant singly (Mandl et al., 1975).

Fumigation history. Adams and Koppe (1959) propose, on the basis of air quality data collected with an automatic fluoride analyzer from surrounding industrial sources, that vegetation is not exposed to continuous fluoride fumigation in the field but rather to irregular, intermittent exposures. Recent evidence provided by gas chamber studies has revealed that intermittent fluoride exposures are less damaging to vegetation than low level, chronic fumigations (Maclean et al., 1969; Adams and Emerson, 1961). Adams and Emerson (1961) explain that "plants may adapt themselves to concentrations of 5 to 10 $\mu gF^-/m^3$ if provided a recovery period between each exposure." Plants exposed to intermittent fluoride fumigations accumulate fluoride at a faster rate than chronic exposures of the same total dosage (Maclean et al., 1969). Maclean and Schneider (1973) reported somewhat contradictory evidence regarding fluoride absorption rates: "When the same HF concentration was used for both types of exposures, with equivalent HF doses achieved by extending the duration of the intermittent exposures, F accumulation was greatest in forage plants exposed continuously."

Old-field plant communities subject to different regimes of SO_2 fumigation showed that "the community impact of more widely spaced SO_2 perturbations of the same intensity was greater than that of the same stresses occurring over a brief interval" (Cocking, 1973). These brief intervals between fluoride exposures were one-day time periods as compared to two-day intervals used by Maclean et al. (1969). Community response to fluoride-induced stress does not appear to be directly related to fluoride accumulation rates.

Summary

Certain postulated effects of fluoride on plant communities can be drawn from the literature cited above. Inherent susceptibility to fluoride may eliminate certain sensitive members of the community, thus altering species composition. Larger, more upright forms of vegetation are more likely to be removed first, as opposed to smaller, sheltered individuals. The elimination of the tree layer could have profound effects on the structural characteristics of the subordinate vegetation. The effects of microclimate, site quality and fumigation history are quite complex, and it is unlikely that their contribution to fluoride-induced changes can be accurately determined in a study of community structure. However, the total effect of these multiple stress factors can be recorded.

Plant Community Structure

Definition. Vegetation structure is defined by Dansereau (1957) as "the organization in space of individuals that form a stand." Three components of vegetation structure may be distinguished: (1) vertical structure or stratification into layers, (2) horizontal structure or spatial distribution of species within a stratum and (3) quantitative structure or species abundance in the community (Meuller-Dombois and Ellenberg, 1974). Recently, community structure has expanded to include community attributes such as species diversity, species distributions, species dominance or any pattern of species associations (Meuller-Dombois and Ellenberg, 1974). In this study vegetation structure is defined as the vertical and horizontal organization of individuals forming a stand to which the quantitative measurements of composition, dominance and diversity may be applied.

Changes in vegetation structure along environmental gradients. Every plant community has a potential climax condition dictated by climate and site quality (Clements, 1928). Structural complexity of a plant community decreases towards the environmental limits of its distribution (Whittaker, 1965). Each stratum of vegetation within a community reacts to the extremes of its own environment (Zobel et al., 1976). Hence, along an ecocline from mesophytic forest to desert grassland, the tallest, most exposed strata are removed sequentially as the environmental limits of each are reached. Zobel et al. (1976) found that diversity within a stratum of a plant community is independent of the diversity of other strata, but stratum dominance may affect the diversity of another. Since dominant (taller) strata control microclimate, niche area, available soil moisture and nutrients of the lower strata, the role of stratum dominance along an environmental gradient is one of suppression and release of subordinate vegetation (Whittaker, 1972).

Changes in vegetation structure due to species removals. The elimination of certain groups of species or a single species from plant communities may significantly alter vegetation structure. The effect of species removal from the community depends upon species dominance, competitive relationships and species abundance (Allen and Forman, 1976). Of special significance to this study is the effect of removal of the largest or dominant life forms on plant community structure. Selective removal of trees by herbicides along utility rights-of-way produced shrub-dominated communities (Neiring and Goodwin, 1974). Reinvasion of the tree layer, suppressed for the last 15 years, was inversely related to shrub density. Dense shrub or grass cover was believed to resist tree seedling invasion due to increased competition for light, moisture and nutrients as well as allelopathic effects. Removal of the tallest individuals of an old-field community caused the greatest species response (Allen and Forman, 1976). Recovery from species removals was fastest in bilayered communities with a dense ground layer than in trilayered canopy communities without a ground layer. There were no significant changes in plant diversity.

Mueggler (1965) found that "tall and intermediate height shrubs decrease in amount as tree canopy increases," and low shrubs persist. When the tree layer was selectively removed by logging, most shrubs increased in frequency and percent cover. The height of the tall shrub layer was generally increased, whereas the height of the low shrub layer was unaffected. Frequency of herbs was reduced after logging, although the frequency of a few opportunist species increased dramatically.

Defoliation of oak (Quercus sp.) trees by gypsy moth larvae (Porthetria dispar) induced increased height growth and survival of understory maple trees (Collins, 1961). These results were explained by increased light intensities to the understory.

These studies demonstrate that removal of the dominant stratum of the plant community: (1) increases the percent cover and height growth of the second dominants, (2) may indefinitely suspend succession back to the pretreatment community, and (3) elicits changes in structure and recovery rates that are related to the initial structural characteristics of the stand.

Changes in vegetation structure due to long-term fluoride exposure.

Hajduk (1969), working along vegetation transects in the vicinity of an aluminum smelter in Europe, found the total percent cover of vegetation decreased with proximity to the smelter and increased in fluoride concentration in vegetation. Exceptions were members of the herb layer. Douglas-fir forests downwind from a phosphate plant incurred extensive tree kill and reduced basal area (Anderson, 1966). In areas most damaged by fluorides, the "herbs increased in number and the mosses and lichens decreased in number."

Changes in vegetation structure due to other air pollutants. Sulfur dioxide from a metal smelter at Falconbrige, Ontario, has been correlated to significant reduction in community height, biomass production, coverage and diversity (Gorham and Gordon, 1960). Controlled fumigations of first year old-field communities with sulfur dioxide demonstrated reductions in biomass and changes in composition through opportunist behavior of resistant species (Cocking, 1973).

Gamma radiation experiments have shown that such a disturbance not only reduces plant diversity to one or two species in the "devastated zone," but also reduces the complexity, structure and composition of oak-pine forests (Woodwell and Rebuck, 1970; Woodwell and Whittaker, 1968). The pattern is one of succession in reverse in which tree species are eliminated first and prostrate lichens last.

Limestone dust accumulation in deciduous forests has been shown to create changes in the structure and composition of the sapling and seedling-shrub layers (Brandt and Rhoades, 1972). The sapling layer in the "dusty plot" displayed patchy distribution and had fewer representatives of the dominant trees when compared to the control stand. The seedling layer of the polluted stand was dense and had even fewer representatives of the dominant tree species.

Zinc smelter emissions have severely reduced the density and percent cover of trees, tree seedlings, shrubs and herbs in a chestnut-oak forest (Jordan, 1975). Recurrent fires in this area have increased the stress on the plant community to the point of denudation. Zinc and cadmium levels in the soil were so high that only vegetatively propagating tree seedlings were able to reestablish themselves after fire. Jordan concludes that without "human intervention to ameliorate the metal toxicity, it is likely that the denuded areas will remain barren for decades or centuries to come."

Vegetation sampling along a distance gradient extending from a copper smelter revealed that density, percent cover and diversity were inversely related to heavy metal concentrations in the soil (Wood and Nash III, 1976). Annual plants suffered the most severe reduction in all these parameters whereas perennial forbes were less affected.

Bryophytes and lichens are among the most sensitive plants to air pollution (LeBlanc and Rao, 1975). In a recent study on the effects of fluoride on mosses and lichens near an aluminum smelter, LeBlanc et al. (1971) found that fluoride pollution affects moisture balance and causes chlorophyll damage. In a study concerning the distribution of bryophytes along a sulfur dioxide gradient, species diversity decreased as pollution intensified and total species coverage increased (Gilbert, 1968). Epiphytic bryophytes and lichens are so sensitive to air pollution and follow such strict patterns of reduced species diversity that their presence is often mapped to indicate indexes of air quality (LeBlanc and Rao, 1975).

Chapter 3

THE STUDY AREA

Location

This investigation has been limited to a localized area at the base of the west slope of Teakettle Mountain (T 31 N, R 20 W, Sec 2 & 34, Figure 1). Damage to vegetation as a result of fluoride emissions has been reported as most severe in this sector (Carlson and Dewey, 1971; Carlson, 1972, 1974). The severity of damage was positively correlated to the proximity of the aluminum plant to Teakettle Mountain, the direction of the prevailing winds, and the nature of the physical setting (Carlson and Dewey, 1971; Gordon, 1974; EPA, 1973).

Fluoride Source

Anaconda Aluminum Co., (AAC) located at the southernmost end of Teakettle Mountain, was established in 1955. At that time two potlines were completed and operating. AAC refines aluminum ore to aluminum through the Hall-Heroult electrolytic reduction system. The pots are of the Vertical Stud Soderberg design (Montana Dept. of Health and Environmental Sciences, 1974). From the standpoint of emission control this design is least efficient. AAC, with the use of multiclones, venture scrubbers, and packed towers, claims a hooding efficiency of 90%. This figure is quite high in comparison with other companies employing the Soderberg design (Montana Dept. of Health and Environmental Science, 1974).

Of the total emissions from AAC, 90% is gaseous and 10% is particulate. The gaseous emissions are primarily hydrogen fluoride (HF) but may include carbon tetrafluoride (CF_4), silicon tetrafluoride (SiF_4), carbon disulfide (CS_2), carbonyl sulfide (COS), hydrogen sulfide (H_2S) and sulfur dioxide (SO_2). The particulate matter consists of cryolite ($Na \cdot AlF_6$)-60%, chiolite ($Na_5Al_3F_{14}$)-20% and aluminum fluoride (AlF_3)-20%. Actual fluoride in particulate matter is 10-15%. Pollution control devices mentioned above, remove 93.3% of the gaseous fluorides and 93.7% of the particulate matter (Montana Dept. of Health and Environmental Sciences, 1974). However, these percentages are only based on a portion of the total emissions from AAC. Lehr (1973) reports that "a significant part of the emissions escape untreated into the atmosphere due to difficulties in locating fume hoods close enough to the Soderberg-type cell."

AAC presently emits about 2903 lb.F^-/day (average for 3 quarters of 1977) (Bolstad, 1977). During the growing season of 1976, emissions were 3016 lb.F^-/day (average for 1 quarter year) (Bolstad, 1977). State stack emission standards permit 864 lb.F^-/day or 1.73 lb.F^-/ton of aluminum produced. AAC has been granted a variance from these standards and is expected to be in compliance by July 31, 1979 ((Montana Dept. of Health and Environmental Sciences, 1974). In order to meet state air quality standards, AAC is modeling it's aluminum reduction operations after the Sumitomo Soderberg Technology. Theoretically this process will reduce fluoride emissions to 824 lb.F^-/day (Minamiura, 1976).

Climate

Precipitation. Frontal systems from the Pacific Northwest have the greatest influence on the climate of Columbia Falls. These weather systems which extend over the northwest corner of the state provide more precipitation than is received in the rest of western Montana. The wettest months of the year are from November to January, and the driest months are August and September. Soil recharge begins in the fall and is completed during spring snowmelt. Mean annual precipitation along the base of Teakettle Mountain is approximately 76.2 cm. Precipitation data from Whitefish indicate that total rainfall in 1976 was 7.6 cm higher than the mean and snowfall was 12.7 cm lower.

Wind patterns. Wind patterns in the northern Flathead Valley are of two types: the upper and lower level winds (EPA, 1973). The upper level winds (1550 m and above) come predominantly from the southwest. The lower level winds move into the north end of the valley from the northeast at night and from the the southwest during the day. At night gaseous fluorides from AAC tend to migrate towards Columbia Falls and accumulate against the west face of Teakettle Mountain. During the day, solar heating of the ground combined with the southwesterly winds will lift and carry gaseous fluorides towards Glacier National Park (EPA, 1973).

Geology and Soils

Along the base of Teakettle Mountain the soil parent material is comprised of colluvial till and Quarternary Glacial Deposits (Johns, 1970). These glacial deposits have several origins. The Cordilleran ice sheet which moved down the Flathead Valley during the last glaciation (Wisconsin), was the major contributor (Johns, 1970). An intermontane glacier formed from Alpine Glaciers of the Swan and Lewis and Clark Ranges, and the valley glaciers of the Northfork and Middlefork of the Flathead River, moved westward through Badrock Canyon and over Teakettle Mountain to join the Cordilleran ice sheet (Flathead National Forest, 1976). The exact chronology of the deposits is quite complex.

The soils along the base of Teakettle Mountain have not been described. Soils of the same parent material described from the Coram Experimental Forest, were used here to approximate soil moisture and soil pH characteristics. Soils derived from glacial till in the Coram Experimental Forest were classified in the Andeptic Cryoboralf subgroup. Five sandy or silty layers overlay more dense material. Deeper horizons are high in sand, gravel and stone. Field capacity and wilting point in the upper soil layers, expressed as percent moisture retention, are 29% and 11% respectively. Compared with other soils of the Coram Experimental Forest, these soils are of intermediate water holding capacity and are often very well drained (Klages et al., 1976; Martinson, 1977). Most soils in this subgroup were slightly to moderately acid in the surface layers. The pH values ranged from 5.7 to 6.4.

Vegetation and Fire History

Fire and selective cutting have played an important role in shaping the present vegetation of Teakettle Mountain. In 1929, the Half Moon Fire swept the entire slope of Teakettle Mountain. The fire was reported to have consumed all forest fuels. However, standing and down snags of Douglas-fir and western larch remain as evidence of the pre-fire vegetation. There is some indication that selective cutting took place on the lower slopes and along the base of the mountain before the 1929 fire.

The vegetation on the west slope of Teakettle Mountain is diverse and variable. This mosaic of vegetation is predominantly due to the variable nature of the physical setting and the uneven burn intensities which are associated with any fire. In general, the dominant tree species along the base of the mountain (970 m) are Pseudotsuga menziesii, Pinus contorta and Larix occidentalis. Pinus ponderosa appears rarely and then only on well-drained sites. Thuja plicata occurs as small isolated stands where drainage is less favorable. Pseudostuga menziesii is evenly distributed along the base of the mountain except where Pinus contorta forms homogeneous stands to the north and where Larix occidentalis is more prevalent to the south. Average tree age is 43 years. The base of Teakettle Mountain is moist, as evidenced by several mesic herbaceous species such as Smilacina stellata, S. racemosa, Thalictrum occidentale, Clintonia uniflora and Fragaria virginiana.

Teakettle Mountain may be classified as the Pseudotsuga menziesii/Physocarpus malvaceous/Physocarpus malvaceous habitat type (Psme/Phma/Phma h.t.) (Pfister et al., 1977). The productivity of this series is considered moderately high (Pfister et al., 1977). The Physocarpus phase commonly contains sufficient quantity of Acer glabrum, Amelanchier alnifolia and Prunus virginiana to support big game (Pfister et al., 1977). In early summer, white-tailed deer, elk and black bear have been observed on the west slope of Teakettle Mountain.

Teakettle Mountain has been classified by the Forest Service as important winter range for deer, elk and moose (Flathead National Forest, 1976).

The impact of fluorides on the vegetation of Teakettle Mountain has economic, biological and aesthetic importance. The reduced radial growth of conifers has been positively correlated to HF fumigation, as have secondary insect infestations on this mountain (Carlson et al., 1974; Carlson and Hammer, 1974). As a result of elevated fluorides in vegetation, deer exhibit osteofluorosis (Gordon, 1974). The loss of sensitive plants on Teakettle Mountain may alter the diversity and stability of the ecosystem. The Forest Service has designated Teakettle Mountain as having a potentially "high visual resource value" (Flathead National Forest, 1976).

Chapter 4

METHODS

Fluoride Gradient Analysis

During the first week of July, 1976, twenty-four fluoride sample sites were established on the west face of Teakettle Mountain. The sites were set up in a grid fashion so that patterns of fluoride accumulation in vegetation would be readily apparent. Sites were chosen to correspond with the protruding ridges that form the face of the mountain. The sites are found at three elevations (970 m, 1200 m, 1500 m) and extend from the southern most end of the mountain to a ridge four kilometers north from AAC. Efforts were made to sample areas with similar aspect and slope.

At each site, *Pseudotsuga menziesii*, *Amelanchier alnifolia*, and *Shepherdia canadensis* were collected for fluoride analysis. Along the base of the mountain, *Pinus contorta* was also collected. Vegetation samples from conifers and shrubs alike were clipped from the highest portion of the plant and from the side facing the aluminum smelter. Samples were placed immediately in plastic bags and stored in a cool place. At each site a one-foot high red stake, bearing the site number was placed beneath *Pseudotsuga menziesii*. Conifers were marked on the trunk with bright orange paint. Shrubs were tagged with orange or blue flagging and were always located on the stand margin.

The vegetation samples were analyzed for fluoride concentrations using the specific ion electrode method (Gordon, 1974). The fluoride content of foliage for each species was regressed with distance from the aluminum smelter for the determination of a continuous fluoride gradient. On the basis of these analyses, a fluoride gradient for the examination of plant community changes was established along the base of Teakettle Mountain (970 m) extending NNW (azimuth 330°) from AAC (see Figure 1).

Plant Community Analysis

Five rectangular 500 m^2 plots were set up along a three kilometer transect at the base of Teakettle Mountain. The experimental plot design is shown in Figure 2. Five life-form strata of the forest community were analyzed: tree layer, tall-shrub layer, short-shrub layer, herb layer and moss layer. Daubenmire's method for determination of canopy coverage was used for the evaluation of the moss and herb layers (Daubenmire, 1959). Percent cover of mosses was taken from thirty 1/10 m^2 microplots and percent cover of herbs from twenty. The percentage shrub-layer cover was determined from five 10 m^2 microplots nested within the macroplot. The height of all shrubs and grasses falling within a one meter radius of the herb layer microplots was measured to the nearest decimeter. The total percent cover of the tree layer was estimated from the entire 500 m^2 plot. Each tree within the experimental plot was evaluated and put in a vigor class (see Appendix A). The diameter at breast height was taken from all stems of the tree layer greater than 5 cm in diameter. In cases where *Acer glabrum* had a stem diameter greater than 5 cm and was also taller than 10 meters, it was included in the tree layer. Segregation of trees into vigor classes allowed for the inclusion of living as well as dead, standing trees in the analysis of this stratum.

Compositional characteristics of the forest community were drawn from the percent cover information. These included relative frequency and

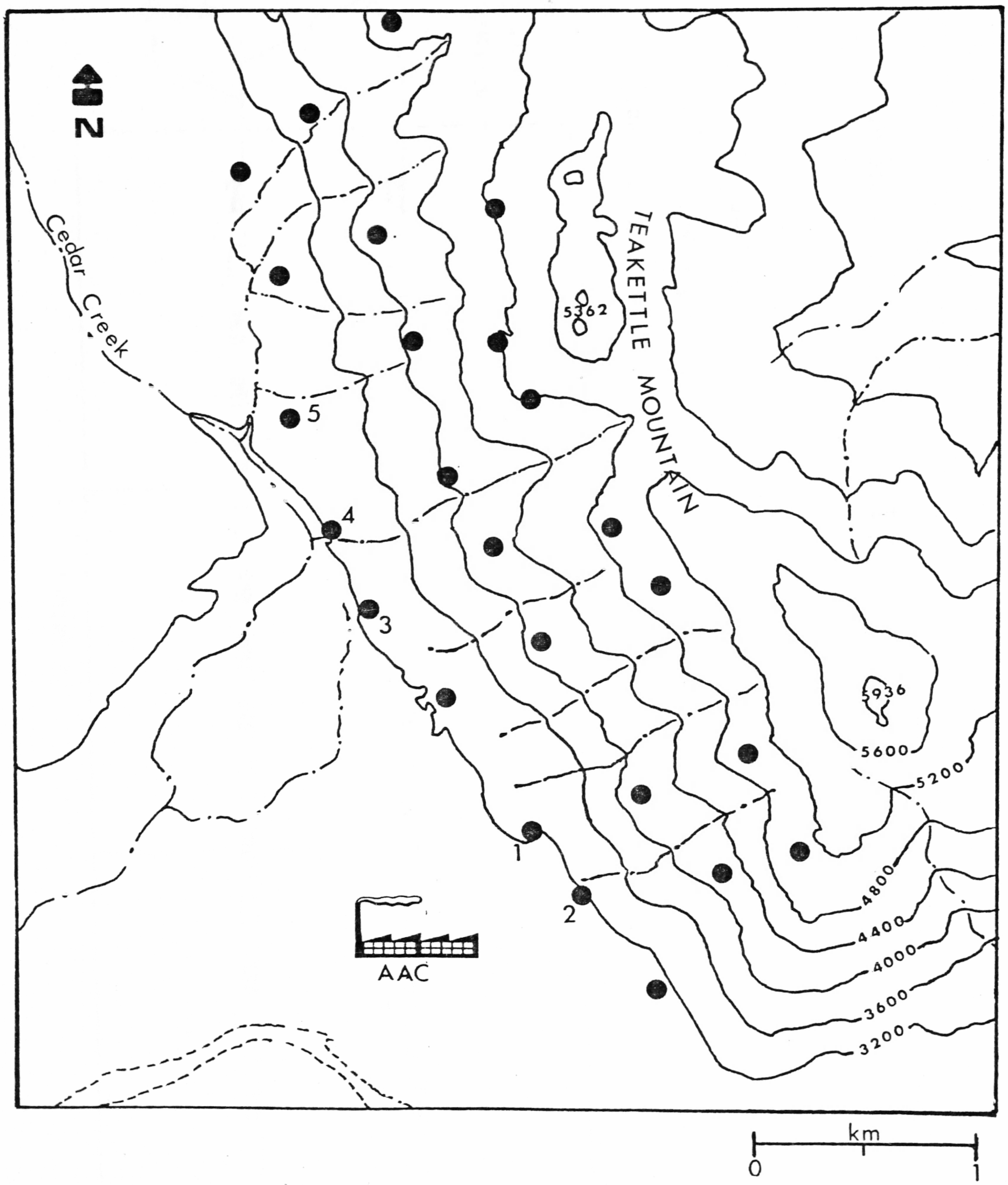


Figure 1. Teakettle Mountain study area. Fluoride sample sites are found at three elveations: 3200',4000', and 4900' Vegetation transect includes plots 1 through 5.

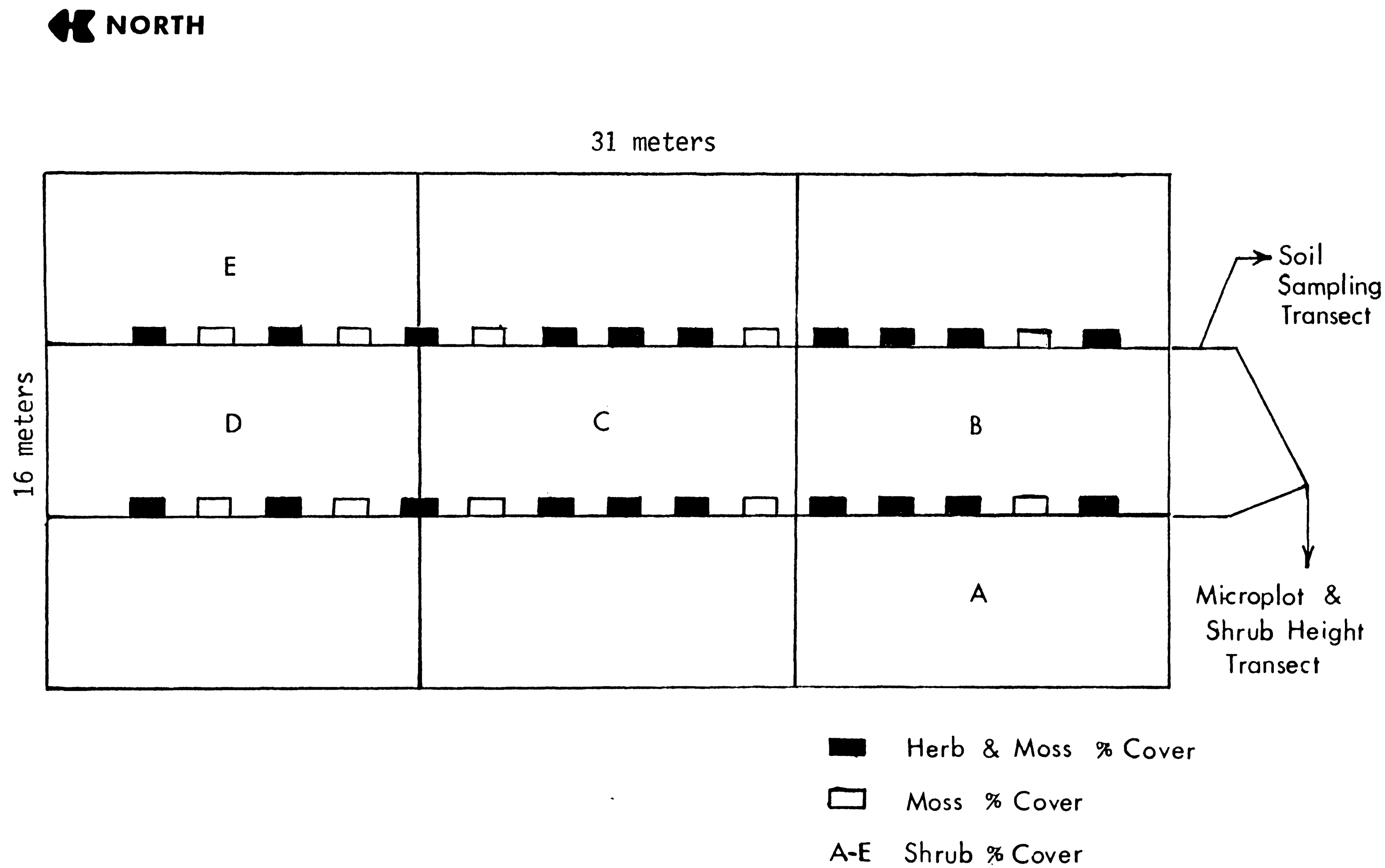


Figure 2. Macroplot organization. Length of plot was oriented parallel to slope of Teakettle Mountian in a north-south direction.

diversity. Diversity of the tree stratum was recorded as species number. Diversity indexes were determined for the shrub, herb and moss strata. These indexes were calculated using MacArthur's equation (MacArthur, 1965):

$$\bar{d} = \sum_{i=1}^{s} (y/n)\log(y/n).$$

In this equation, $\bar{d}$ is a measurement of the concentration of dominance (Whittaker, 1965). The greater the value of $\bar{d}$, the greater the diversity and, hence, the smaller the concentration of dominance. Total percent cover values (using the midpoint of Daubenmire's coverage classes) were used as the species importance variable, y. This equation is especially useful when species number is low and when the appearance of a few dominants is important to the evaluation of the plant community along an environmental gradient.

Microclimate Analysis

Collections of soil moisture and soil pH samples were taken along one transect within the macroplots (see Figure 2). Both soil moisture and soil pH were taken at depths of 15 cm below the mineral soil surface. Ten soil moisture and three soil pH samples were collected per plot. Soil moisture was determined gravimetrically, and soil pH was measured in a soil slurry with an Analytical pH Meter, Model 707 (Wilde and Voigt, 1955).

Measurements of understory light intensity were taken at twenty herb layer microplots at a height of one meter from the ground. Light readings were recorded at midday from a planar photoelectric cell (Weston Illuminator Meter, Model 756) held horizontally. All physical parameters measured at each plot were collected within a two-hour time period.

Chapter 5

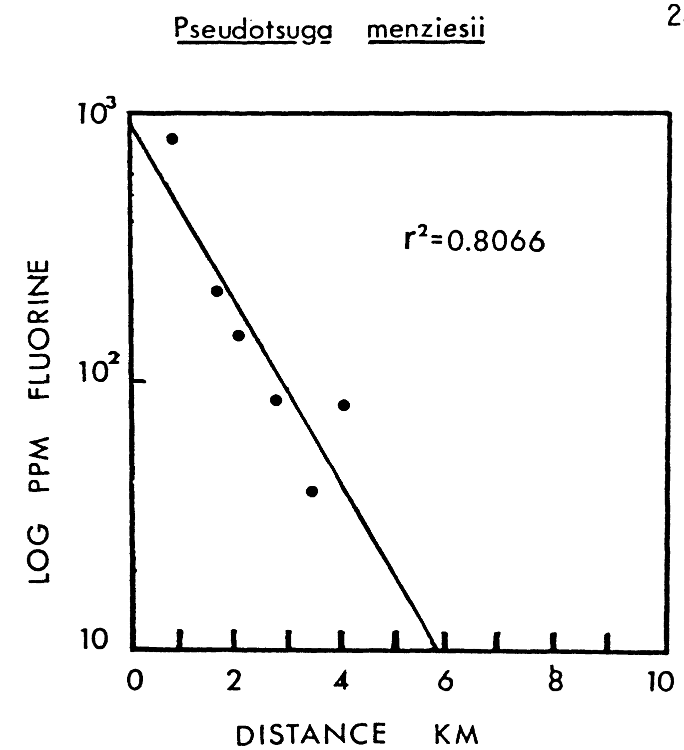
RESULTS

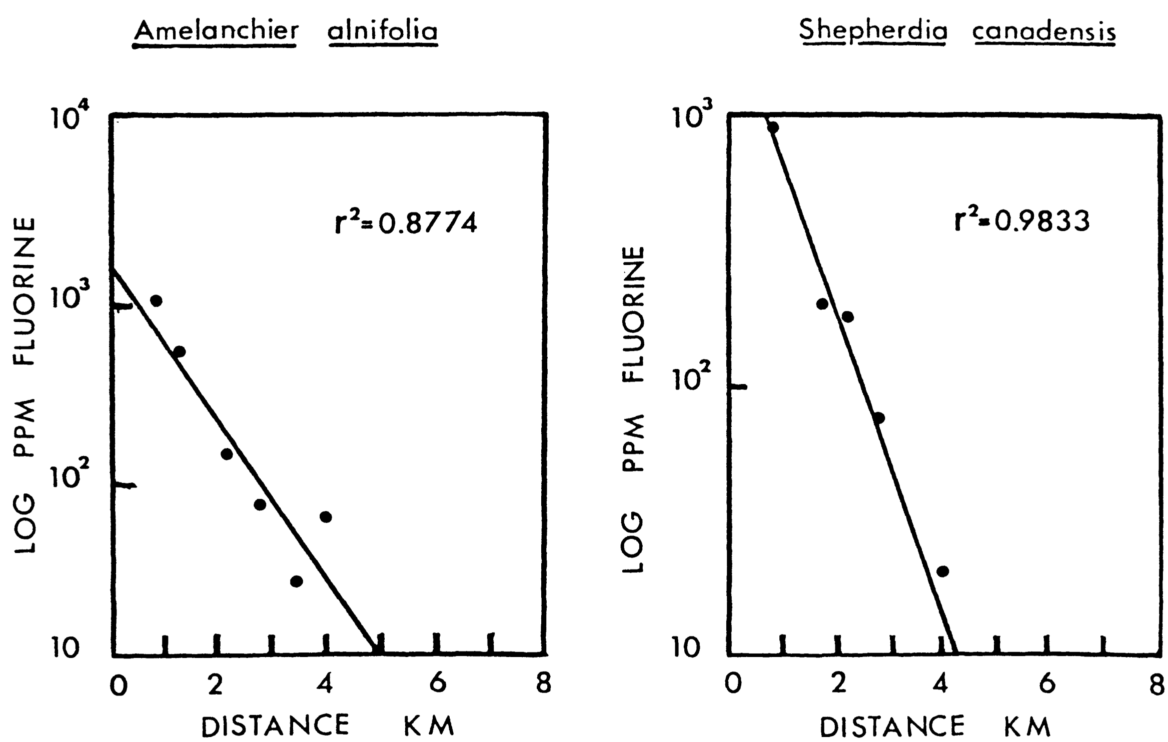
The Fluoride Gradient

The three-kilometer transect along the base of Teakettle Mountain, extending north from just behind AAC to the headwaters of Cedar Creek Reservoir, represents a continuous fluoride gradient. Regression analyses for ppm fluoride (see Figure 3) in Pseudostuga menziesii (Douglas-fir), Amelanchier alnifolia (serviceberry) and Shepherdia candensis (buffaloberry) versus distance from AAC show significant coefficient of determination values. The relationship of fluoride concentrations in vegetation to distance from AAC is log-linear along this transect.

The fluoride concentrations of all samples collected on Teakettle Mountain in 1976 are presented in Appendix B. A topographic map in Appendix C shows the location and code numbers for the collection sites. Carlson (1972) cites 3.2 ppm fluoride as the baseline fluoride concentration for vegetation in northwestern Montana. Compton et al. (1971) found an average of 2.9 ppm fluoride for shrub and conifer species in Warrenton, Washington, prior to aluminum smelter operations. The average fluoride level in control samples collected 12 miles south of Teakettle Mountain is 3.8 ppm fluoride. All fluoride concentrations in vegetation collected from Teakettle Mountain are significantly higher than the control levels.

Figure 3. Regression analysis ppm F^- in vegetation with distance from Anaconda Aluminum Company.





Changes in Microclimate

The means and confidence intervals at the 95% level for percent soil moisture and soil pH are presented in Figure 4. There is no significant difference in percent soil moisture between plots 1 through 4. An approximate t-test for means with unequal variance reveals that the mean of percent soil moisture in plot 5 is significantly different from those of all other plots except plot 3. The interesting aspects of the mean percent soil moisture of plot 5 are its relatively low value (ca. 25% less) and the compressed confidence interval. The comparatively low but consistant readings for soil moisture in plot 5 may be a result of a dense, continuous overstory which limits the amount of throughfall precipitation to the soil surface. Such a decrease in throughfall precipitation can significantly depress the herb layer (Anderson et al., 1969).

Soil pH shows no significant trend along the base of Teakettle Mountain. The sample size was too low to accurately reflect similarities or differences between plots. Soil pH in all plots lies within the neutral to slightly acidic range but is less acidic than similar soils from the Coram Experimental Forest.

Regression analyses reveal that understory light intensity is negatively related to distance from AAC, percent cover of the tree layer and positively related to fluoride concentration in vegetation. Understory light intensity regressed with distance is shown in Figure 5. The coefficients of determination for these regressions are high, as is shown in these results:

y		x	r^2
Light Intensity	vs.	Distance	0.8937
Light Intensity	vs.	% Cover Trees	0.8067
Light Intensity	vs.	F^- Concentration	0.8757
F^- Concentration	vs.	% Cover Trees	0.9886

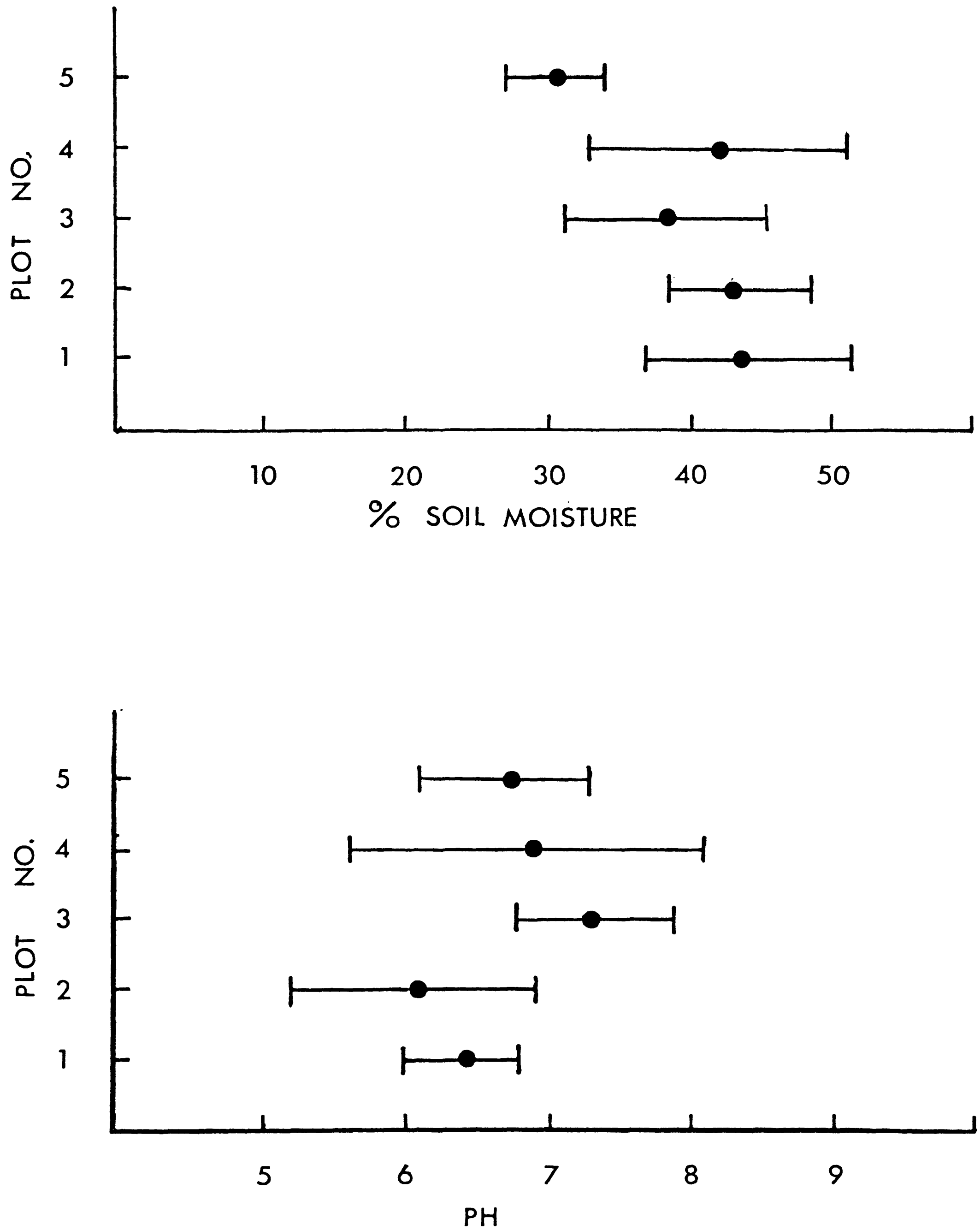


Figure 4. Means and confidence intervals at the 95% level for percent soil moisture and soil pH per plot.

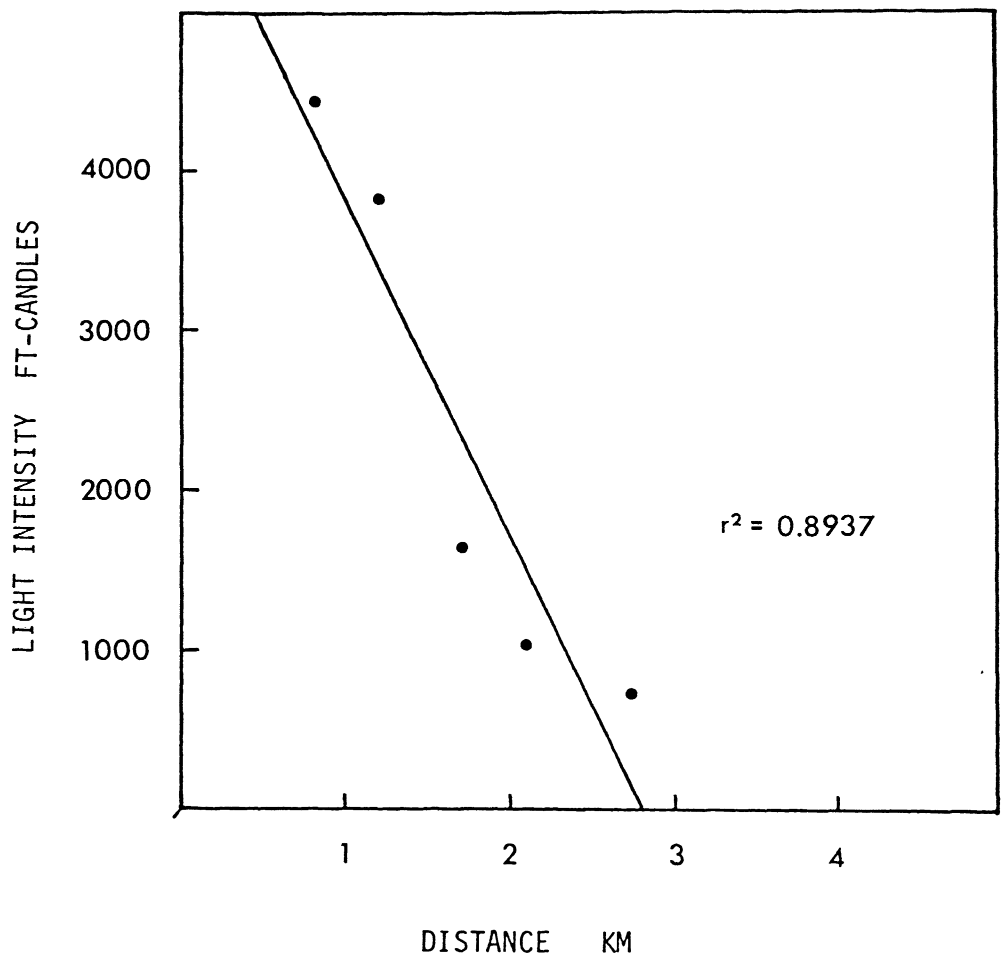


Figure 5. Regression analysis understory light intensity with distance from Anaconda Aluminum Company.

Fluoride damage to the tree layer has evidently created openings in the canopy and thus has significantly increased the amount of light available to the understory.

Changes in Percent Cover

Changes in total percent cover of vegetation along the fluoride gradient are illustrated in Figure 6. In general, total percent cover of the tree stratum and combined shrub stratum increases in plots farthest from the fluoride source. Conversely, herb layer and moss layer percent cover decreases with increasing distance from the aluminum smelter. The shrub layer is particularly interesting in that percent cover is at or below 60% in plots 1 and 2, rises sharply to over 100% in plots 3 and 4, and then declines again to 80% in plot 5. This bimodal distribution of shrub cover becomes more apparent when the height and percent cover of individual shrubs are examined.

Changes in Height of the Shrub Layers and Herb Layer

Comparisons of average percent cover and mean height of tall shrubs are presented in Figure 7. Changes in height with respect to cover are generally of two types. Height of the tall shrubs may exhibit its own pattern along the fluoride gradient or changes in height may mimic changes in percent cover. The height patterns seen in *Holodiscus discolor* and *Physocarpus malvaceus* are of the latter type. However, the height of *Holodiscus discolor* decreases despite an increase in average percent cover in plot 1, closest to the aluminum smelter. *Acer glabrum* decreases in height and percent cover in plots closest to the fluoride source. Height continues to increase at the distal end of the gradient but the cover of *Acer glabrum* in the tall-shrub stratum decreases. *Amelanchier*

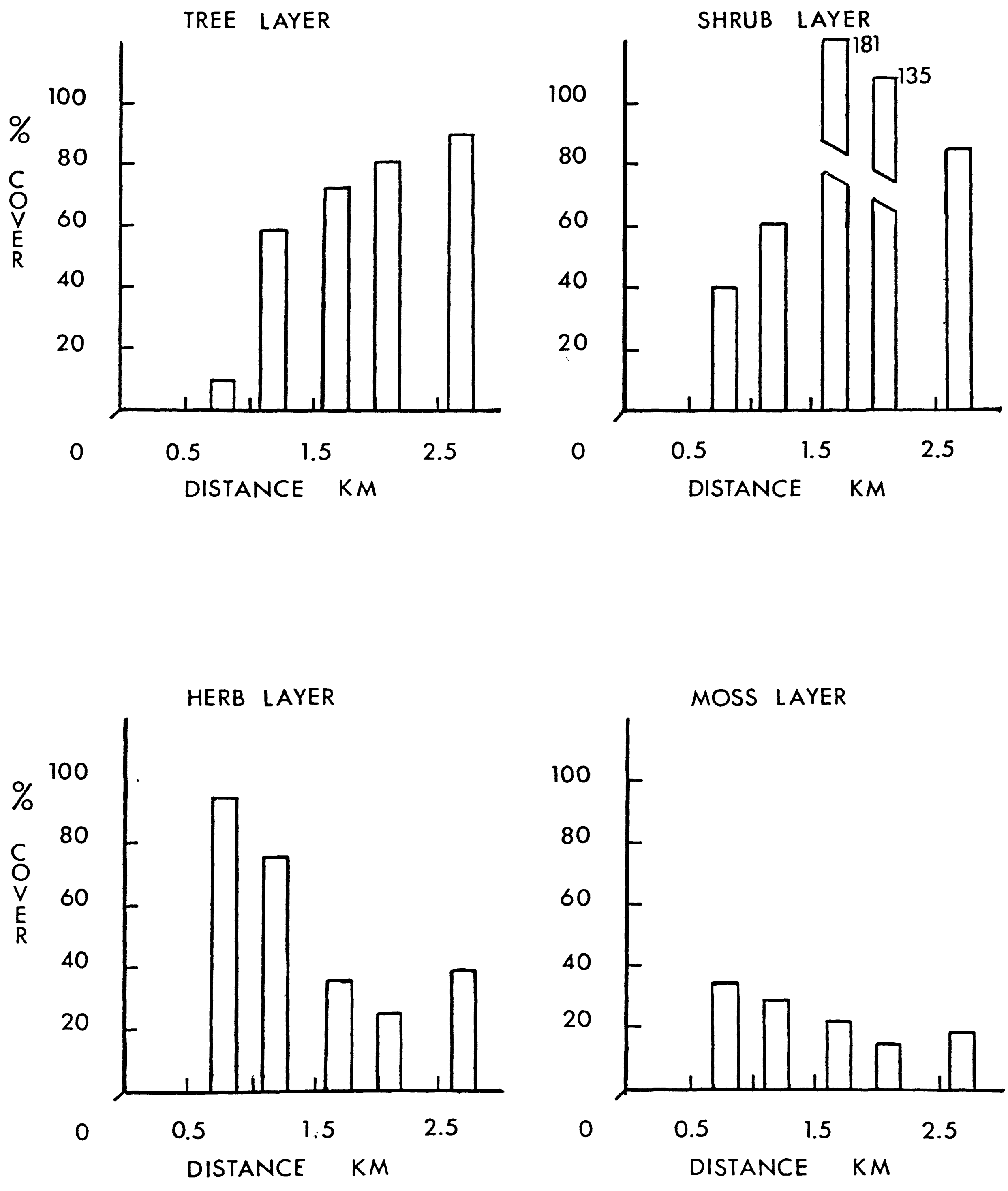


Figure 6. Total percent cover of four life-form strata within the forest communities as a function of distance from Anaconda Aluminum Company.

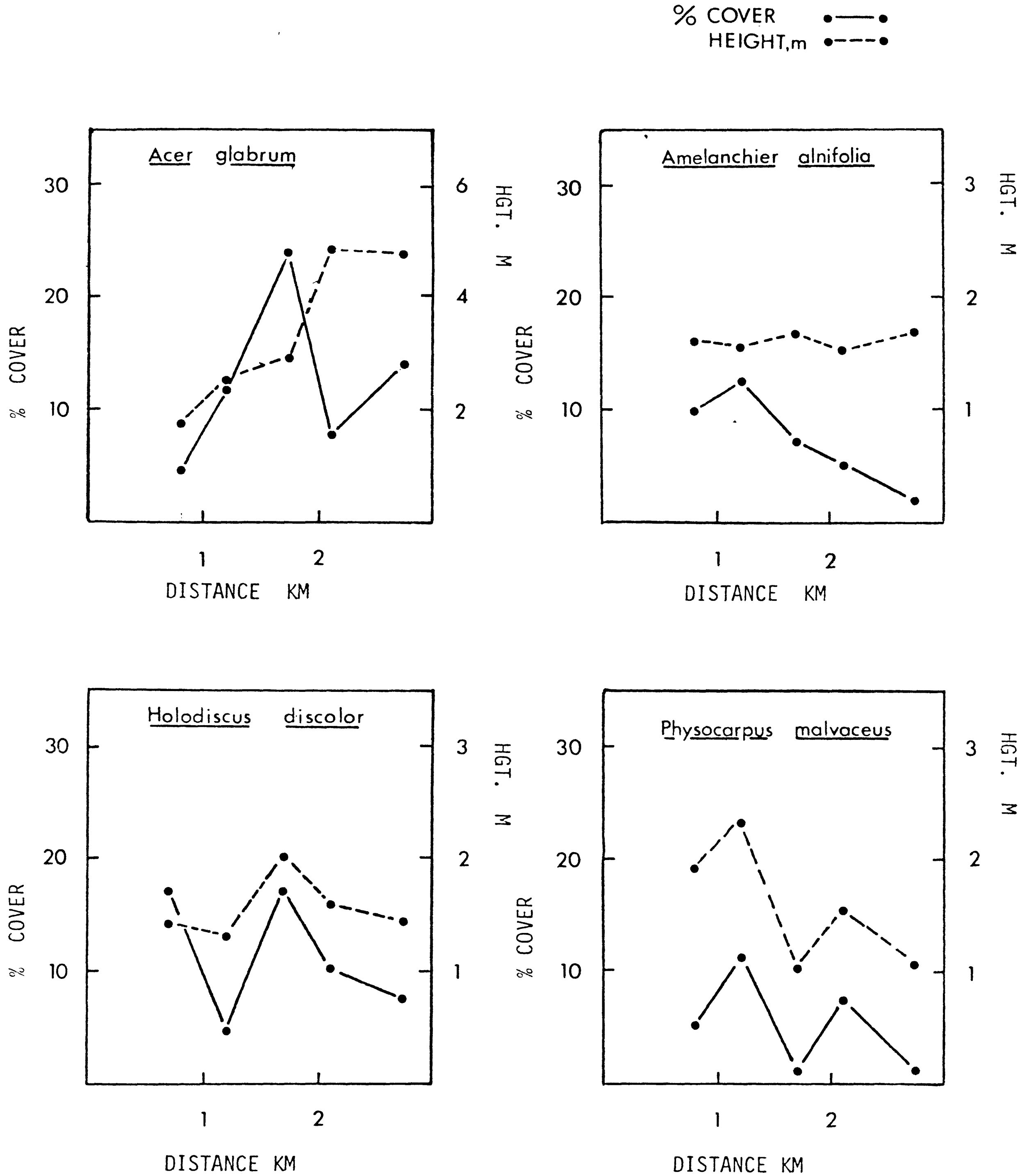


Figure 7. Average percent cover and mean height of tall shrubs along the fluoride gradient.

alnifolia shows no change in height along the fluoride gradient, although average percent cover steadily increases with proximity to the aluminum smelter and then drops in plot 1.

The results of the short-shrub layer analysis, illustrated in Figure 8, show a marked reduction in percent cover and height with proximity to the aluminum smelter. Plots 1 and 2 have a severely altered short-shrub layer with average percent cover reduced to about 1% and height reduced from 0.6 meters to approximately 0.3 meters. Rosa sp. frequency was so low in plot 1 that an adequate height sample was impossible to obtain. Although there is only a slight reduction in height of Spiraea betulifolia, average percent cover decreases sharply in plots closest to AAC. Note the bimodal height - percent cover curves for Symphoricarpos albus. This same type of curve represents the height of Holodiscus discolor and the average percent cover of Amelanchier alnifolia and Acer glabrum. Thus, height and percent cover may be suppressed at both ends of the fluoride gradient.

The graminoid response to changes along the fluoride gradient are shown in Figure 9. Both height and average percent cover increase with proximity to the fluoride source. Height appears to be a stronger indicator of response to changes along the fluoride gradient than is percent cover. Average percent cover of graminoids in plots 3 through 5 is quite similar, whereas changes in height are more distinct.

Changes in Species Composition Along the Fluoride Gradient

Tree stratum. The most severely altered stratum within the Douglas-fir community is the tree layer. The percent mortality and percent basal area reduction of all tree species is shown in Figure 10. Percent

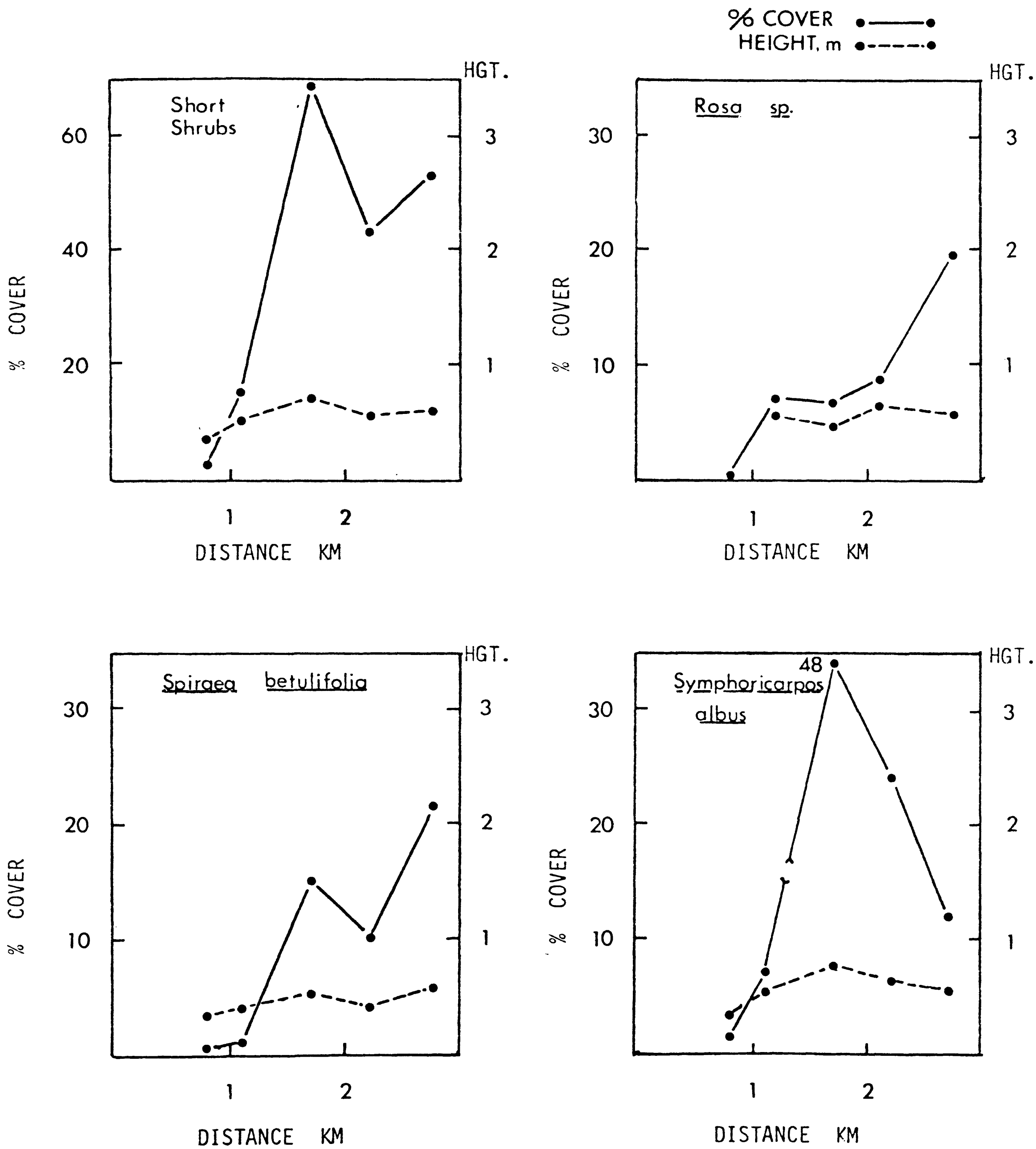


Figure 8. Average percent cover and mean height of short shrubs along the fluoride gradient.

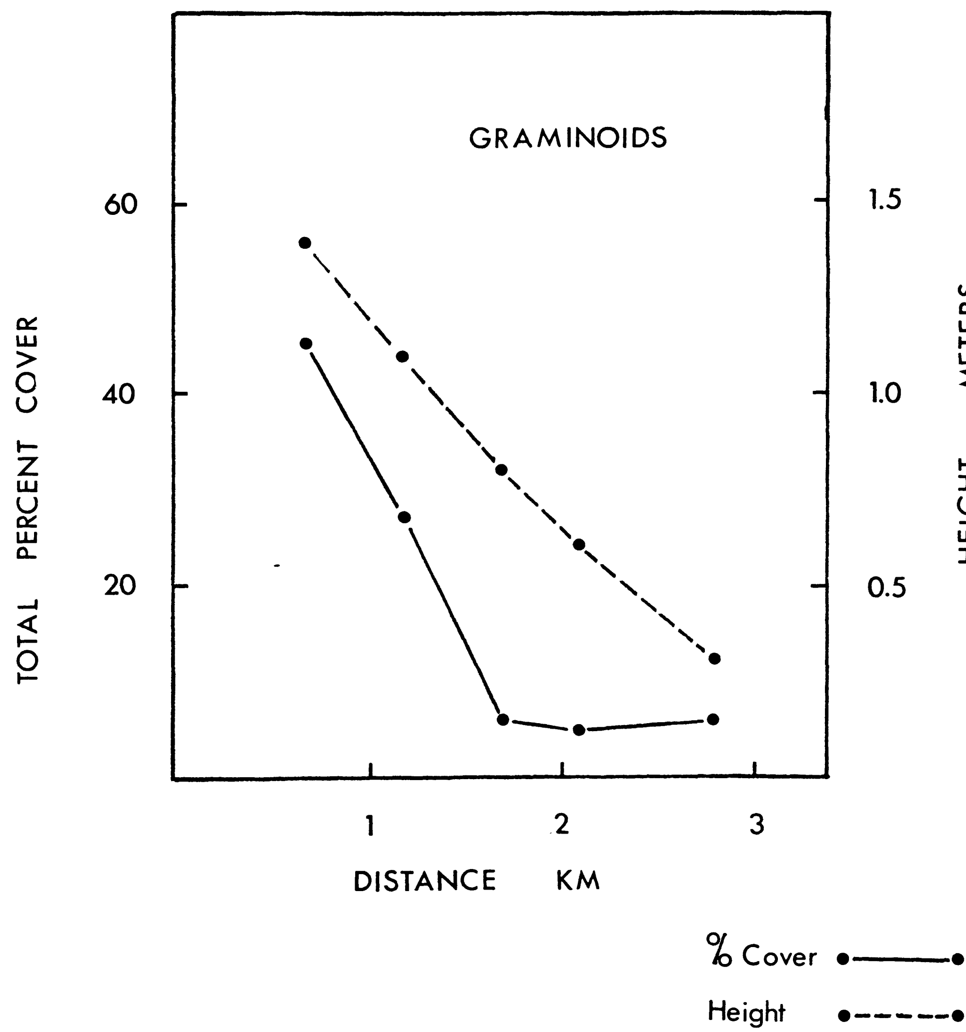


Figure 9. Total percent cover and mean height of graminoids versus distance from Anaconda Aluminum Company.

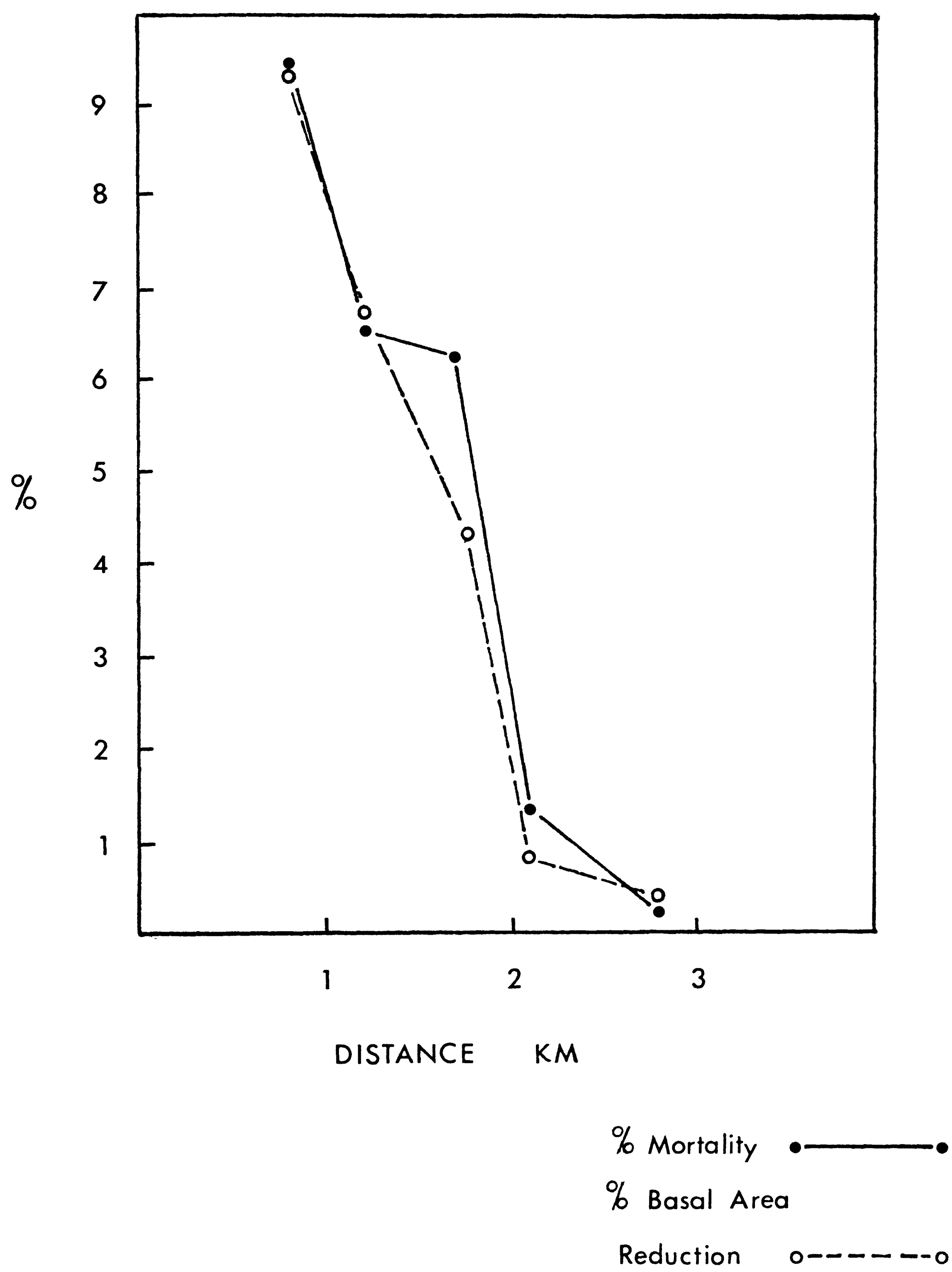


Figure 10. Percent mortality and percent basal area reduction of the tree stratum versus distance from Anaconda Aluminum Company.

mortality approaches 100% in plot 1. Aerial photographs taken in 1970 reveal that percent mortality in plot 1 was only about 8%, although severe fluoride damage was apparent throughout the tree layer. Most of the trees within this plot appeared to have died about five years ago. In general, percent mortality and basal area reduction follow the same trend, i.e., greatest mortality and basal area reduction in areas closest to the aluminum smelter.

Figure 11 shows the percent of dead and living stems within three diameter classes for each plot. Total basal area and density per 500 m^2 plot are also tabulated. The greatest percent mortality has occurred in the smaller diameter classes. This is especially evident in plots 1 and 3 where tree density is relatively high. As percent mortality decreases away from the fluoride source, this pattern of highest mortality in the smaller diameter classes persists.

When the relative density (%) of total standing stems to living stems of each tree species is examined, certain trends in composition appear (see Figure 12). In general, deciduous members of the tree stratum become relatively more important closest to the aluminum smelter. There are no changes in deciduous tree density at the distal end of the fluroide gradient. Mortality of Pinus contorta reduces its relative density in all plots except in plot 1 where it was not present and in plot 5. Larix occidentalis increases in relative density in all plots but 1 and 5. Pseudostuga menziesii decreases in relative density in plots 1 through 3 only. Pinus contorta and Pseudotsuga menziesii both appear more sensitive to fluoride fumigation than does Larix occidentalis.

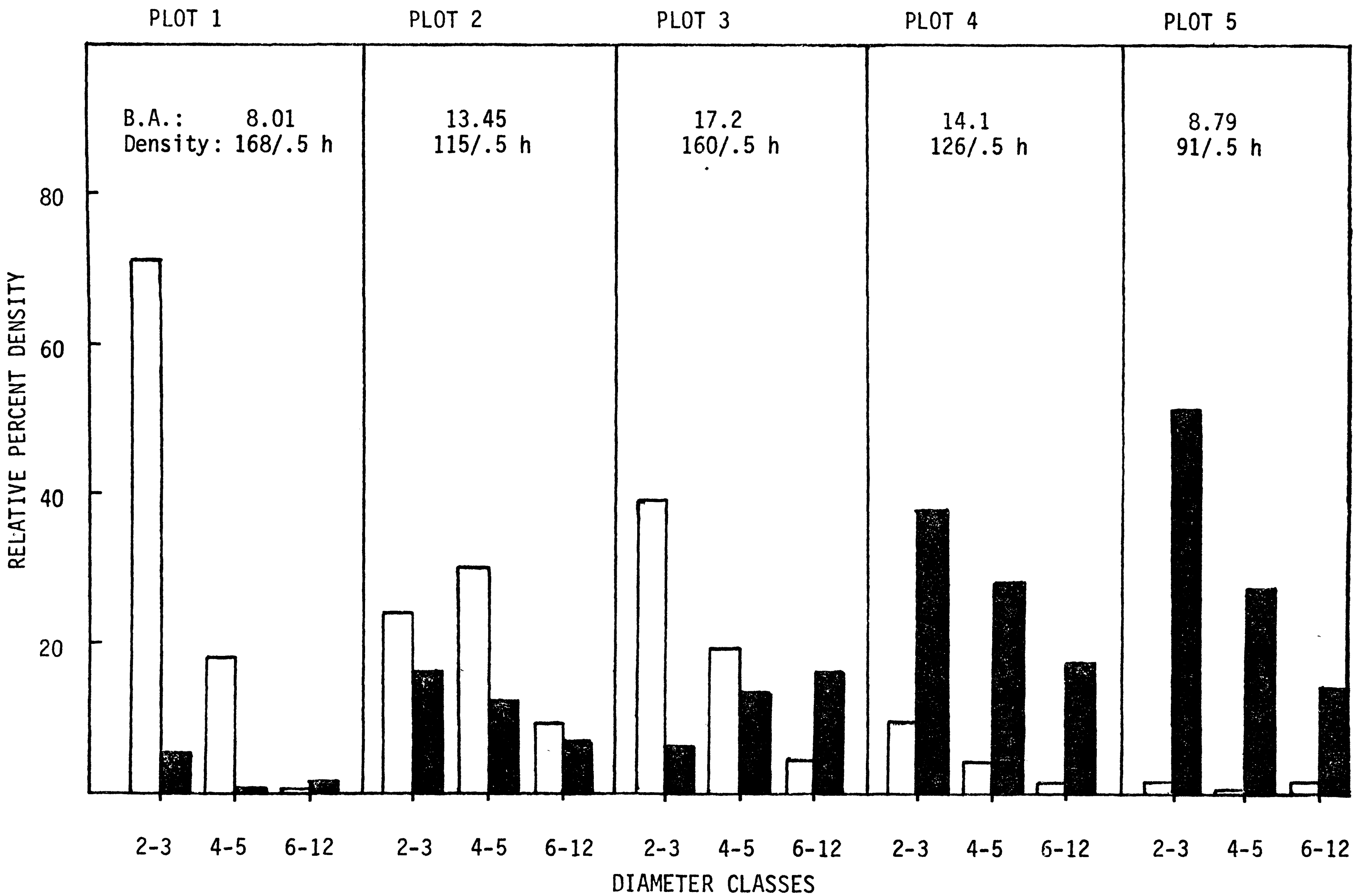


Figure 11. Percent total standing stems (clear bars) and living stems (darkened bars) per diameter class in each plot.

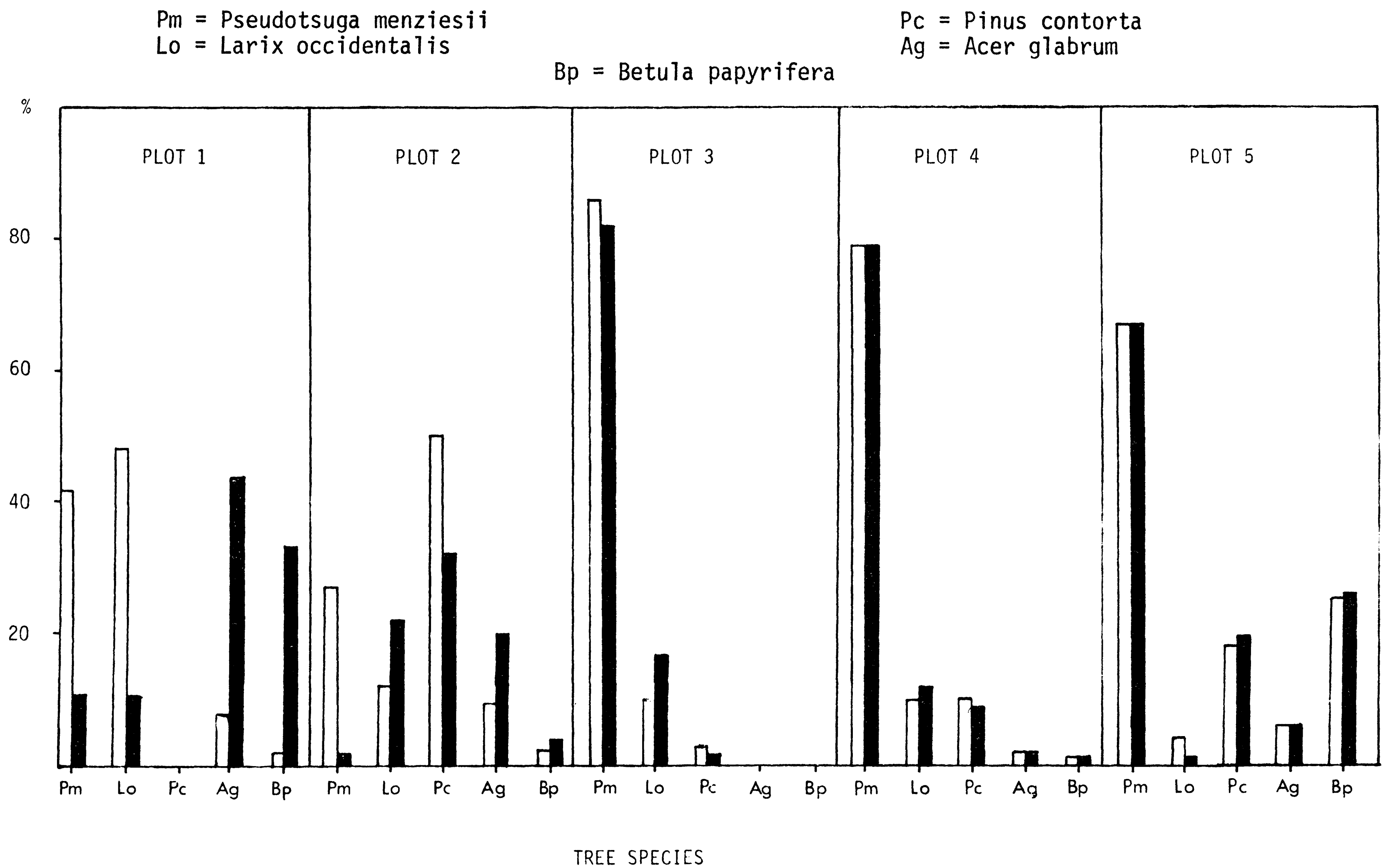


Figure 12. Relative density (%) of tree species per half hectare plot. Clear bars represent standing stems; darkened bars represent living stems only.

Tree regeneration. The distribution of shrub and tree seedlings along the fluoride gradient is shown in Table 1. Regeneration of shrubs and conifers is lowest in plot 1. Shrub regeneration is also least at the far end of the fluoride gradient in plot 5. Thus, shrub seedlings are suppressed at both ends of the gradient. *Pseudotsuga menziesii* seedlings, which are moderately shade-tolerant, do not appear as affected by low light intensities as are the shrub seedlings in plot 5. Plot 2 exhibits the highest tree seedling percent cover and frequency. In plots 3, 4 and 5, tree seedling percent cover diminishes. Note the increased percent cover and frequency of shrub seedlings in plots 3 and 4. These values reflect the high total percent cover of shrubs in the same plots.

Table 1. Distribution of shrub and tree seedlings along the fluoride gradient. Average percent cover/percent frequency.

		Distance from AAC				
Species	km	0.8	1.2	1.7	2.1	2.7
Acer glabrum		+/10		+/15	1/30	+/+
Amelanchier alnifolia		+/10	+/15	1/25	2/30	+/+
Symphoricarpos albus			+/5	4/30		
Pseudotsuga menziesii			3/70	1/40		2/60
Pinus contorta			4/40			
Populus tremuloides						+/20

+/+ less than 0.6% average cover and frequency
\+ with frequency insufficient to be encountered in microplots

Shrub stratum. The distribution of short and tall shrubs along the fluoride gradient is shown in Table 2. Shrub species exhibiting severe to moderate foliar fluoride injury in plots 1, 2 and 3 are marked with an asterisk. Note once again the sharp reduction in short-shrub percent cover and frequency. Plot 1 has the greatest number of species, although 50% of them are found in trace amounts. Trends in percent cover and frequency suggest that _Acer glabrum_, _Symphoricarpos albus_, _Spiraea betulifolia_ and _Rosa_ sp. are likely to be eliminated from the plant community. _Holodiscus discolor_ and _Physocarpus malvaceus_ have increased percent frequency in plots closest to the fluoride source, although average percent cover is not significantly different. It is possible that greater numbers of these two individuals have recently become established but, because of their relatively young age, show a lag in percent cover.

MacArthur's diversity index for short and tall shrubs combined is illustrated in Figure 13. Diversity of the shrub layer is negatively related with proximity to the fluoride source. Shrub stratum diversity in plot 1 increases slightly due to the presence of _Philadelphus lewisii_, _Salix_ sp., _Ribes viscosissimum_ and _Shepherdia canadensis_.

Table 2. Distribution of short and tall shrubs along the fluoride gradient. Average percent cover/percent frequency.

	Distance from AAC				
Species km	0.8	1.2	1.7	2.1	2.7
Philadelphus lewisii	+/5				
Salix sp.	+/5				+/5
Ribes viscosissimum	+/5				
Shepherdia canadensis	+/10				+/+
Holodiscus discolor	17/65	5/45	17/50	10/60	8/45
Acer glabrum*	5/30	12/50	24/45	8/45	14/45
Amalanchier alnifolia*	10/40	13/85	7/50	5/55	2/50
Physocarpus malvaceus	5/60	11/30	1/10	8/10	1/10
Prunus virginiana				+/5	
Symphoricarpos albus*	2/55	7/85	48/90	24/100	12/65
Spiraea betulifolia*	+/30	1/25	15/50	10/60	22/85
Rosa sp.*	+/+	7/55	6/20	1/40	20/90

+/+ less than 0.6% average cover and frequency
+ with frequency insufficient to be encountered in microplots
* species exhibiting severe to moderate foliar fluoride injury in plots 1, 2 and 3

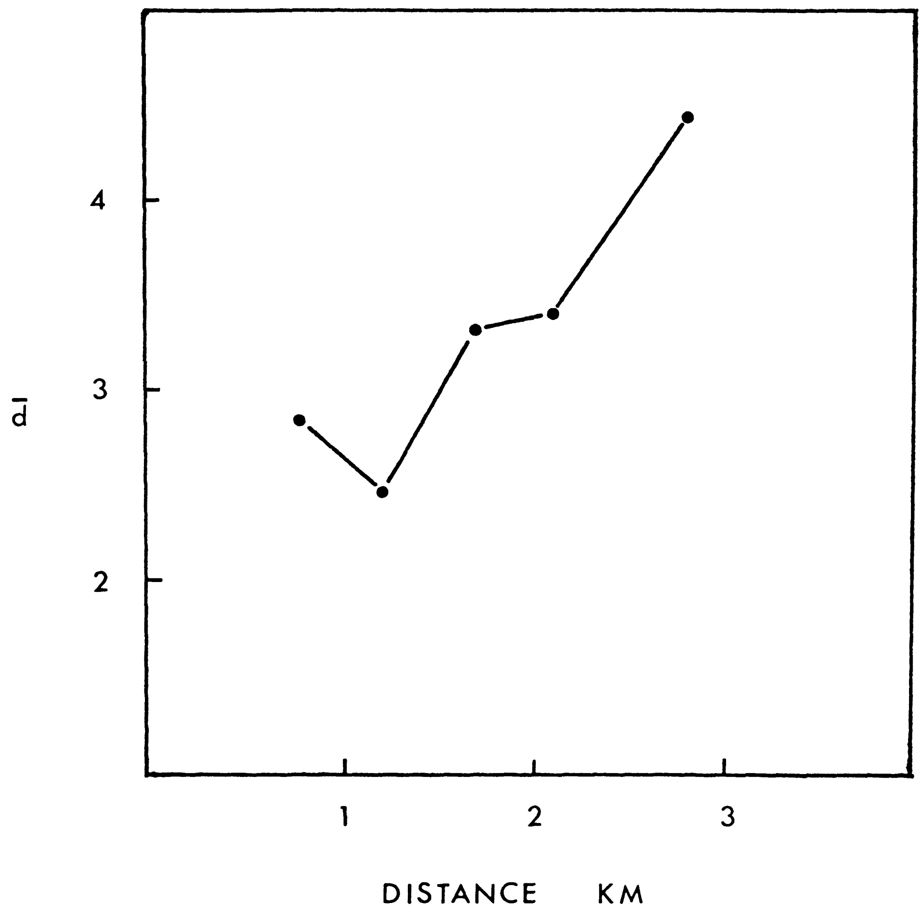


Figure 13. Diversity index ($\bar{d}$) of the combined shrub layer (tall and short) versus distance from Anaconda Aluminum Company.

Herb stratum. Table 3 shows the distribution of herbaceous species in relation to distance from AAC. Herbaceous species exhibiting severe to moderate fluoride injury in plots 1, 2 and 3 are marked with an asterisk. The absence of a highly HF-sensitive herbaceous plants in plots close to AAC would be suspect of eventual elimination from the immediate vicinity. In general, herbaceous species do not seem threatened in this manner. One exception is Berberis repens which shows a steady decrease in percent frequency with proximity to the aluminum smelter. This evergreen perennial has been noted as very sensitive to fluoride by others (Carlson and Dewey, 1971).

The distribution chart does show a significant species composition shift from plot 1 to plot 5. The distribution of graminoids shows an increase in species number, average percent cover and percent frequency in plots closest to AAC. Plots 1 and 2 also contain introduced or exotic species like Dactylis glomerata, Bromus inermis, B. tectorum, Verbascum thapsis, Artemisia absinthium and Cirsium arvense. Instead of a direct elimination of herbaceous species sensitive to fluoride, there is an invasion of species with higher tolerance to fluoride; these proliferate in disturbed areas.

Diversity and total percent cover of herbaceous species are plotted in Figure 14. Diversity of the herb stratum increases at both ends of the fluoride gradient. The concentration of dominance among a few species like Linnaea borealis and the graminoids has caused the observed depression of herb layer diversity in plot 1.

Moss stratum. Bryophyte distribution along the fluoride gradient is shown in Table 4. Species exhibiting foliar necrosis in plots 1 and 2

Table 3. Herbaceous species distribution along the fluoride gradient. Average percent cover/percent frequency.

	Distance from AAC				
Species km	0.8	1.2	1.7	2.1	2.7
Dactylis glomerata*	10/40				
Poa interior	+/5				
Bromus inermis	2/10	6/40			
Bromus tectorum	+/+				
Trisetum sp.	+/+	1/5	3/25		
Elymus glaucus	+		+/5		
Bromus vulgaris	10/30	+/+	1/5		
Festuca occidentalis	10/40	4/20	+/5		1/10
Oryzopsis asperifolia	12/45	4/25	+/15	+/+	3/35
Calamagrostis rubescens	+/15	12/45	3/30	+/5	1/30
Arctostaphylos uva-ursi	+/+				
Verbascum thapsis	+/+				
Artemisia absinthinum	+/+	+			
Cirsium arvense	+/+	+			
Epilobium angustifolium*	3/15	+			
Aster conspicuous	+/10	+			
Galium boreale	1/20	+/5			
Aster sibiricus	+/5	+	+/5		
Clematis columbiana*	+/10	+/10	14/30		
Ozmorhiza chilensis	+/5	+/10		+/5	+/5
Berberis repens*	+/+	+	2/20	4/25	2/40
Viola adunca	+/5	+/15	1/20	+/5	+/15
Fragaria virginiana*	+/+	2/15	1/25	+/20	+/10
Fragaria vesca*	6/30	8/35	+/5	1/10	2/25
Smilacina stellata*	+/15	5/30	12/75	1/5	+/10
Linnaea borealis	20/40	12/45	+/10		9/55
Disporum hookerii*	5/15	7/30	+/5	2/25	2/10
Smilacina racemosa*		2/15	+/+		
Allium cernuum		+		+/10	
Apocynum androsaemilifolium *		1/10			
Adenocaulon bicolor	2/20	3/15			1/20
Thalictrum occidentale			+/5		
Galium triflorum			+/5		
Antennaria neglecta			+/5	5/10	
Arnica cordifolia			+/15	2/20	+/10
Rubus parviflorus*		1/5			7/10
Lonicera ciliosa			7/35	+/+	1/30
Clintonia uniflora	+/+	+			2/30
Xerophyllum tenax				+/5	+/+
Aralia nudicaulis*					+/10

+/+ less than .6% average cover and frequency
\+ with frequency insufficient to be encountered in microplots
* species exhibiting severe to moderate foliar fluoride injury in plots 1, 2 and 3

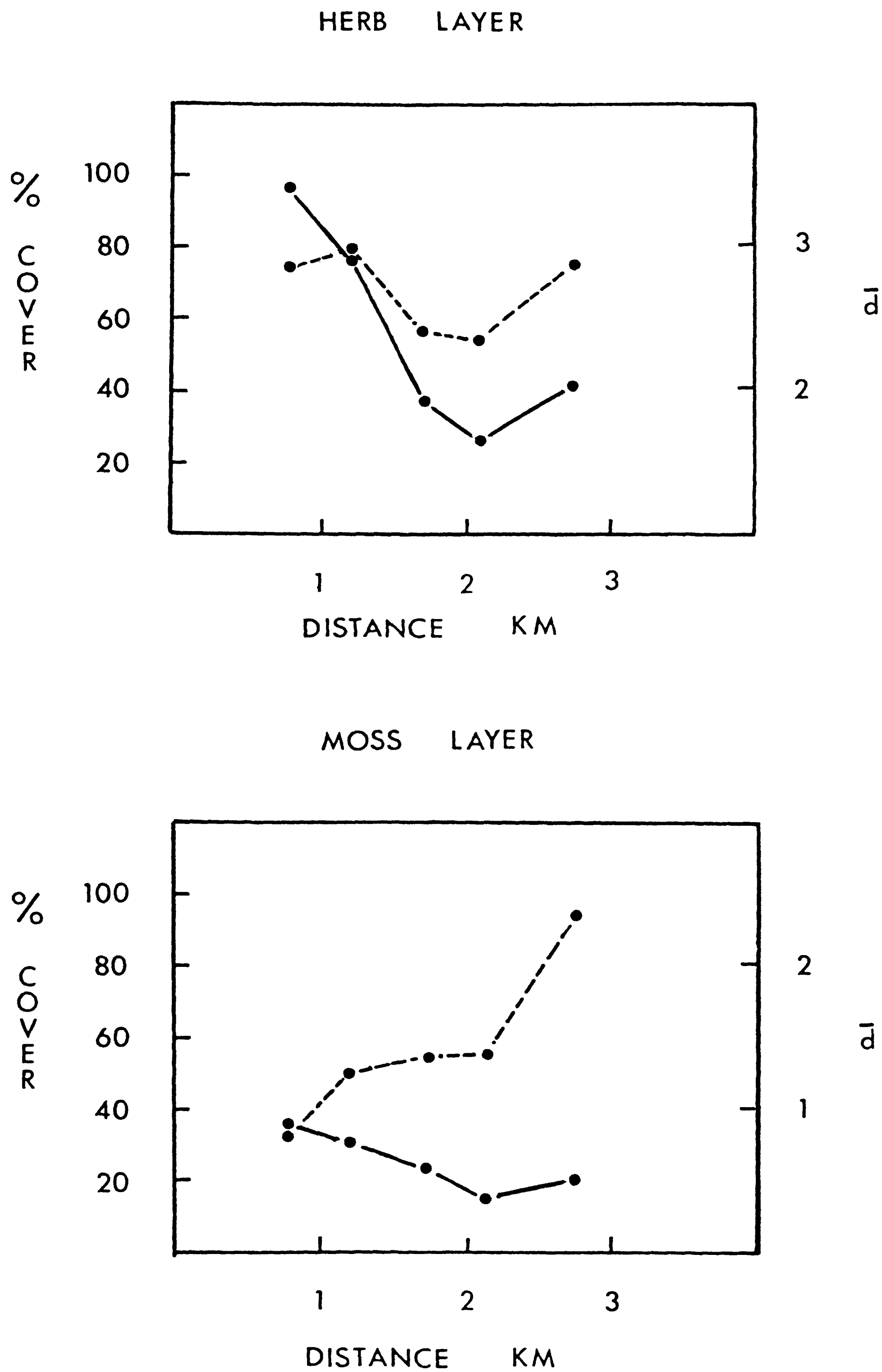


Figure 14. Diversity index ($\bar{d}$) and total percent cover of the herb layer and moss layer versus distance from Anaconda Aluminum Company.

Table 4. Bryophyte distribution along the fluoride gradient Average percent cover/percent frequency.

		Distance from AAC				
Species	km	0.8	1.2	1.7	2.1	2.7
Ptergynandrum filiforme			+			
Brachythecium spp.		24/80	25/70	15/80	8/77	9/80
Dicranum tauricum		+/7	+/10	4/30	+/+	4/40
Drepanocladius ucinatus var. ucinatus		+/+	+/+	+/6	2/23	+
Auloconium androgynum*		+	+/+	+/+	+/+	+/10
Polytrichum juniperinum		+	+/+			+/10
Brachythecium hylotapetum		4/10	+/10			+
Pohlia nutans*		+	+		+	+/13
Tortula ruralis			+/+	+/13	2/30	+/3
Dicranum scoparium				+/6	+	+/13
Rhytidiopsis robusta				+/+	+	+/6

+/+ less than .6% average cover and frequency
\+ with frequency insufficient to be encountered in microplots
* species exhibiting severe to moderate foliar fluoride injury in plots 1, 2 and 3

attributable to fluoride are marked with an asterisk. The leaves of Pohlia nutans showed severe tip and marginal necrosis and only in those leaves near the apical portion of the stem. Auloconium androgynum and Polytrichum juniperinum displayed tip necrosis of the apical leaves only. Polytrichum juniperinum may brown at the leaf apices naturally, and therefore its sensitivity to fluoride is only suspect here.

The distribution chart suggests that Auloconium androgynum, Pohlia nutans, Tortula ruralis, Dicranum scoparium, and Rhytidiopsis robusta may be eliminated from areas closest to the fluoride source. Dicranum scoparium and Rhytidiopsis robusta do not occur in plots 1 and 2 and are only found in trace amounts in plots 3 and 4.

Brachythecium spp. (Brachythecium albicans and other Brachythecium sp. indistinguishable in the field) occurs with equal frequency along the fluoride gradient. However, average percent cover in plots closest to the aluminum smelter increases. This increase in average percent cover is also seen in Brachythecium hylotapetum. These species of moss occurred in diffuse, prostrate mats under the herb layer. Their abundance was especially noticeable in plot 1 where graminoids and Brachythecium spp. dominated the lower strata of the community.

Diversity of the moss stratum and total percent cover are shown in Figure 14. Total percent cover increases closest to the fluoride source and diversity decreases. The concentration of dominance of the moss stratum in plot 1 is due to the loss of certain sensitive members and the proliferation of Brachythecium spp.

Chapter 6

DISCUSSION

In a gradient analysis of this type, where there is more than one physical parameter under consideration, the delineation of cause-effect relationships is not a simple matter. Of interest in this investigation is the separation of the direct effects of fluoride on the Douglas-fir community from fluoride-induced indirect effects like understory light intensity and soil moisture. A further consideration is the effect of compositional characteristics particular to each stand on observed community changes along the fluoride gradient. The ensuing discussion will attempt to evaluate all of these factors.

Tree Stratum Response

The loss of sensitive members of the tree layer is the most critical direct effect of fluoride fumigation on the Douglas-fir forest community. Of all five strata in the community, reduction in percent cover of the tree layer occurs first and is most significant. Their relative sensitivity to fluoride is related to several factors. The growth form contributes most to the susceptibility of trees to fluoride. Conifers are inherently more sensitive to fluorides than are broadleaved trees (Carlson and Dewey, 1971; Gordon, 1974). Trees are the tallest individuals in the forest community and therefore scavenge the greatest amounts of fluoride (Knabe, 1969; Gordon, 1976; Gordon et al., 1977). The dominant growth forms are also exposed to greater extremes of the environment: full sunlight, higher wind speeds, rapid changes in temperature and evapotranspirational stress, whereas plants below the forest canopy exist in a moderated microenvironment, less subject to rapid changes or extremes. These environmental factors could become critical in fluoride-damaged trees or in trees with significant fluoride accumulation in foliage. Certain changes in microclimate which occur after exposure to fluoride, such as high light intensity (Rohmeder et al., 1967), increased temperatures and moisture stress, increase the severity of injury due to fluoride (Wiebe and Poovaiah, 1973).

A more fundamental characteristic of the tree stratum is the critical ratio of respiring to photosynthetic tissue. Large growth forms have a greater proportion of respiring, living support tissue to photosynthetic tissue than smaller plants. Any defoliating agent has a greater physiological impact on trees than on shrubs or herbs since the balance of photosynthesis to respiring tissue becomes unfavorable. Woodwell (1970) uses this principle to explain, in part, the extreme sensitivity of trees to chronic gamma irradiation. The impact of fluoride on the respiration/photosynthesis imbalance may be compounded by two things. Fluoride is known to increase bark respiration and decrease photosynthesis in trees (McLaughlin and Barnes, 1975). As certain trees succumb to fluoride injury, the forest stand is thinned and openings result. The decrease in percent cover and tree density in plots closest to AAC attest to this fact. When stands of trees are mechanically thinned, codominant or suppressed individuals of the tree layer may experience severe respiration/photosynthesis imbalances (Smith, 1962; Staebler, 1956). This is due to increased respiration rates related to elevated temperatures inherent in stand openings (Staebler, 1956). In severe cases, these trees may eventually succumb. Furthermore, when stands are mechanically or otherwise thinned, trees which had formerly nourished the unthrifty through root grafts may be lost (Smith, 1962).

Greatest percent mortality in experimental plots along the fluoride gradient were found in the smaller diameter classes. This trend was most marked in plots 1 and 3 where stand density was highest. In the absence of fluoride, mortality of the shorter, suppressed individuals of the tree stratum gradually occurs over a period of time. In fluoride fumigated stands, taller individuals might be prone to mortality first, simply because of exposure. Apparently this is not entirely true along the base of Teakettle Mountain. Mortality of the smaller-diameter classes has occurred within the last five years (1971-76). It is possible that the combined effects of stress from competition for moisture, nutrients and light; respiration/photosynthesis imbalances incurred by "fluoride-thinning," and loss of root graft relationships may render the smaller individuals more susceptible to mortality due to fluoride.

The drastic nature of tree stratum mortality in plot 1 (96%), as compared to other plots along the fluoride gradient, attest to the influence of high tree density and continuous fluoride fumigation on the severity of injury. Plot 1 is in the prevailing wind patterns and is only 0.8 km from AAC. The investigator experienced nausea and a burning sensation of nose and throat every day that she worked in plot 1. Plot 1 has probably been exposed to chronic fluoride fumigation since the beginning of plant operations in 1955. Continuous fluoride exposures have been shown to be more detrimental to plants than intermittent fumigations (Adams and Emerson, 1961; Maclean et al., 1969). The predominance of trees in smaller diameter classes in plot 1, as compared to those in plot 3 which has similar tree density, suggests that fluoride has contributed to decreased radial growth of Pseudotsuga menziesii and Larix occidentalis for several years. Decreased radial growth due to fluorides has been observed by Treshow (1967) in P. menziesii and by Carlson and Hammer (1974) in Pinus contorta. The sudden death of trees since 1970 is undoubtedly also associated with acute fumigation episodes from the increased fluoride emissions of 7,500 lbs F^-/day in 1969 and 1970, subsequent to completion of the fifth potline in 1968.

Tree Stratum Regeneration

In areas closest to AAC it is improbable that conifer seedlings will survive. As soon as they reach a height which is above the shrub layer in open areas, they are exposed to ambient fluoride concentrations which cause terminal and lateral dieback of the uppermost branches. This was observed by the author on several occasions, along the base of Teakettle Mountain as well as the west slope at higher elevations. Some conifer seedlings exhibit a relative resistance to fluoride in areas (0.7 km from AAC) closest to the fluoride source. They have assumed a short shrublike appearance with evidence of successive dieback of the terminal shoot. Although not particularly sheltered, needle necrosis was minimal or absent in these individuals. Dwarfism of trees near fluoride-emitting industries has been reported by Gottfried and Kisser (1967).

If fluoride emissions are significantly reduced or abated entirely in the near future, present conifer regeneration in disturbed communities along the fluoride gradient may indicate future trends. Removal of the forest canopy by logging or thinning practices has shown that conifer regeneration is best on clearcuts and is positively related to low tree density in thinned stands (Walker and Johnson, 1975). Adequate light, moist surface soils and moderate temperatures are among the most important factors contributing to successful seedling germination (Cochran, 1973). Thinning (Dahms, 1973; Orr, 1968; Herring, 1970; Anderson, et al., 1969) and clearcutting (Herring, 1970) practices increase soil moisture. Clearcuts with a thin layer of vegetation have a higher daytime soil temperatures and lower nighttime soil temperatures than forested stands (Gary, 1968). Concomitant with stand openings is increased light intensities to the understory vegetation (Anderson et al, 1969). Light has been shown to be more important to conifer seedling survival under the forest canopy than soil moisture (Kramer et al., 1952). Interesting to Kramer's (1952) data was the fact that conifers have a higher percent survival at the forest margin than in the open.

In northwestern Montana, Pinus contorta and Larix occidentalis are fire dependent species which require seed release from cones and a mineral seed bed, respectively, for successful establishment (Larsen, 1929; Habeck, 1968). Pseudotsuga menziesii may germinate on bare soil or seed in any time after the establishment of these two species, provided light is not too limiting (Habeck, 1968).

There is no indication of Larix occidentalis regeneration along the fluoride gradient. One would expect greatest seedling frequency in plots closest to AAC where the forest canopy has been adequately thinned. In plot 1, conifer seedlings are absent. This could be due to the high total percent cover of herbs in this plot. Inhibition of tree seedling establishment has been correlated with high shrub and herb densities

(Neiring and Goodwin, 1974). Such exclusion of tree regeneration has lasted 15 years with no indication of reversal. Competition for moisture, nutrients and niche space can be limiting in such circumstances. Emmingham and Waring (1973) found maximum leader elongation in Douglas-fir in open, bare areas with little competing vegetation. Baret (1970), working with Pinus ponderosa, found that diameter and height growth of saplings were reduced by 40 percent by understory vegetation. In plot 2, percent cover of Pseudotsuga menziesii and Pinus contorta seedlings is highest. Canopy openings, increased light intensity, decreased fluoride exposure and reduced herb cover in plot 2 probably contribute to these observations. Percent cover of conifer seedlings diminishes as understory light intensity decreases away from the fluoride source.

Shrub Stratum Response

Light and fluoride fumigation intensity are the most important factors responsible for changes in height of tall and short shrubs. Take for example Acer glabrum (see Figure 7). A. glabrum is an arborescent shrub capable of attaining heights that reach the lower limits of the tree stratum (about 10 meters). A. glabrum decreases in height when the forest canopy is opened (Mueggler, 1965). The complete loss of the tree layer by logging, in the absence of fluoride fumigation, causes a 35% decrease in height of A. glabrum (Mueggler, 1965). In plot 1, whose tree layer is virtually absent, the height of A. glabrum has decreased by 63%. This shrub also assumes a dense, bushy form when the tree canopy is removed (Mueggler, 1965). The average percent cover of this shrub in plot 1 is less than 5%--the lowest average percent cover of all experimental plots. This shrub exhibited extreme to severe foliar necrosis and terminal-lateral branch dieback in plot 1. Necrosis of terminal buds was observed frequently on *Acer glabrum* and *Amelanchier alnifolia*. Gordon (1974) reported elevated fluoride accumulation in terminal buds of shrubs in the vicinity of AAC. Fluoride directly diminishes the height and percent cover of certain shrubs by necrosis of foliage and terminal buds. Indirectly, fluoride may decrease the height of *A. glabrum* by opening the forest canopy. The effect of fluoride on the quality and quantity of winter range and its significance to big game is an aspect which deserves attention in the future.

Amelanchier alnifolia also demonstrates the effect of fluoride emissions on height. This shrub increases in height in response to increased light (Mueggler, 1965). Its height is suppressed by fluoride fumigation in plots closest to AAC and by insufficient light intensity in plots at the distal end of the gradient. Hence, the straight line graph shown in Figure 7 represents height along the fluoride gradient. Percent cover appears less sensitive to the effects of fluoride than height, but trends in percent cover are mediated by patterns in percent frequency (see Table 2). Despite the decrease in height of *A. alnifolia* in plot 1, average percent cover also decreases. Any possible attempt to increase percent cover in response to height loss, is repressed by exposure to fluoride. Height has been considered an indication of plant vigor (Heady, 1957). The observed depression of height and percent cover of *A. glabrum* and *Amelanchier alnifolia* strengthens a hypothesis which can be drawn from distribution charts--that these shrubs will eventually be eliminated from the plant community.

The height of short shrubs is static when the forest canopy is opened (Mueggler, 1965). The height of all short shrubs decreased with proximity to the fluoride source. *Symphoricarpos albus* height is suppressed by fluoride in plots closest to AAC and by low understory light intensities in plot 5. Since the tall shrubs are the largest members of the plant community in plot 1, one would expect short shrubs to be less susceptible to fluoride. *Rosa* spp., *S. albus* and *Spiraea betulifolia* all exhibited severe foliar necrosis in plots closest to AAC. It is possible that fluoride combined with competition from the herb layer decreases the relative success of these individuals, despite their stratal position in the community. Apparently sensitivity to fluoride is not simply a function of stature.

Herb Stratum Response

The marked increase in total percent cover of the herb stratum in plots 1 and 2 is due to the increased frequency of several graminoids and introduced weeds. When canopy cover decreases, increases in understory light intensity, throughfall precipitation and niche area stimulate understory herbaceous vegetation (Anderson et al., 1969). In addition, throughfall precipitation was more important than light to herbaceous response. Percent soil moisture (an indirect measurement of throughfall precipitation) in the upper soil layer is highest in plots 1 through 4 and lowest in plot 5. Understory light intensity, however, is significantly correlated with canopy cover. The linear relationship of graminoid height with distance from AAC shown in Figure 9 attests to the importance of light to the response of the herb stratum in the experimental plots. Throughfall precipitation is probably highest in plot 1, but this is not reflected in soil moisture readings. This may be due to the evapotranspirational demand of the herb layer.

Shade-intolerant weeds indicate the degree of disturbance in plots 1 and 2, suggesting once again the importance of understory light intensity. Mueller-Dombois (1965) found, in the cut-over and burned stands of the coastal Douglas-fir and western hemlock zones, all species characteristic to the undisturbed forest associations. But species numbers were greater "due to a number of weed species that had invaded after logging." He also points out that "these shade-intolerant weeds were rather ubiquitous in relation to moisture regime differences as their major controlling factor was light." Herbaceous species distribution (Table 3) along the fluoride gradient suggests that shade-tolerant species common in plot 5 may be partially displaced in disturbed plots by graminoids and introduced weeds. This contradiction to the results reported by Mueller-Dombois (1965) may be due to the relative fluoride resistance of graminoids and exotic species. Certainly, the herb stratum as a whole is responding to increases in understory light intensity, soil moisture and the additional space, a result of fluoride-induced tree mortality.

The relative fluoride resistance exhibited by the herb stratum is likely due to its low stature, inherent resistance to fluoride and perennial growth form. In general, the height of herbaceous plants affords them protection from fluoride exposure. However, certain graminoids and introduced weed species attain heights equal to that achieved by the tall-shrub layer, the tallest individuals in plot 1. Verbascum thapsis and Bromus inermis are good examples. These individuals showed no signs of foliar necrosis attributable to fluoride. Vegetative propagation from underground parts, characteristic of all herbs found in plots 1 and 2 (except Bromus tectorum), has been shown to be an advantage over annual growth form in polluted areas (Jordon, 1975; Wood and Nash III, 1976). The exception to these generalities is Berberis repens, a perennial evergreen with low stature but high relative sensitivity to fluoride. Inherent resistance to fluoride appears to be the most important factor controlling plant response to fluoride.

Moss Stratum Response

Although the number of bryophyte genera encountered along the base of Teakettle Mountain is low, the kind and number of genera found in the Pseudotsuga/Physocarpus association of eastern Washington, bears remarkable similarity to those found in this study (Cooke, 1955). The observed reduction in moss species diversity with proximity to AAC may be the result of four factors: (1) inherent fluoride sensitivity, (2) increases in herbaceous plant litter, (3) increases in herbaceous density and (4) changes in the microhabitat of the moss layer. Mosses tend to suffer more from an intolerance of dead plant debris than from shading by herbaceous cover (Briggs, 1965; Bard, 1965). As density of herbaceous vegetation increased in old-field secondary succession, there was an increase in trailing mat growth forms and a decrease in tufted forms (Bard, 1965). Pohlia nutans (tuft) was an exception (Bard, 1965). Mueller-Dombois (1965) found that mosses were markedly reduced in distribution in cut over stands. He attributes this to the dessicating microclimate of logged areas and the disruptive nature of invading weed species. To date this is the first study reporting the fluoride sensitivity of terrestrial bryophytes in forest ecosystems of the northwest. Pohlia nutans and Auloconium androgynum were the only bryophytes along the fluoride gradient which exhibited foliar necrosis attributable to fluoride (injury symptoms after Comeau and LeBlanc, 1972). Their distribution along the fluoride gradient is too erratic to conclude that fluoride has induced the observed disparity of their occurrence in this area. *Pohlia nutans* is suspect of elimination since it has been reported elsewhere as a major component of grassland habitats (Bard, 1965) but is found only in trace amounts along the fluoride gradient excluding plot 5.

Brachythecium spp., a mat-forming bryophyte, is most abundant in areas with high herb cover--plots 1 and 2. The absence of *Tortula ruralis* and *Dicraunum scoparium* (erect tufts) and *Rhytidiopsis robusta* (wefts or erect mats) in plots closest to AAC is worthy of note. Although fluoride necrosis was not observed in these species, it is possible that they are sensitive to fluoride because of their stature.

Interesting to the bryophyte distribution along the base of Teakettle Mountain is the increase in total percent cover and decrease in diversity with proximity to the aluminum smelter. This is the identical trend described by Gilbert (1968) in the vicinity of a sulfur dioxide polluting source. The increase in percent cover and the increase in the concentration of dominance of the moss stratum is due to the opportunist behavior of *Brachythecium* spp. in plots 1 and 2.

Trends in Diversity

With increasing fluoride concentrations, there is a marked decrease in diversity of the tree, combined shrub and moss strata, but an increase in herb stratum diversity. It appears that diversity of the lower strata is inversely related to dominance of the larger growth forms. With fluoride-induced reduction in tree and shrub cover, there was an increase in herb stratum diversity. With an increase in herb stratum dominance in plots closest to AAC, there was a radical reduction in bryophte diversity. Zobel et al., (1976), in a structural analysis of forest communities of the central western Cascades of Oregon, contends that the pattern of diversity within a single stratum varies in a manner unrelated to the diversity of other strata, but herbaceous diversity is related to the coverage of shrubs and trees.

Chapter 7

CONCLUSIONS

Fumigation of the forest community along the base of Teakettle Mountain has initiated a chain of structural changes which begins with the mortality of the tree stratum. The degree to which the tree layer was altered determined to the greatest extent the relative abundance of species in the understory strata. The increase in understory light intensity was significantly correlated with openings in the forest canopy and appeared more important than soil moisture in controlling understory response. When the height, average percent cover and percent frequency of the understory strata were evaluated, inherent susceptibility to fluoride was more reliable than stratal position in predicting sensitivity to fluoride.

The susceptibility of the tree stratum to fluoride can be attributed to several factors: height and related accumulation rates of fluoride, exposure to extremes of the ambient environment, and the delicate ratio of respiring to photosynthetic tissue. The susceptibility of trees to ambient phytotoxins is not an uncommon observation (Sinclair, 1969; Woodwell, 1970). Plant community studies show that trees are more sensitive to sulfur dioxide (Gorham and Gordon, 1960; Wood and Nash III, 1976; Sheffer and Hedgcock, 1955; van Haut and Stratmann, 1970), oxidants (particularly ozone) (Taylor, 1973), fluorides (Anderson, 1966; Hajduk, 1963; Adams et al., 1952), and gamma irradiation (Woodwell and Whittaker, 1968) than other smaller growth forms.

The selective removal of certain trees from forest communities is often a widespread phenomenon in the vicinity of polluting industries (Gorham and Gordon, 1960; Gordon, 1976, Carlson and Dewey, 1971). As a consequence, alterations in the subordinate strata in forest communities can be expected to occur to an extent proportional to the degree of defoliation or mortality of the forest canopy. Openings in the forest canopy often create increased tree regeneration, stimulate shrub and herbaceous growth, and increase the total diversity of the subordinate strata. In areas closest to AAC this was not the case. Coniferous tree regeneration was impaired by fluoride damage and competition from the herb layer. The height and percent cover of fluoride sensitive shrubs has diminished under open canopies. Diversity of the combined shrub strata (tall and short) and the moss stratum has decreased in severely polluted plots. Furthermore, certain understory species are suspect of eventual elimination from the Douglas-fir community, either directly due to fluoride sensitivity or indirectly either by competitive exclusion or the unsuitability of the altered habitat.

In principle, the observed changes in vegetation structure along the fluoride gradient, NNW of AAC, are quite similar to the modifications which occur along natural environmental gradients. Structural complexity of plant communities decreases towards the limits of their distribution (Whittaker, 1972). Plot 1, closest to AAC, has been reduced from a Douglas-fir forest to a shrub-grassland community. It is evident that this five-layered forest community containing tree, tall-shrub, short-shrub, herb and moss layers will be simplified to a community consisting of three strata: tall-shrub, herb and moss layers. Each stratum of vegetation within a community responds to the controlling factors of its own environment (Zobel et al., 1976). Along the fluoride gradient, diversity of the lower strata is inversely related to the dominance of the larger growth forms. However, removal of fluoride sensitive species from areas closest to the fluoride source, regardless of stratal position, demonstrates the individualistic behavior of plants within the community (Gleason, 1926). The fluoride resistance of exotic or weedy species in plots 1 and 2 supports the hypothesis that hardy individuals adapted to environmental extremes are likely to be resistant to artificial disturbances (Brayton and Woodwell, 1966). Plants dominating severe environments often are low in stature and have underground reproductive parts (Mueller-Dombois, 1974). The dominance of vegetatively reproducing shrubs and herbs in areas closest to AAC is a modification of the Douglas-fir forest which enhances the stability of the community. The fluoride-induced decrease in height of tall shrubs and the suppression of tree regeneration, contribute further stability to the shrub-grassland community.

In the event of significant reductions of fluoride emissions from AAC or the abatement to near zero pollution, the return of severely altered Douglas-fir communities back to prefumigation state will require an additional disturbance such as fire. Any attempts by forest managers to reseed conifers in areas where conifer mortality has approached 80% to 100% would be futile. Whether in the presence or the absence of fluoride pollution, measures should be taken to suppress the herbaceous vegetation that is so well established in severely polluted areas. Such practices should ameliorate conifer seedling regeneration.

Chapter 8

SUMMARY

This study was initiated to elucidate changes in plant community structure and composition that may occur after prolonged fluoride fumigation of a Douglas-fir forest in northwestern Montana. The investigation was conducted in five experimental plots along a three kilometer fluoride gradient, NNW from the Anaconda Aluminum Company reduction plant in Columbia Falls, Montana. Five life-form strata, tree, tall-shrub, short-shrub, herb, and moss layers were analyzed by use of percent cover and height measurements.

Of all five strata within the Douglas-fir community, reduction in total percent cover of the tree layer occurred first and was most significant. Within the tree layer, Pseudotsuga menziesii and Pinus contorta were more sensitive to fluoride fumigation than Larix occidentalis. Of these species, mortality was greatest in the smaller diameter classes.

The degree to which the tree stratum was altered determined to the greatest extent the relative abundance of species in the understory strata. Reduction in total percent cover was observed in the tall-shrub and short-shrub layers in areas closest to the fluoride source. Conversely, high fluoride levels were associated with an increase in total percent cover of the herb layer and the moss layer. The height of fluoride-sensitive tall shrubs and short shrubs decreased with proximity to the fluoride source, whereas herb layer height increased, most notably among the graminoids. When foliar fluoride injury, height, total percent cover and percent frequency of the short-shrub layer was analyzed, it became apparent that this layer would be eliminated from plant communities closest to AAC. Other species in the herb and moss layers may be lost to areas closest to the fluoride source. This suggests that inherent susceptibility to fluoride is more reliable than stratal position in predicting sensitivity to fluoride fumigation among understory species.

Diversity of the lower strata of the forest community was inversely related to the dominance of the larger growth forms. With increasing fluoride concentrations, there was a marked decrease in diversity of the tree, combined shrub and moss strata, but an increase in herb stratum diversity.

The increase in total percent cover, diversity and height of the herb stratum was attributed to increases in understory light intensity, soil moisture, niche area and fluoride resistance of graminoids and exotic species. The dominance of the herb stratum and the sensitivity of conifer seedlings to fluorides has prevented successful conifer regeneration in severely altered Douglas-fir communities and in areas closest to AAC.

Areas most exposed to elevated levels of chronic fluoride fumigation will eventually become reduced to trilayered shrub-grassland communities. The decrease in stature and the inhibition of conifer reestablishment imparts stability to this altered forest community.

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APPENDIX A
CONIFER VIGOR CLASSIFICATION

VIGOR CLASS	POINT RANGE	ESTIMATED % CANOPY COVER LOSS	DESCRIPTIONS
1	0	0	- Normal to vigorous - No signs of past or present needle necrosis, dieback or insect disease
2	1 - 8	20%	- Needle tip burn and light necrosis - > 4 yr. needle retnetion - Lateral dieback on less than 25% branches
3	9 - 14	30%	- Needle burn & necrosis moderate to heavy - Tree unthrifty (< 4 yr. needle retention) - Partial lateral dieback
4	15 - 22	50%	- Class 3 plus/or Crown dieback with moderate lateral dieback
5	23 - 30	75%	- Class 3 plus/or Crown & Lateral dieback - Only living material is found close to tree trunk
6	31 - 40	95%	- Whole Needles Necrotic over all of tree - Needle Retention 1 - 0 yrs. - Lateral dieback - Crown dieback Standing Skeleton - (40 Points)

APPENDIX B

FLUORIDE CONCENTRATIONS IN VEGETATION FROM TEAKETTLE MOUNTAIN

Site No.	Elevation (ft.)	Plant Species	ppm Fluoride Months Exposure 2	14	26	38	Site No.	Elevation (ft.)	Plant Species	ppm Fluoride Months Exposure 2	14	26	38
2A	5080	D.f.[1]	56.9	130.0	187.4	231.0	2B	4190	D.f.	95.5	221.2	314.5	384.6
		A.a.[2]	249.7						A.a.	544.0			
		S.c.[3]	134.8						S.c.	258.2			
3A	5010	D.f.	42.4	90.3	142.9	192.5	3B	4120	D.f.	---	---	---	---
		A.a.	207.9						A.a.	401.8			
		S.c.	216.1						S.c.	390.6			
5A	5040	D.f.	49.8	224.6	311.9	426.9	5B	4180	D.f.	---	---	---	---
		A.a.	305.8						A.a.	426.0			
		S.c.	307.3						S.c.	586.3			
6A	4960	D.f.	57.4	216.9	365.7	461.3	6B	4280	D.f.	78.8	242.7	437.0	534.3
		A.a.	370.0						A.a.	607.1			
		S.c.	282.2						S.c.	378.7			
7A	4800	D.f.	42.9	93.9	235.6	250.3	7B	4040	D.f.	50.0	145.1	275.7	417.1
		A.a.	355.9						A.a.	395.1			
		S.c.	126.0						S.c.	308.5			
8A	4760	D.f.	18.1	109.9	155.1	212.8	8B	4080	D.f.	30.1	59.9	119.7	142.5
		A.a.	130.5						A.a.	183.8			
		S.c.	191.0						S.c.	136.1			
9A	4880	D.f.	23.6	65.6	96.0	155.1	9B	4120	D.f.	28.2	45.3	73.9	
		A.a.	105.1						A.a.	77.8			
		S.c.	88.2						S.c.	42.1			
11A	4720	D.f.	16.3	45.9	63.4	77.4	11B	3920	D.f.		39.7	59.5	78.0
		A.a.	45.0						A.a.	77.1			
		S.c.	72.7						S.c.	70.2			
Control A		D.f.	2.9	2.4		7.2	Control B		D.f.	3.5	1.9	4.3	3.6
		A.a.	3.6						A.a	5.7			
		S.c.	---						S.c.	3.3			

Site No.	Elevation (ft.)	Plant Species	ppm Fluoride Months Exposure 2	14	26	38
Control C	3240	D.f.	2.2	2.8	3.3	5.2
		P.c.[4]	3.5	2.5	2.4	a
		A.a.[5]	1.4			
		A.a.[6]	5.7			
		S.c.[5]	5.1			
		S.c.[6]	4.9			
1C	3200	D.f.	26.5	93.5	177.7	184.6
		P.c.	---	---	---	---
		A.a.	95.8			
		S.c.	91.7			
2C	3200	D.f.	94.2	311.5	480.6	591.7
		P.c.	46.4	185.3	343.8	368.2
		A.a.[5]	564.6			
		A.a.[6]	823.5			
		S.c.[5]	382.2			
		S.c.[6]	373.3			
3C	3200	D.f.	146.7	451.6	750.0	826.2
		P.c.	52.4	269.6	a	a
		A.a.[5]	1122.1			
		A.a.[6]	833.0			
		S.c.[5]	903.9			
		S.c.[6]	442.9			
5C	3220	D.f.	---	---	---	---
		P.c.	62.1	167.2	380.4	a
		A.a.	559.7			
		S.c.	819.8			

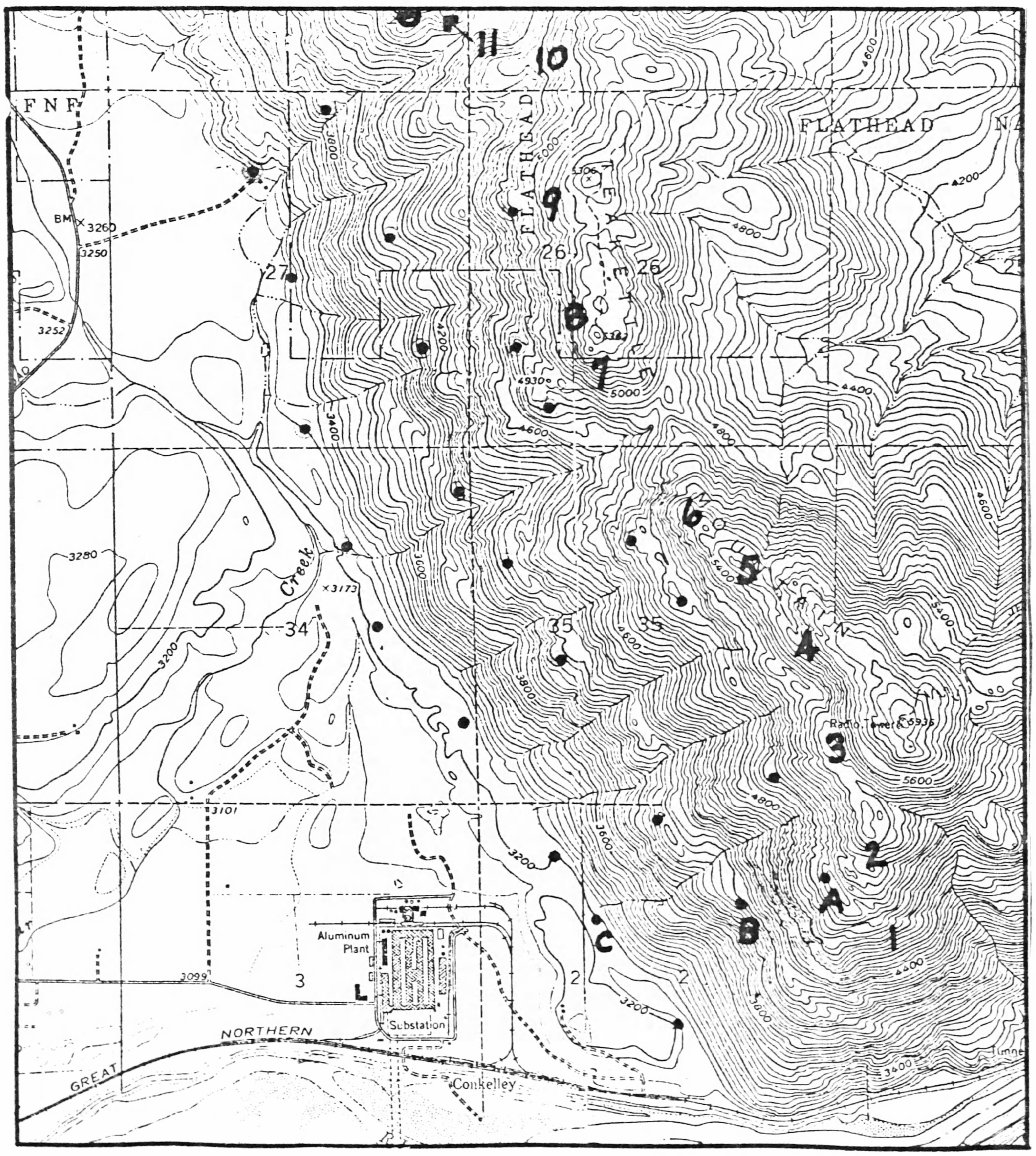
Site No.	Elevation (ft.)	Plant Species	ppm Fluoride Months Exposure 2	14	26	38
6C	3200	D.f.	53.7	165.0	205.5	221.7
		P.c.	30.7	65.0	152.0	a
		A.a.[5]	296.5			
		A.a.[6]	154.5			
		S.c.[5]	205.6			
		S.c.[6]	175.4			
7C	3220	D.f.	32.3	78.2	143.9	155.1
		P.c.	19.1	90.2	128.0	a
		A.a.[5]	153.2			
		A.a.[6]	116.7			
		S.c.[5]	186.7			
		S.c.[6]	151.7			
8C	3280	D.f.	36.5	54.6	85.4	86.8
		P.c.	10.8	54.1	84.4	b
		A.a.	79.6			
		S.c.	79.3			
9C	3300	D.f.	11.7	24.7	38.0	40.2
		P.c.	8.9	20.3	43.3	66.6
		A.a.	28.2			
		S.c.	27.0			
11C	3350	D.f.	20.9	40.9	95.8	83.8
		P.c.	22.6	52.0	81.5	b
		A.a.	65.6			
		S.c.	---			

1. *Pseudostuga menziesii* Mirbel (Franco) Douglas fir
2. *Amelanchier alnifolia* Nutt. (Service berry)
3. *Shepherdia canadensis* (L.) Nutt. (Buffalo berry)
4. *Pinus contorta* var. *latifolia* Engelm. (Lodgepole pine)
5. Sampled in the open.
6. Sampled 20 feet into the stand of trees.

a. Insufficient needle retention.
b. Needle minor infestation and insufficient needle retention.

APPENDIX C

C-1. Teakettle Mountain study area fluoride sample sites. Letters A through C represent vertical elevation. Numbers 1 through 11 represent distance from the aluminum plant.



C-2. Control study area fluoride sample sites.